REACTIVE POWER CONTROL IN DIYALA CITY RING POWER SYSTEM USING STATIC SYNCHRONOUS COMPENSATOR (STATCOM) DEVICE

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THESIS APPROVAL PAGE

I certify that in my opinion the thesis submitted by Mohammed Kadhim Mohammed AL-mamoori titled "REACTIVE POWER CONTROL IN DIYALA CITY RING POWER SYSTEM USING STATIC SYNCHRONOUS COMPENSATOR (STATCOM) DEVICE" is fully adequate in scope and in quality as a thesis for the degree of .

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Mohammed Kadhim Mohammed ALmammori

ABSTRACT

M. Sc. Thesis

REACTIVE POWER CONTROL IN DIYALA CITY RING POWER SYSTEM USING STATIC SYNCHRONOUS COMPENSATOR (STATCOM) DEVICE

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Population increase raise demand for energy. For this reason, new generation units must be installed to confront this challenge. Although installing new generating units is not difficult, but to increase power generation new transmission lines is needed which is a very cumbersome task. Technical, economic and governmental regulatory constraints encountered in the planning and operation of a power system. Power system engineers who face these challenges are looking for solutions to operate the system in a more flexible way. One of the most important solutions to this problem is to increase the capacity of the current transmission lines by adding new devices.

In this thesis, the challenge concerning power quality and the importance of management of reactive power is discussed. The role of FACTS devices in controlling reactive power is evaluated. Among FACTS family, STATCOM has the upper hand over other devices which is one of the objectives of this research to demonstrate. STATCOM was introduced on the 132 kV transmission lines to the Diyala city ring power system to enhance the stability of this network during transient abnormal conditions, through reactive power management. Load flow analysis of Diyala network that comprises 11-bus was performed using the Newton-Raphson method. Comparative results of load flow analysis with and without STATCOM showed an improvement in power quality with STATCOM in the studied system. The outcome of this study could motivate the decision makers in Iraq to adopt the idea of integrating such devices into the national electrical system.

Key Words : STATCOM, Reactive Power, Load Flow, Newton Raphson Method, Power System.

Science Code : 90513

ÖZET

Yüksek Lisans Tezi

STATİK SENKRON KOMPANSATÖR (STATCOM) CİHAZI İLE DİYALA ŞEHİR RİNG GÜÇ SİSTEMİNDE REAKTİF GÜÇ KONTROLÜ

Mohammed Kadhim Mohammed ALmammori

Karabük Üniversitesi
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Nüfus artışı enerji talebini artırıyor. Bu nedenle, bu zorluğun üstesinden gelmek için yeni nesil üniteler kurulmalıdır. Yeni üretim üniteleri kurmak zor olmasa da, elektrik üretimini artırmak için yeni iletim hatlarına ihtiyaç duyulmaktadır ki bu çok zahmetli bir iştir. Bir güç sisteminin planlanması ve işletilmesinde karşılaşılan teknik, ekonomik ve resmi düzenleyici kısıtlamalar. Bu zorluklarla karşılaşan güç sistemi mühendisleri, sistemi daha esnek bir şekilde çalıştırmak için çözümler arıyor. Bu sorunun en önemli çözümlerinden biri, mevcut iletim hatlarının kapasitesini yeni cihazlar ekleyerek artırmaktır.

Bu tezde, güç kalitesi ile ilgili zorluk ve reaktif güç yönetiminin önemi tartışılmaktadır. FACTS cihazlarının reaktif gücü kontrol etmedeki rolü değerlendirilir. FACTS ailesi arasında STATCOM, bu araştırmanın amaçlarından biri olan diğer cihazlara göre üstünlüğe sahiptir. STATCOM, reaktif güç yönetimi yoluyla geçici anormal koşullar sırasında bu ağın kararlılığını artırmak için Diyala şehir halka güç sistemine 132 kV iletim hatlarında tanıtıldı. 11 otobüsten oluşan Diyala ağının yük akış analizi Newton-Raphson yöntemi kullanılarak yapılmıştır. STATCOM'lu ve STATCOM'suz yük akışı analizinin karşılaştırmalı sonuçları, çalışılan sistemde STATCOM ile güç kalitesinde bir iyileşme gösterdi. Bu çalışmanın sonucu, Irak'taki karar vericileri bu tür cihazları ulusal elektrik sistemine entegre etme fikrini benimsemeye motive edebilir.

Anahtar Kelimeler : STATCOM, Reaktif Güç, Yük Akışı, Newton Raphson Metodu, Güç Sistemi.

Bilim Kodu : 90513

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SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS

FACTS	:	Flexible Alternating Current Transmission System
STATCOM	:	Static Synchronous Compensator
SVC	:	Static Var Compensator
TCSC	:	Thyristor-Controlled Series Capacitor
TCPST	:	Thyristor-Controlled Phase Shifting Transformer
SSSC	:	Static Synchronous Series Compensator
IEEE	:	Institute of Electrical and Electronics Engineers
HVDC	:	High Voltage Direct Current
DFC	:	Dynamic Flow Controller
VSC	:	Voltage Source Converters
GTO	:	Gate Turn-Off
IGBT	:	Integrated Gate Bipolar Transistor
IEGT	:	Injection Enhanced Gate Transistor
IGCT	:	Integrated Gate Commutated Thyristor
UPFC	:	Unified Power Flow Controller
TCR	:	Thyristor Controlled Reactor
TSA	:	Trajectory Sensitivity Analysis
DVR	:	Dynamic Voltage Restorer
PST	:	Phase Shifting Transformer
IPFC	:	Interline Power Flow Controller
TSC	:	Thyristor-Switched Capacitor
SVG	:	Synchronous Voltage Generator
NR	:	Newton Raphson
GS	:	Gauss Seidel

PART 1

INTRODUCTION

Power system stability is its ability to stay in a stable operating equilibrium status over normal operating circumstances and return to acceptable equilibrium status after subject to a disturbance [1]. One of the requirements for voltage stability is that the magnitude of bus voltage increases when the reactive injection of power in the same bus is increased to specific operating conditions for each bus in the system. The voltage of the power system is stable when the voltage after disturbance is close to the voltage under normal operating conditions. When voltages drop unpredictably owing to equipment failure or a sudden increase in demand, a power system becomes unstable. Although voltage stability is typically a local issue, its implications is highly effect on the power system. Voltage collapse and blackouts are a result of this effect. The generator reactive power restrictions, load characteristics, and transmission lines all play a role in the system's voltage stability. Voltage and reactive power regulation must be appropriately dealt with to keep voltage in the entire buses to satisfactory limits for efficient and dependable power system operation. When the load changes, the requirement of reactive power of the transmission system change. Due to the inability to transfer reactive power over long distances, losses increase. Hence, it is critical that voltage control be accomplished by identifying suitable compensating devices. The correct selection and placement of compensators for managing the reactive power and voltage are the key power system concerns [2].

The electric power system is an important dynamic system which operates in a dynamic environment with continuously changing loads, generator outputs, and important operating elements [3]. The system stability is determined by the nature of the disturbance that may affect it, as well as the circumstances in which the disturbance may happen for a short or long period [4].

The electric power system has various operation status besides time-varying configurations and characteristics. With the growth of the population, the demand for energy increases. As a result, there will be a constant need for new generating units to meet this demand. It is not difficult to install new generating units, but as electricity generation escalates, new transmission lines must be constructed. The task of installing new transmission lines is very difficult. Constraints in planning and operating of a power system include technical, economic, and regulatory regulations [5].

In modern power systems, the power grid has become more adaptable because of the new progress and innovations in technology of power electronics, where all variables in the system, including phase angle, reactive power, active power and voltage, can be controlled using self-switching devices. Engineers are looking for ways to operate the system flexibly and efficiently. One of the basic solutions to this problem is to add additional devices to existing transmission lines to increase their capacity i.e., power flows [6].

The phrase "power flow" denotes to the actual and reactive power flows which pass through a power system during steady state conditions. These power flow researches are necessary for the electrical system to be evaluated and analyzed on a regular basis and in near real-time operation. Such studies are also utilized in power systems design and planning [7].

Procedures for assessing system security and stability analysis of traditional power flows do not incorporate devices such as FACTS controllers which have been developed recently. In developing country such as Iraq that has many problems related to power sector particularly power quality, there are only a few researchers in this field who have dealt with the problem of how to simulate and implement FACTS devices for calculations of load flow and improve the power quality [8].

FACTS modeling in power flow studies has become a significant research subject. It arises as a prerequisite for power system analysis, planning, design, and control operations. Many models for FACTS devices that are used in power flow calculations have been performed generally using the Newton-Raphson approach due to its outstanding quadratic convergence capabilities. The steady state models development of FACTS controllers, specifically STATCOM, has been reported by several researchers [9].

In the seventies of the last century, Hingorani suggested the use of power electronics in power system adjustment. Later, several studies on the use of high-power semiconductors in transmission networks have been applied. FACTS is defined by Hingorani as the idea and presented the vast range of potential applications in 1988. FACTS technology has showed a lot of promise recently. There are numerous FACTS devices and controllers currently in use [10].

With FACTS devices help, power systems instability can be alleviated or minimized. The use of FACTS controllers in power transmission systems has resulted in a wide range of applications for these controllers including not only improving the present power network resources stability but also providing operational flexibility to the power system [11]. Furthermore, because FACTS technology requires a lower initial investment than new transmissions or generation services, it helps industry to better use the present transmission and generation investments, thereby improving the performance of power system. The generated electricity would have to be routed through the national system to various load centers across the country [12]. FACTS devices are considered high speed electronic devices that deliver or absorb actual and/or reactive power, considerably improving performance of power system. Additionally, they enhance supply quality and make the most use of available resources [11].

Generally, the connection mode of power system classifies the FACTS devices into three categories which Shunt devices, including the SVC and the static synchronous compensator (STATCOM) that mainly utilized for voltage control and reactive power flow control; series devices, such as TCSC, TCPST, and SSSC. The series devices are primarily utilized for active power flow control.

Controlling the power flow and improving system stability are vital for establishing a match between demand and supply of power, which FACTS devices can help with. FACTS machinery has now become indispensable. Using FACTS devices to increase the efficiency of the electricity system has become a need. FACTS devices are a low-cost alternative to building new transmission lines [11].

A FACTS device is controlled by one or more parameters within the power transmission system. The quantity of voltage, the voltage angle, and the transmission line impedance are among these characteristics. Real and reactive power, flux, voltage, and the compensation of reactive power can all be regulated by adjusting these parameters [12].

STATCOM that is utilized to correct the instantaneous reactive power to improve the system voltage profile and make the electrical system more stable and reliable, is the most important equipment among the FACTS devices. STATCOM is a shunt-type of FACTS controllers that can use either a voltage- or current-sourced converter. STATCOM is used in a variety of applications, including [13]:

- Increasing the capacity of existing transmission lines.
- Transmission line voltage regulation.
- Improving transient and steady-state stability.
- Improving power oscillation damping.
- Damping and power factor correction.
- Getting rid of current harmonics.
- Improving the performance of HVDC-links.

When the system voltage is low (STATCOM is capacitive), STATCOM devices provide reactive power. The system absorbs reactive power (STATCOM inductive) when it is activated due to the high voltage. The device is made up of blocks which are inter-connected. A DC-link capacitor, a transformer, a measurement system, an inverter/converter circuit, a controller, and a transformer. The STATCOM's primary working principle is based on coupling inductance between two AC sources (System and STATCOM) with the same frequency. Adjusting the amplitude of the VSC output voltage allows for the exchange of reactive power between the system and STATCOM (Vout). The reactive power exchange among the STATCOM and the system will be zero if the amplitude of the VSC output voltage is equal to the voltage of the system [14].

1.1. PROBLEM STATEMENT

The Iraqi electricity system includes high voltage transmission lines of 132 kV and 400 kV. The Iraqi Central Region National Network (ICRNG) is a vital populated area represented by the cities: Baghdad, Diyala, Anbar and Waist. The load demand of Diyala Governorate represents a significant percentage of total load of ICRNG. The national network of Diyala consists of 11 bus bars at 132 kV. As a result of the overload, the public utility serving Diyala governorate witnessed many equipment malfunctions, in addition to frequent outages within the electricity system. Furthermore, technical problems such as power fluctuations, oscillations, and loss of synchronization were also present. These conditions generate problems in the electricity system, ranging from instability to blackouts. When the active and reactive power balance fails, or when the associated devices fail to provide the required reactive support, voltage breakdown occurs. In addition to overloads, continuous demand in the electrical power system grid leads to system instability and thermal boundary stress.

1.2. METHODOLOGY OF RESEARCH

1. Surveying FACTS devices in literature and related studies.
2. Collecting all information and data for the electrical network of Diyala city.
3. Programming the Newton Raphson algorithm for load flow studies.
4. Comparing the results before placing the STATCOM device and after placing the device using IEEE standard test systems.

5. Simulating the Diyala city power system in MATLAB and implementing the STATCOM devices and reporting their effect.

1.3. OBJECTIVE OF RESEARCH

1. Investigating the implementation of the Static Synchronous Compensators (STATCOM), to improve the capacity performance of the general power transmission network of the city of Diyala.
2. Finding the appropriate location for the STATCOM devices and the appropriate capacity for each loading situation as well as arriving at the appropriate values for the components of STATCOM.

1.4. SIGNIFICANCE OF THE STUDY

By providing reactive power locally, it is possible to reduce the loading of transmission lines, enhance the stability of system voltage, and raise the available lines utilization. This is achievable using static synchronous compensators, which have been successfully tested in a variety of systems around the world. As the load demand increases, it is necessary to add additional lines or enhance the utilization of existing ones. Since it is difficult to install additional lines, especially in crowded areas, enhancing the performance of existing lines would be the best choice. This can also be achieved by the use of STATCOM devices and this is our plan for the Diyala city transmission system asset. The significance of this research can be summarized as follows:

1. STATCOM is used in electrical systems to relieve the overloaded lines. This would postpone investment cost related to network extension infrastructure.
2. Improving the stability and quality of the Diyala power network and increasing the utilization of available lines.

1.5. THESIS ORGANIZATION

The thesis consists of five chapters; the first chapter provides an introduction, problem statement of the study, methodology and the research objectives. In the second part, provides a literature review on the topic is presented. Detailed methodology of the research is introduced in chapter three. Simulation results are analyzed in chapter four. In the chapter five of the thesis, main conclusion and future work are provided.

PART 2

LITERATURE REVIEW

2.1. INTRODUCTION

The continual demand in the electric power system network has overloaded the system, causing voltage instability. On the other hand, FACTS devices includes important characteristics to avoid the technical difficulties of the power system. Also, these devices enhance the transmission lines effectivity. STATCOM is considered a member in FACTS family. It injects compensatory current with line voltage in phase quadrature; it can imitate inductive or capacitive reactance to provide capacitive power for the AC grid or to pull inductive power from the AC grid to manage line power flow [15]. The power networks expose to sever challenges because of increasing demand and the market operations. This requires to operate the network to be closer to its stability limits. Stability issues wreak havoc on power system operations, resulting in unpredictable system behavior. Network extensions are chosen over cost-effective options. Permits to install new transmission lines are difficult to come by in many nations; therefore, the existing network must be enforced to meet changing demands [16].

The power in power system moves from the generation station to the load across many network branches. The reactive or active power flow is called power flow or load flow. The analysis of load flow is utilized by the power engineers to plan and determine the steady status operation of the power system. Researches and studies about power flow offer a systematic mathematic model to determine reactive power flows, phase angles, bus voltages and active by various branches, transformer settings, generators and load over steady-state circumstances. The electric circuit is used to represent the power system which consists of generators, generators, transmission, and distribution. A distribution network and a network [17].

The basic outputs of power flow or load flow analysis are the phase angles of load bus voltage and magnitudes, voltage phase angles and voltage phase at the generator bus, real and reactive power flows on lines of transmission and power in the reference bus and other variables are stated [18]. Power flow equations, which are nonlinear equations in terms of power, should be solved by the use of iterative procedures and digital approaches. The digital approaches are strategies for structuring the mathematical equations and therefore they can be solved using the arithmetic procedures only [19].

In the last three decades, various mathematical analysis methods were used in order to solve the analysis of load flow problems throughout. Gauss-Seidel, Newton-Raphson, and Fast Decoupled techniques [20],are the most often utilized iterative algorithms. With the advancement of industry in society, the power system grew, and the dimension of the load flow equation grew to thousands. It is not possible for any numerical method to be close with a correct answer at this growth. At this regard, electrical engineers must search for more reliable solutions. The challenge for power industry is to determine the most suitable method for power system study. In order to determine the optimal solution to analyze the flow of power, it is necessary to get high degree of accuracy and faster time of solution [21].

Hand calculations are fine for estimating the operational parameters for few circuits of individual, but accurate predictions of load flows or short circuits is impossible without using computer systems. Since the mid-1950s, digital computers have been used in order to calculate load flow. Different methods for calculating load flow have been utilized. The core requirements of load flow computation, including convergence qualities, processing efficacy, memory demand, ease, and conduction flexibility have driven the development of these approaches [21]. Researches and studies of the entire types of power system such as load flow, may now be conveniently implemented because to the existence of quick and large-screen digital computers [22]. Because the numerical method uses a computer to discover a solution, it is important to figure out which numerical approach is the fastest and most consistent to get the best results of load flow analysis [21].

2.2. REACTIVE COMPENSATION

As system demand fluctuates, the presence of reactive power and the transmission system's requirements fluctuate as well, causing congestion in the transmission corridor and leaving limited room for active power flow. Excessive demand for reactive power at load centers causes RI^2 and XI^2 losses, as well as voltage decrease, resulting in overall system voltage instability. Unfortunately, in such conditions, meeting system power demand through the transmission corridor may be impossible due to insufficient reactive power supply and reserve limitations voltage [23].The active power generated cannot be efficiently transported to the load centers due to these transmission line problems, necessitating the need to improve the transmission lines loading capability. Voltage regulation must be achieved using specific devices scattered throughout the system since reactive power cannot be economically and effectively delivered over long distances [24].To ensure efficient distribution of real power to the loads independent of the transmission lines and maintain the voltage at the load buses, compensation must be manually or automatically implemented into the system [23].

Absorb or generate an appropriate amount of capacitive or inductive reactive power to achieve one or more desired effects in an electric power system is known as reactive power adjustment [25].Improved voltage profiles, higher stability, and increased transmission capacity are among these effects. There are two forms of compensation available: Compensation for load and line.

2.2.1. Load Compensation

This is the reactive power regulation in order to enhance quality of supply in terms of voltage stability and power factor levels. However, in an ideal circumstance, the reactive power absorbed should equal the reactive power created, resulting in a flat voltage profile. However, losses cause the reactive power in the system to fluctuate. As a result, in order to maintain a sufficiently flat voltage profile, reactive power generation is controlled or changed concurrently regarding a single load, and the recompensing device is linked to the load [23]. In order to avoid the extra cost of larger conductors and limit transmission line losses, researchers recommend that transmission networks be designed depending on the capability of active power transfer and that reactive power be met nearby by connecting shunt compensating devices (capacitors and inductors) at the point of load where they are needed [24].

2.2.2. Line Compensation

Line compensation requires to use electrical circuits to alter the electrical lines features particularly the line length, in order to improve power transfer capacity, maintain a near flat voltage profile, and achieve a cost-effective method of reactive power management. In general, series and shunt compensators, such as capacitors and inductors, are placed at appropriate positions on the line to change the effective transmission line impedance, allowing more power to be transferred [24]. Enhancing load ability is based on this principle. The load ability of a transmission line can be defined as the transmission line's maximum power transfer capability under a certain set of operating conditions. To maintain the power system safely and to benefit from the transfers of bulk power, the transfer abilities should be estimated, and the power system must be planned and controlled similarly that the power transmitted does not exceed the transfer capability ,transmission lines' power transfer capability is limited by heat constraints, voltage drop limits or control restrictions, and stability limits [24].

2.3. THE CRITICAL NEED FOR REACTIVE POWER COMPENSATION

Because active power cannot flow if system voltage is not high enough, and controlled reactive power is critical to active power transfer across the lines of transmission and distribution to load centers, voltage and reactive power control are two major features of power system support for reliability and transaction across transmission systems. The system creates reactive power which should be sunk at low system loading, but it consumes a lot of reactive power which should be replaced at high system loading. Consequently, the reactive power consumption of the system over time as load levels vary needs to be investigated and applied [26].

Voltage support and load adjustment are the two basic functions of reactive power compensation. The compensation of reactive power is used in voltage support to decrease the voltage variation at a specific transmission bus or distribution line to the bare minimum, whereas the goal of load compensation is to enhance the power parameter of the system, provide voltage regulation, balance the per phase real power consume from the AC supply, and mitigate voltage flicker caused by large nonlinear industrial loads. When reactive power in a transmission system is corrected, the communicable active power increases, improving stability of system, it maintains a significant level of voltage profile at all levels of transmission and distribution, increases transmission line efficiency, manages transitory overvoltage, and lowers the occurrence of blackouts. In addition, the dynamic reactive compensation of power necessary to minimize the slow increase or decrease of voltage, the quick increase or decline of voltage, and the overvoltage generated by switching transients [27].

2.3.1. Impact of Reactive Power on the Power System

Blackout is one of the major consequences of inadequate reactive power in the electrical system (power outage). A blackout can refer to the loss of electric power supply to a specific sector of the power system network for a short or lengthy period of time. Blackouts appear to be similar in different countries around the world as measured by the duration of the disruption. A power cut in the United Kingdom is defined as a power disruption lasting more than three minutes, but a power cut in Sweden and the United States lasts one and five minutes, respectively. There is no clear definition of how big a blackout is [28].

The majority of large transmission blackouts are produced by a single event that causes cascading outages and eventually the system's entire collapse. Over years, engineers and academics have attempted to reduce the original catastrophe in order to avoid the possibility of further line and generation outages. Given the immensity and complexity of today's power systems, it may not be possible to completely prevent system blackouts, but there are techniques to reduce the risk of blackout by understanding the fundamental cause and nature of incidents. Blackouts can be caused by human mistake, a single transmission line failure, or a generator failure. However, prompt operator involvement or adequate automatic management can prevent a single accident from resulting in a large blackout [29].The shunt and series reactive power principles are the same alternatives to compensation which are outlined below [26].

2.4. SHUNT COMPENSATION

A simple AC system is constituted by a source, power line and standard inductive load. The principles and theoretical consequences of shunt reactive power compensation are depicted in Figure 2.1. Figure 2.1(a) clarifies the system without compensation and the related phasor graph. The phase angle of the current in the phasor graph is linked to the load side which refers that the active current in the phase with load voltage. Because the load is designed to be inductive, it needs reactive power that should be connected by the source, which raises the current by the generator and via the power lines as a result. The current of line can be eliminated or decreased if the reactive power is supplied near the load which decrease the loss of power and enhance the voltage at the load terminals. This can be accomplished by the use of one of the following three methods:

1. Using a capacitor.
2. Making use of a voltage source.
3. Using a live source.

The current source device (b) is used in order to compensate for the reactive component of the load current in Figure 2.1. As a result, regulations of system voltage improves, and the reactive current element of the source is removed or reduced completely [26].

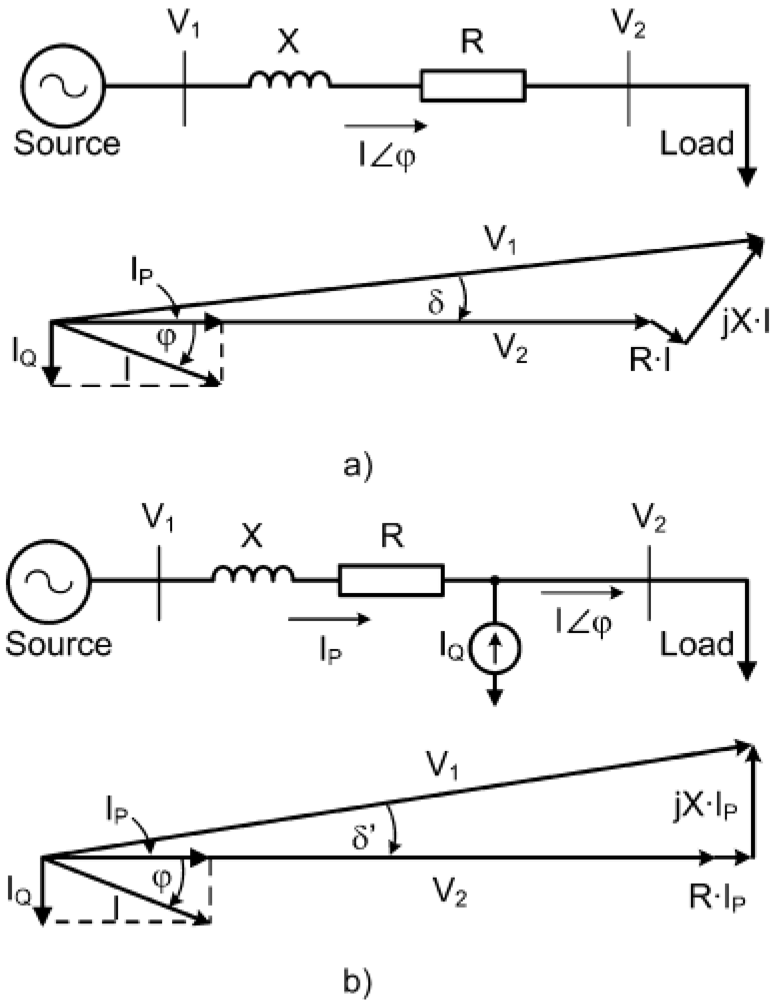


Figure 2.1. Shunt compensation concepts in radial system: (a) without compensatory action (b) current source shunt compensation.

The indicator is necessary if the load requires leading modification. In addition, the source of voltage or current is used to compensate the inductive shunts. The reactive power created by voltage- or current-source Var generators (rather than inductors or capacitors) is unaffected by voltage at the connection point [29].

2.5. SERIES COMPENSATION

In general, the capacitors are commonly utilized in the series compensation system in order to minimize the equivalent reaction of the power line at decreased frequency. The series capacitor connected to series produces reactive power which self-regulates a percentage of the line's transfer reactance. The power transmission system's functionality is improved due mainly to:

1. Increased power corridor angular stability.
2. Better power corridor voltage stability.
3. Improved power distribution between the parallel circuits.

Series compensation such as shunt compensation, can be used with current- or voltage-source devices recompense for shunt. The angle would be changed in this case by the addition of voltage among the line and the load, which is now the voltage at the load side. When the size is adjusted appropriately, the power factor of unity can be attained. Because it lags the current, creates a voltage in the opposed direction of the line inductance voltage descent, as shown in the phasor chart of Figure 2.2 (b) [29].

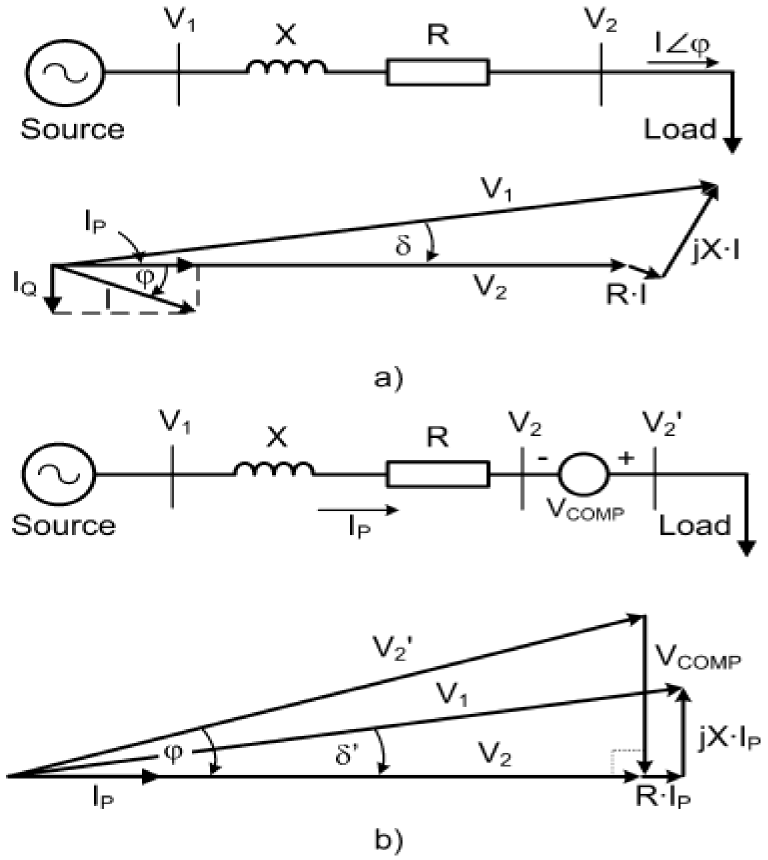


Figure 2.2. Series compensation principles a) Without compensation, the same system as in Figure 2.1(a). b) voltage source compensation in series.

As previously stated, the most typical technique is series compensation with capacitors. As illustrated in Figure 2.3, the series capacitors are connected in series with the line of transmission, implying that the whole equipment should be located on a platform which is adequately isolated for the system voltage (both of the terminals in the line voltage). In addition, the main capacitor overvoltage protective circuits are positioned on this platform [29].

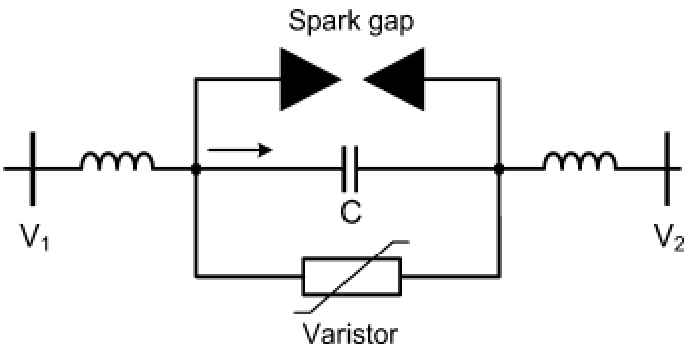


Figure 2.3. The compensator of series capacitor and related protection system.

Because the capacitor bank must sustain the throughput fault current, even in the event of a catastrophic local fault, overvoltage protection is a critical design feature. The nonlinear metal–oxide varistors, a spark gap and the quick bypass switch are commonly utilized as primary overvoltage protection. The secondary protection is provided by ground-mounted electronics that react to signals from the high-voltage circuit's optical current transducers. Var generators must meet a variety of requirements, regardless of the source type or system design, in order to operate successfully. Some of those needs are harmonic distortion, cost, dynamics, reliability and controllability. The sections that follow explain several Var generating solutions, in addition to their associated operating principles and compensation features [29].

2.6. POWER ELECTRONICS APPLICATION IN POWER SYSTEM

Electrical power transmission occurs at high voltages and sometimes above long distance, while the distribution occurs at lower voltages and regularly above short distance [18]. This disparity arises from the fact that the power transmission quantity is influenced by both voltage and current while the losses are mostly influenced by current and distance traveled. By decreasing the current and increase the line voltage, the power losses across distances and the power transmission amount can be decreased. However, the amount of components and bulky are increased when the voltage increases. Consequently, minimizing power loss comes at a price. As such, capital expenditure for equipment to minimize losses for efficient power transfer is an option. Its application in the systems of distribution and transmission has greatly increased. HVDC connections and FACTS are both employed in the transmission system as power electronics devices (FACTS). HVDC links are used to transport electrical power in a different way, whereas FACTS devices are used to adjust for and improve AC systems [29]. Recently, using power electronics devices has largely increased.

The first power electronics device to be utilized on a transmission line was the HVDC transmission system [17].HVDC is more commonly used in long-distance overhead and underground transmission networks as a power transmission alternative. It's also used to connect different frequency AC systems [18].FACTS devices are used to correct for and improve an existing AC transmission system with a need to increase the system's power delivery capacity. It has been established that there is a dramatic increase in demand of electrical power, resulting in transmission system difficulties [19].When you consider the time and money it takes to establish a new transmission line, FACTS emerges as a feasible and appealing option.

2.7. FACTS (FLEXIBLE AC TRANSMISSION SYSTEMS)

The AC transmission system has two types of constraints including the static limits and dynamic limits. The power transactions are decreased because of the limitations in internal power system which decrease the use of the current transmission capacity. The synchronous generators, capacitors, series and shunt are all used to solve many problems. Nevertheless, the use of these traditional tools are restricted. The desired performance could not be achieved successfully. Wear and tear on mechanical components, in addition to delayed response, were at the root of the problems. Another solid-state electronic technology with fast reaction abilities was in increasing demand.

Global reorganization of electric firms, tighter ecological and efficacy rules, and the trouble of acquiring licenses and right-of-way to construct above transmission lines have added to the demand. All of this with the discovery of the Thyristor switch (semiconductor device), cleared the door for FACTS regulators in power electronics. The leap from old Thyristor-based FACTS regulators to current state-of-the-art voltage source converter-based FACTS regulators make it possible to quick development in high-power semiconductor devices [30]. FACTS controllers are used at efficacies in the whole countries since the 1970s, when the first efficacy installation of the first FACTS family, the Static VAR Compensator (SVC), was completed. FACTS controller research and development has taken a long time since then. The FACTS technology allows you to do the following [31]:

- Increase transmission line loading capacity.
- Avoid power outages.
- Boost generation efficiency.
- Decreases the quantity of circulating reactive power.
- Increases system stability.
- Cut down on voltage flicker.
- Reduce damping and vibrations in the system.
- Manage power flow so that it follows the authorized paths.

Because of limited resources and environmental constraints, the usage of electrical power has expanded dramatically recently, while the growth of power generation and transmission has been rigorously regulated. Transient stability is a critical factor in maintaining system stability in the face of high liabilities and disruptions. The FACTs devices can regulate the flows of reactive and active power in the line of transmission, as well as improve the performance of bad ac systems and increase transmission capacities across long AC lines, by adjusting the series and shunt characteristics.

The FACTs devices have the potential to increase system performance and power flow across transmission lines [2]. In addition, these devices are utilized to enhance the steady state of transmission lines and transient stability, control dynamic response, enhance voltage stability, and control impedance and phase angle [3].

Power systems are nonlinear systems that operate under a variety of situations and have time-varying setups and characteristics. FACTS were created to increase the weak ac systems performance and to improve capacities of transmission through lengthy ac lines.

All three status of the power systems are covered by FACTS controllers: post transient steady state, steady state, and transient. FACTS devices are used to control active and reactive power in addition to voltage magnitude [4, 5]. FACTS are solid-state flexible devices that help transmission lines handle more power, have better transient stability, system dependability, load management, and control of power flow. The conventional (mechanically switched) and power electronics-based devices are the two types of power flow control devices. There is shunt, series, and mixed placement modes for this technology in the network, as depicted in Fig. 2.4.

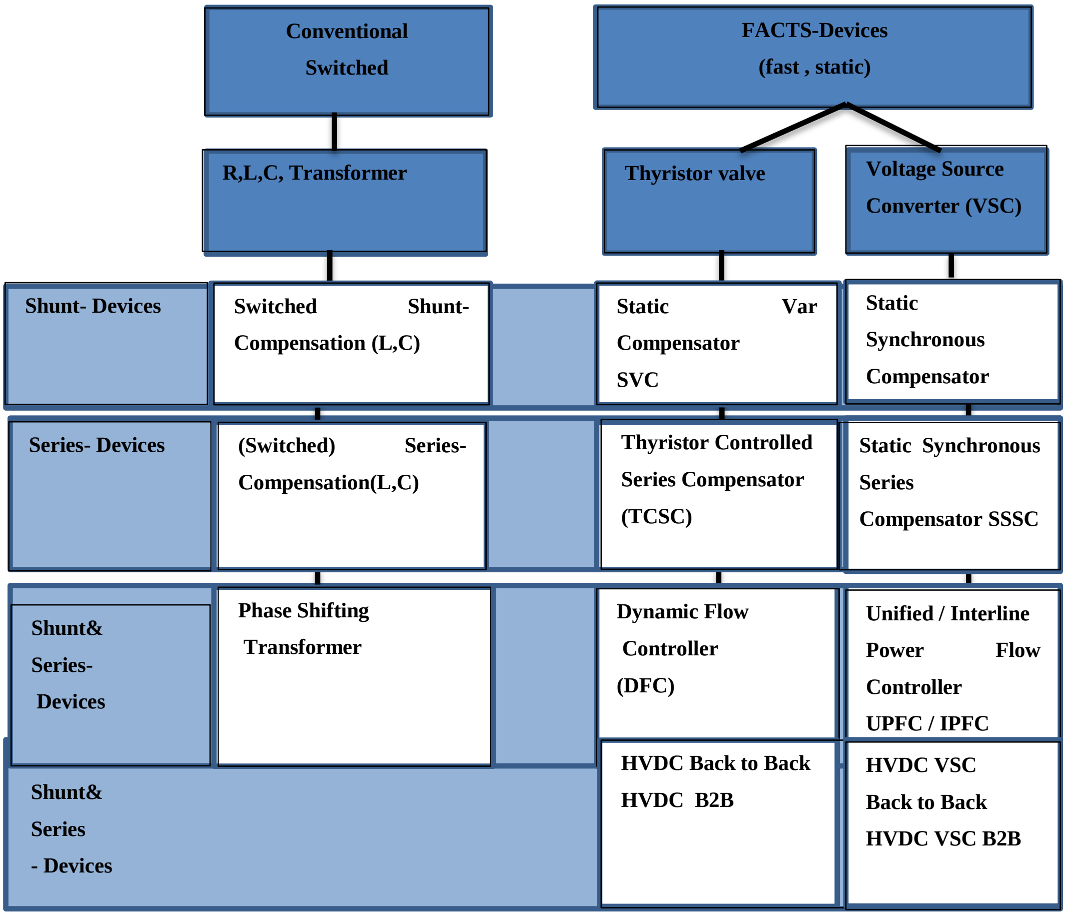


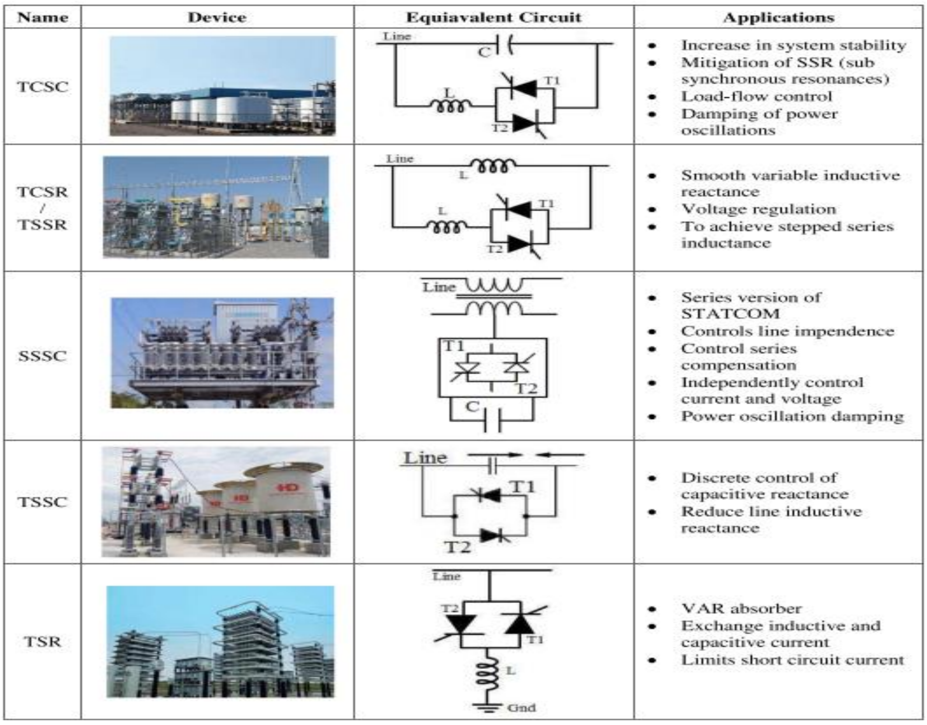
Figure 2.4. Types of power flow control devices.

2.7.1. Types of FACTS Devices

Reactive power compensation devices come in two varieties, the first employs traditional thyristor switched reactors and capacitors, while the second employs VSC such as GTO thyristor, IGBT, IGCT, and IEGT [32]. FACTS and its controllers are an irregular current transmission system comprised of power electronic-based static controllers designed to enhance the system variable managing and power transfer capability in the electric power transmission system. Many mechanically controlled reactive power compensators have been replaced by electronics-based FACTS devices, and they are now playing an essential part in the operation and control of modern power systems [33].FACTS devices are divided into four groups:

1. Series devices
2. Shunt devices
3. Combined Series-Series devices
4. Combined Series-Shunt devices

Figure 2.5 illustrates how FACTS devices and equivalent circuits are used. FACTS devices have significant advantages, as can be seen.



Name	Device	Equiavalent Circuit	Applications
TCSC		Line, C, L, T1, T2	• Increase in system stability • Mitigation of SSR (sub synchronous resonances) • Load-flow control • Damping of power oscillations
TCSR / TSSR		Line, L, L, T1, T2	• Smooth variable inductive reactance • Voltage regulation • To achieve stepped series inductance
SSSC		Line, T1, T2, C	• Series version of STATCOM • Controls line impendence • Control series compensation • Independently control current and voltage • Power oscillation damping
TSSC		Line, T1, T2	• Discrete control of capacitive reactance • Reduce line inductive reactance
TSR		Line, T2, T1, L, Gnd	• VAR absorber • Exchange inductive and capacitive current • Limits short circuit current

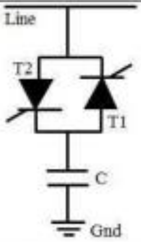
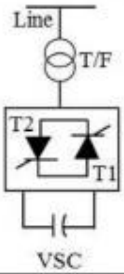
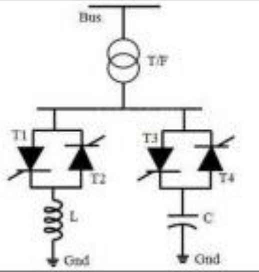
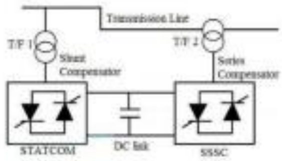
Name	Device	Equiavalent Circuit	Applications
TSC			• Controls power harmonics • Optimize reactive power • Eliminate harmonic current • Reduce grid loss T/F load ability • Improve Power factor • Suppress synchronous resonance
STAT COM			• Grid transient stability • Inhibit 3 phase un balance • Restrain voltage flicker • Power factor improvement • Voltage regulation • Reduce line loss
SVC			• Damping of power oscillations • Increase in system stability • Dynamic reactive power control • Improvement in voltage quality
UPFC			• Two-way power flow control • Reactive/active current compensation • Impedance control • Transmission angle control

Figure 2.5. Type of FACTS with equivalent circuit and application, source: ABB and Siemens.

2.7.1.1. Series Devices

As indicated in Fig. 2.6, these devices can be a variable impedance device like a reactor, capacitor, thyristor switched device or a power electronics-based variable source that injects voltage in series with the line. The injected variable series voltage is equal to the variable impedance which multiplied by the current going over the line. In this case, the device requires the usage of an outside source of power. The variable reactive power is created or absorbed when the voltage is greater than 90 degree out of phase with the line current [34].

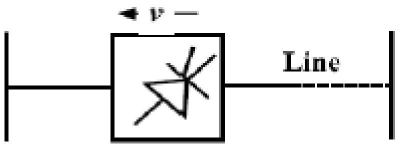


Figure 2 6. Basic Series FACTS Device

2.7.1.2. Shunt Devices

The shunt devices may include variable current or voltage source, reactor, impedance, capacitor or a power electronic based variable source which is attached to the shunt of the system to inject the current of the variable to the line as shown in Figure 2.7. the shunt devices may either absorb or supply the variable reactive power when the injected current is more than 90 degrees out of the phase with the voltage of line [34].

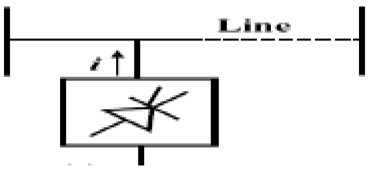


Figure 2.7. Basic shunt FACTS device.

2.7.1.3. Combined Series-Series Devices

Combined series devices combine between two or more distinct series devices that are all controlled in the same time. These devices can use the DC link to balance both the actual and the flow of reactive power in line allowing the system of transmission to be fully utilized. For true power transfer, the DC terminals of all device converters are connected together, hence the name Unified Power Flow Controller (UPFC). The series-shunt mechanism is depicted in Figure 2.8 [34]

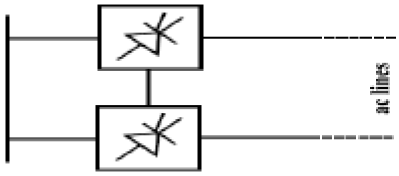


Figure 2.8. Basic series-series FACTS device.

2.7.1.4. Combined Series-Shunt Devices

They are devices that coordinate the operation of many series and shunt controllers. With the series component, both of the shunt controllers and combined series inject the voltage in series in the line, and with the shunt part, current to the system. Fig. 2.9 depicts a series-shunt device [34].

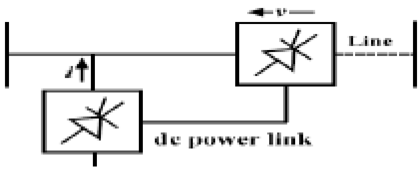


Figure 2.9. Basic Series-Shunt FACTS Device.

2.8. FACTS SERIES CONTROLLERS

As indicated in Figure 2.10, these FACTS controllers could be variable impedance devices such as reactors, capacitors or power electronics-based variable sources which is in theory, inject voltage in series with the line. Given that the voltage is in quadrature stage with the current of line, the series controller only distributes or ingests the variable reactive power. Dealing with true power will be a part of any other phase relationship. The following are some of the most common uses for series compensators:

1. Keeping voltage fluctuations to a minimum during power transmission changes.
2. System oscillation dampening improvements.
3. Short circuit current limits in networks or substations [26].

The power system load ability and stability are improved by the use of the series FACTS devices. These devices work as a variable inductive or capacitive impedance that may be altered in the series with the line of transmission to dampen fluctuation in the system, as illustrated in Figure 2.10. This can be implemented by the injection of correct voltage phasor in series with the line of transmission that visible as a voltage through series impedance. If the voltage of line in the phase quadrature with the current of line, the controller sinks ore generates reactive power. otherwise, the device sinks or generates active and reactive power. Equations (2.1) and (2.2) below are used to manage the power flow.

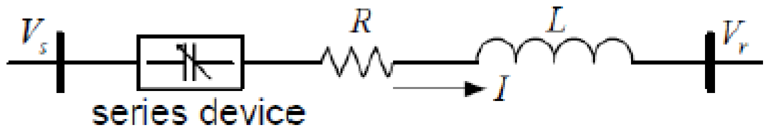


Figure 2.10. Series FACTS Device operating principle.

$$Pr = |Vr||Vs|X \sin\theta \quad (2.1)$$

$$Qr = |Vr||Vs|X \cos\theta - |Vr|X \quad (2.2)$$

A portion of the transmission line reactance is balanced by the gadget through the capacitive mode. The reactance will be enhanced in an inductive mode to decrease the flow of the power [35].

2.8.1 Thyristor Controlled Series Capacitor (TCSC)

IEEE defines the TCSC as "a capacitive reactance compensator which consist of a series capacitor bank shunted by a thyristor controlled reactor to deliver a efficiently shifting series capacitive reactance"[2]. TCR branch reactance is controlled by inverse-parallel thyristor, and the total impedance of the TCSC is modified by a fixed capacitor[36].TCSC modifies line impedance in a single cycle [37],making system control faster than with a mechanically switched device. The TCSC configuration is shown in the diagram below suggests TSA approaches to analyze the power system transient solidity with TCSC under various operating situations [38].

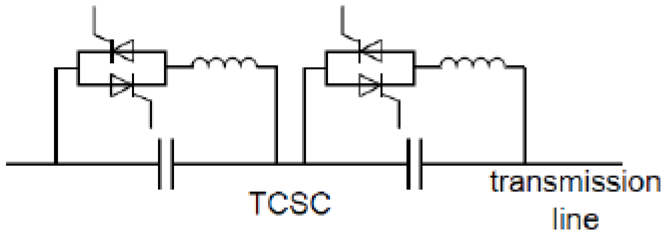


Figure 2.11. TCSC configuration.

2.8.2 Thyristor Switched Series Controller (TSSC)

TSSC can be defined as "a capacitive reactance compensator which consist of a series capacitor bank shunted by a thyristor switched reactor to offer step-wise regulation of series capacitive reactance." The TSSC switches the capacitor bank with a thyristor, which provides a quicker reaction comparing with mechanical compensator switches. The TSSC can only inject capacitance into the lines, as shown in Figure 2.12 below; it cannot limit the current flowing through them. [36].

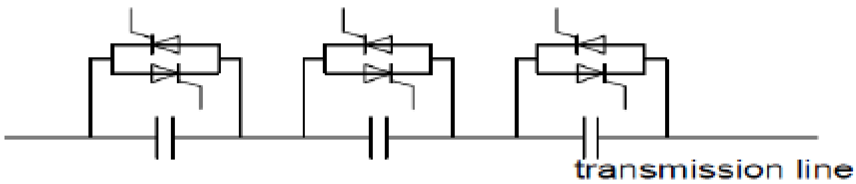


Figure 2.12. TSSC configuration.

2.8.3 Static Synchronous Series Compensator (SSSC)

SSSC is linked in series with the transmission line (SSSC). It obliquely injects a regulated voltage magnitude to the line. The SSSC's manner of operation for managing the transmitted electric power determines the voltage injected. The SSSC is a series compensator that operates without the use of an external energy source and has an output voltage that is in quadrature with the current of line and can be regulated autonomously of it. The aim is to control the flow of power by adjusting the entire reactive drop of voltage through the line.[36].A SSSC line layout is shown in Figure 2.13.

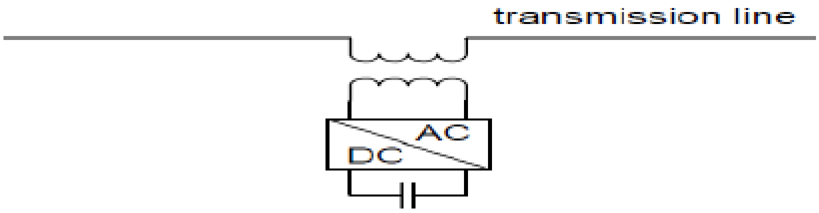


Figure 2.13. ASSSC line configuration.

2.8.4. Dynamic Voltage Restorer (DVR)

The DVR is a VSC which is frequently coupled in series; this configuration allows it to automatically alleviate voltage dips by injecting voltage directly whenever there is a voltage drop [23]. The connecting of a DVR to a distribution system is shown in Figure 2.6. The main benefit of using DVR to reduce the voltage drop is its dynamic performance and it is independent of the source impedance. It's also useful for compensating for uneven voltage and filtering voltage harmonics. The device's only drawback is a cost increase due to the need for an enhanced protection system in the event of a short-circuit problem farther down the device [39].Table 2.2 tabulates a a functional comparison between SSSC, TCSC, and TSSC.

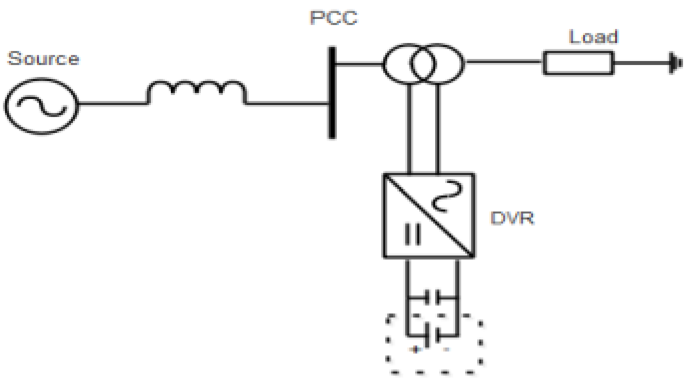


Figure 2.14. DVR connected to a distribution grid.

Table 2.1. Comparison in the functional details between the converter type and thyristor type series compensation devices.

SSSC	TCSC	TSSC
The SSSC is a series compensator for voltage source inverters	The TCSC is a series compensator of the impedance type.	The TSSC is a series impedance compensator.
The SSSC is responsible to internally generate a programmable compensatory voltage spanning equal Inductive and Capacitive ranges, regardless of the line current amount.	The TCSC may preserve recompensing voltage and reducing the current of line throughout a control range determined by the current boosting competencies of the thyristor measured reactor..	The compensatory voltage of the TSSC is relative to the current of line through a specified range of control.
Regardless of the series compensation degree, the SSSC can line with an outside DC power source to deliver compensation to the resistance of the line by injecting real power in addition to compensation for line reactance by injecting reactive power, in order to maintain a high efficient X/R ratio.	The only power which can be exchanged between the TCSC and transmission line is the reactive power not the real power.	The only power which can be exchanged between TSSC and the transmission line is the reactive power not the real power.
The GTO thyristors is used by SSSC. Currently, SSSC devices have lower current ratings and voltage and lower values of short-	In the TCSC, traditional thyristors (without inner turn-off ability) are employed. These thyristors characterize by	The TSSC employs traditional thyristors (with no inner turn-off ability). These thyristors are high-performance

term surge current. If the projected line fault current isn't too large, they're only appropriate for short-term bypass operations. As a result, for external rapid protection through simple line faults, an auxiliary traditional thyristor with a pass switch is necessary.	high-performance power semiconductors with high voltage and current rating, as well as the highest surge current capacity. They also include a short-term bypass function that protects the coupled capacitors from line disruptions..	power semiconductors with high voltage and current rating, as well as the highest surge current capacity. They also include a short-term bypass function that protects the coupled capacitors from line disruptions.
A DC storage capacitor and a coupling transformer valued about 0.5 p.u. of the entire series recompensing range are required by the SSSC. However, it is installed in a structure at ground probable and operates at a low voltage. As a result, it is necessary to have low voltage insulation and a control interface for the cooling system.	Because they are directly connected to the transmission line, TCSCs are placed on the high voltage platform. Because of the high voltage insulation requirements and control interface, the cooling system and control locate in the ground.	TSSC are in the high voltage platform because they are connected in direct way to the transmission line. Also, because of the control interface and high voltage insulation requirements, the cooling system and control locate on the ground.
At rated line current, the SSSC would show a loss of 0.7 to 0.9 percent of the rated Var output.	At rated line current, the TCSC would show a loss of 0.5 percent of the rated Var output.	At rated line current, the TCSC would show a loss of 0.5 percent of the rated Var output.

2.9. COMBINED DEVICES

At this section, we will introduce PST, UPFC, and IPFC.

2.9.1. Phase Shifting Transformer (PST)

The PST is a specialty transformer that controls the active power flow in a three-phase electric power network of transmission. The power flow across the grid is relative to the sine of the difference in phase angle of the voltage between the sending and receiving ends of an AC transmission line. The transformer must be appropriately connected to achieve phase shift among the power supply and the load [40]. A simplified circuit design of a PST with two separate transformers is shown in Figure 2.15: a variable tap exciter that varies the voltage amplitude and the transformer of series that inserts voltage in the proper phase angle, allowing power flow between lines to be divided and overload prevented [41].

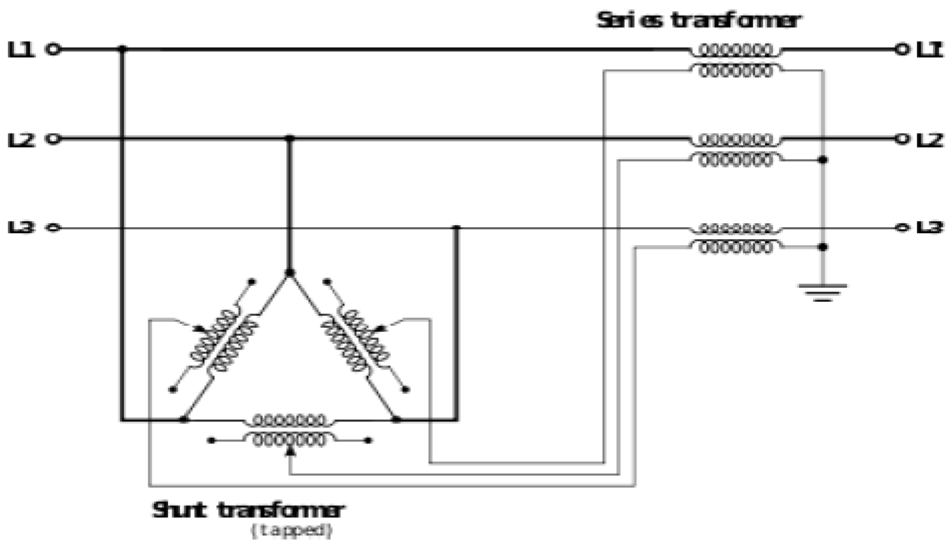


Figure 2.15. Simplified circuit diagram of a PST.

2.9.2. Unified Power Flow Controller (UPFC)

A STATCOM and an SSSC are joined by a popular DC-link to form the UPFC. This enables bi-directional flow of active power between the SSSC and STATCOM's series and shunt output terminals correspondingly, and is controlled to deliver real and reactive series compensation of line without the use of an external electric energy source.[42]. Figure 2.16 shows that the device with two shunt and series transformer converter is powered by a DC connection delivered by a DC storage capacitor.

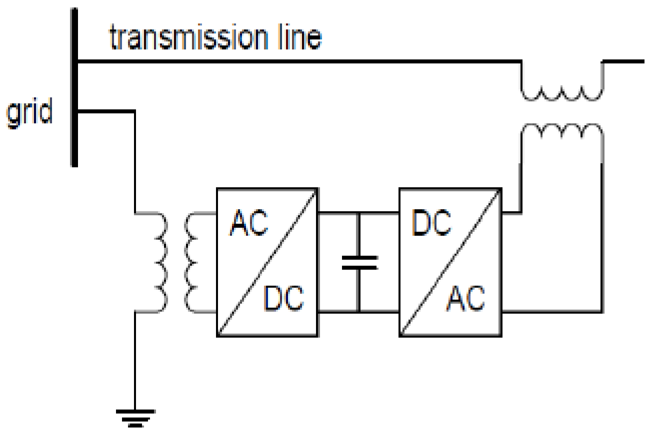


Figure 2.16. Simplified circuit diagram of UPFC.

2.9.3. Interline Power Flow Controller (IPFC)

IPFC includes two series converters coupled by a common DC link in distinct lines. Unlike traditional FACTS controllers, which control a single transmission line's parameter, the IPFC manages and compensates power flow in a multi-line transmission system as clarified in Figure 2.17. Both converters can provide series reactive compensation on their respective lines as SSSCs, and a shared DC link allows them to interchange active power and make active adjustments [43].

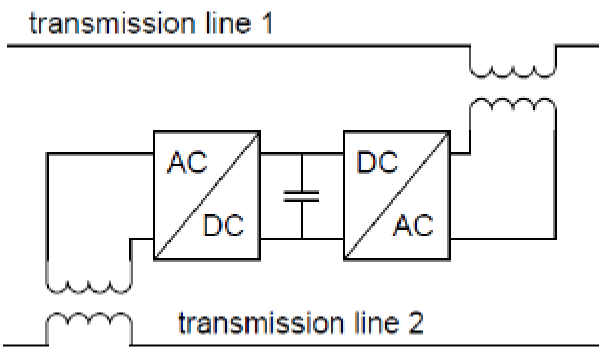


Figure 2.17. Interline Power Flow Controller Configuration.

2.10. FACTS SHUNT CONTROLLERS

Variable impedance devices including capacitors, reactors, or power electronics-based variable sources which are shunt coupled to the line in order to inject variable current, as shown in the diagram, could be used as FACTS controllers. Provided that the injected current is in the phase quadrature with the voltage of line, the shunt controller merely consumes or allocates variable reactive power. Dealing with true power will be a part of any other phase relationship. The major applications of shunt compensators are [30]:

1. Loss reduction and reduction of undesirable reactive power flows.
2. Consumer compensation and improved power quality in applications with large demand variations, including railway, subterranean train systems, metal melting plants and industrial equipment.
3. Transient stability improvement.

2.10.1. Operational Principle of Shunt Devices

The concept of functioning of a shunt device is to give reactive power to the load by altering its impedance and injecting reactive current Ish, hence controlling the line current I indirectly. that illustrate in Figure 2.17. The voltage drop over the transmission line is proportional to the difference between the transmitting and receiving end voltages, according to Ohm's law (i.e. Vs-Vr). The voltage at the transmitting end (Vs) is believed to remain constant, whereas a shunt device controls the magnitude of the voltage at the receiving end |Vr|. [43].

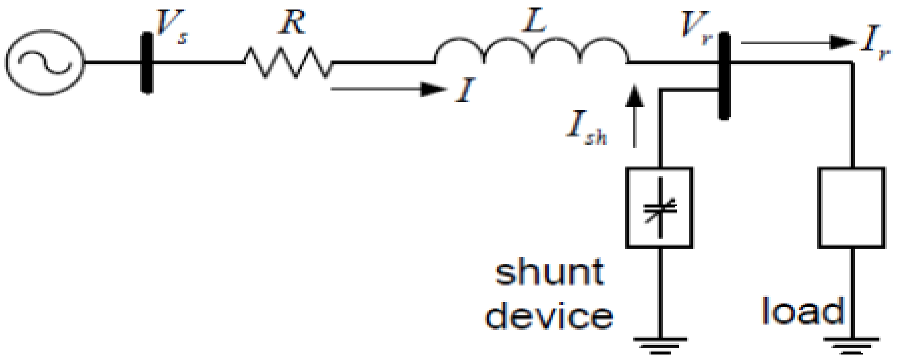


Figure 2.18. Shunt device operating principle.

The equation (2.3) shows the relationship between the injected current Ish by the shunt device and the voltage at the receiving end Vr:

$$V_r = V_s - IZ \qquad (2.3)$$

$$= V_s - (I_r - I_{sh})Z$$

Where $Z = R + j\omega L$

As indicated in equation, the shunt device may control the voltage magnitude by adjusting its impedance (2.3). The line current I generates a voltage drop in a heavy load condition, which is alleviated by the shunt current Ish, which works as a partial compensation for the massive load current Ir. Shunt controllers include switched shunt inductor and capacitor devices, SVC and Static Synchronous Compensator (STATCOM) [33].

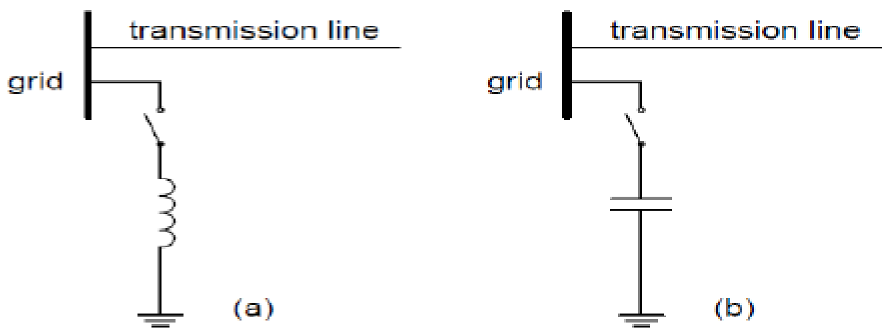


Figure 2.19. Configuration of switched shunt inductor and capacitor: inductor, (b) capacitor.

2.10.2. Static VAR Compensator (SVC)

SVC raises the transferred electrical power by raising the voltage of transmission line across capacitive vars when the machines quicken, and it decreases the sent electrical power by reducing the voltage across inductive vars when the machines slow, as shown in Figure 2.18. With sufficient synchronization of the capacitive and inductive reactance, the output of var is always changed between the capacitive and inductive ratios of the equipment. The SVC is commonly used to reactivate the compensation of power, regulation of voltage and modifications of power factor.[44]. The TSC and TCR are combined in the SVC. It can compensate for both capacitive and inductive effects.

2.10.3. Thyristor-Controlled Reactor (TCR)

The TCR is a shunt compensator that provides a equal continuous variable inductive reactance via phase-angle control. The current magnitude is controlled by the firing angel. When measured from the voltage's zero crossing, the firing angle can range from 90° to 180°. At 90°, the reactor is completely entered in the circuit, and at 180°, it is completely removed.[44].The single line diagrams of TCR and TSC are illustrated in Figures 2.19(a) and 2.3(b) correspondingly.

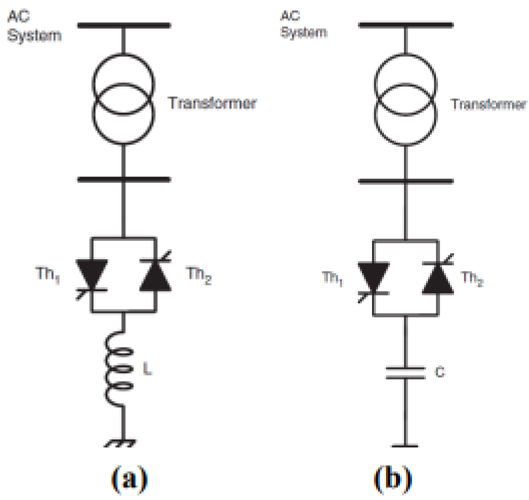


Figure 2.20. a) single line diagram of TCR, b) single line diagram of TSC.

2.10.4. Thyristor-Switched Capacitor (TSC)

The TSC is a shunt compensator that creates an equal continuous variable inductive capacitance. TSC is a capacitor that only turns on when the voltage is switched to zero (TSC). This means that the voltage through the thyristor terminals must be zero when turn-on. Due thyristor require positive anode–cathode voltages to be activated, it may be somewhat positive in practice (high anode–cathode voltages during turn-on, nevertheless, may create a massive current spike that could damage the thyristor because of this switching features) [44]. Figure 2.21 depicts the SVC as a single line diagram.

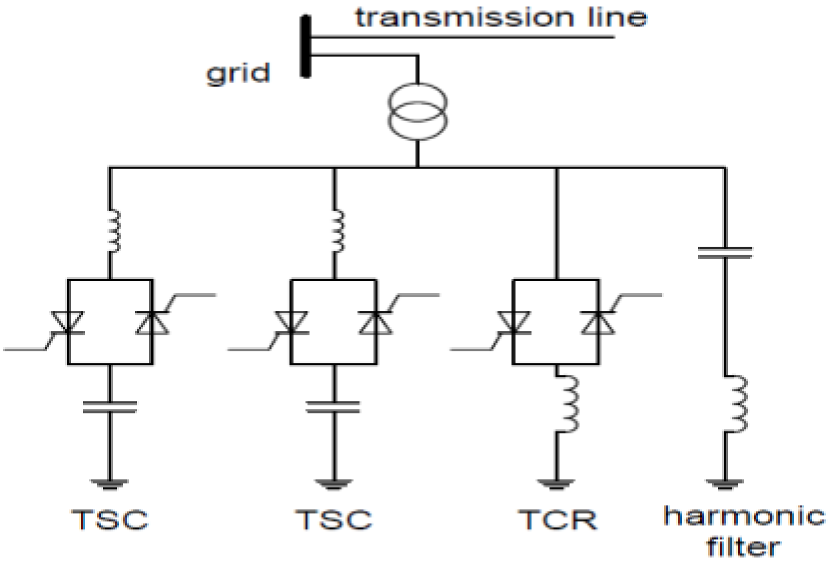


Figure 2.21. Single line diagram of SVC.

2.10.5. SVC Operation, Configuration and Control Principles

TSC and TSR/TCR are the components of the TSC and TSR/TCR in the TSC and TSR/T. The reactive power is changed as a result of the synchronized control of these divisions. The SVC operates using shunt-connected variable reactance. The basic role of SVC is to create or drain reactive power in order to maintain the voltage level of the power system. SVC installations are made up of many different blocks of building. The most essential valve is the thyristor valve, which consists of stack assemblies of series connected antiparallel thyristors to permit controllability.[12].

The reactive power parameters utilized in conjunction with the thyristor valves are air core reactors and high voltage AC capacitors. An SVC power transformer provides the equipment with a step-up connection to the transmission voltage. The thyristor valves, as well as ancillary systems, are housed within an SVC building, whilst the air core reactors and capacitors, as well as the transformer of power are housed outdoor [12]. The reactor may be flexibly switched into the circuit via phase angle modulation switched by the thyristor, providing a constantly changeable reactive power absorption (or injection) to the electric network. The capacitors give coarse voltage control in this system, while the thyristor-controlled reactor provides smooth control thyristor-controlled capacitor switching can give smoother control and more versatility [45].

2.11. DEFINITION OF STATCOM

According to IEEE, STATCOM can be defined as "a self-commutated switching power converter which is supplied from a suitable electrical source of energy and operated to create many adaptable multiphase voltages which can be coupled to an AC power system in order to exchange independent controllable real and reactive power".

When connecting two AC sources with the same frequency by a series inductance, the flows of active power from the leading source to the lagging source, and the flows of reactive power from a higher voltage magnitude AC source to the lower voltage magnitude AC source. The flow active power can be determined by the phase angle difference between the sources, whereas the flow of reactive power is determined by the voltage magnitude difference between the sources. As a result, by altering the fundamental section of the converter voltage in phase and magnitude regarding the AC bus bar voltage, STATCOM may achieve reactive flow of power [45]. The three functioning structural components of the STATCOM have been defined in accordance with CIGRE/IEEE.

1. The first is static: it depends on the solid state switching devices with no rotating sections;

2. The second is synchronous: it is similar to an ultimate synchronous machine with three sinusoidal phase voltages at essential frequency and
3. The third is recompensed [46].

2.11.1. Characteristics of STATCOM

As a result of researchers and engineers' groundbreaking research on FACTS devices over the last couple of decades, many STATCOM controllers based on self-commutated solid state VSC were developed and commercially operate to control system dynamics across stressed circumstances. Static condenser, synchronous solid state VAR compensator, VSC-based SVC or self-commutated SVC or static synchronous compensator, static condenser, synchronous solid state VAR compensator, synchronous solid state VAR compensator, synchronous solid state VAR compensator, synchronous solid state VAR compensator, synchronous solid state VAR compensator, synchronous solid state VAR compensator, synchronous solid state VAR compensator, synchronous solid state VAR compensator, synchronous solid state VAR compens (STATCOM).VSC technology, which is based on self-commutating programmable solid state switches, has ushered in a new generation of FACTS controllers, including STATCOM and UPFC. The self-commutating VSC, also known as a DC-to-AC converter, is the heart of these controllers, and it manages reactive current by create and absorb regulated reactive power using various solid-state switching methods.[32].

The STATCOM is a shunt-connected reactive compensation device which may create and/or absorb reactive power and whose output may be modified to maintain control over particular electric power system elements. Because the STATCOM uses solid state power switching circuitry, fast controllability of the three phase voltages, both in amplitude and phase angle, is possible without the mechanical inertia of a spinning synchronous compensator. STATCOM provides voltage support to buses during dynamic disturbances by modifying bus voltages to improve transient features, enhance the margins of transient stability, and attenuate system fluctuations produced by these turbulences.[45].

The STATCOM is a SVG based on power electronics. It's a shunt-connected FACTS device which deliver capacitive or inductive output current for compensation of reactive power to address a range of voltage stability and instability issues in power systems.[12].

STATCOM is a shunt VSC which is linked to the grid as clarified in Figure 2.18. The line reactive power is managed by the device by the use of the output reactive current without interfering with the AC voltage. It enhances the stability of voltage angle, raises transmission line power delivery capacity, and adjusts line voltage.[47].

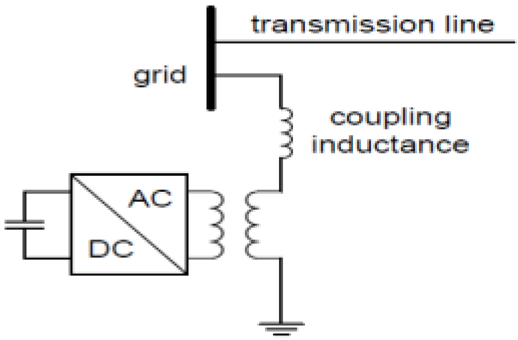


Figure 2.22. The configuration of STATCOM.

Figure 2.21 shows the schematic diagram of a STATCOM. The charged capacitor Cdc delivers a DC voltage to the converter that generates three-phase output voltages that are synced with the AC power system. The amplitude of the output voltage may be varied to modify the reactive power. When the output amplitude exceeds the AC system voltage VT, it is possible to control the exchange between the converter and the AC system. The converter's reactance permits current to pass (coupling transformer), resulting in a leading current, meaning that the STATCOM is considered as a capacitor in the AC system. When the output voltage falls below that of the AC system, the trailing current amplitude decreases. Because STATCOM is used as an inductor in the current results, reactive power is absorbed in this circumstance. If the amplitudes are equivalent, there is no power exchange [26].

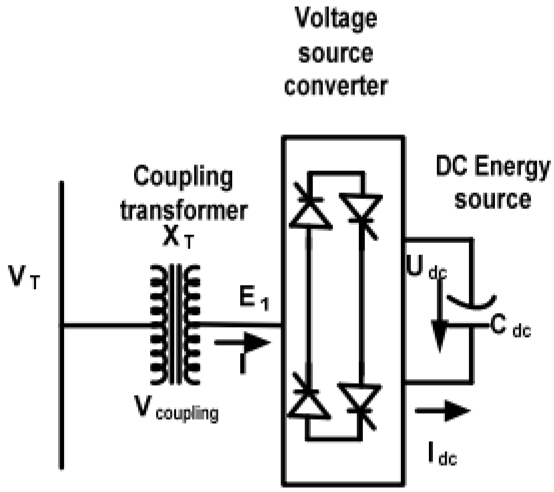


Figure 2.23. Static Synchronous compensator.

If no action was taken, the energy stored in the capacitor may be reduced by the converter's inherent losses. To offset the losses in the converter, the converter takes a little quantity of active power from the AC system by producing the converter's output voltages lag the AC system voltages by a slight angle. In addition, the active power generation can be regulated using the phase angle adjustment method (refer Figure 2.22). If the converter is only used for reactive power exchange, the AC output voltage can be controlled by adjusting the amount of DC connection voltage. This is conceivable because the magnitude of output voltage AC is relative to the capacitor voltage of DC [48].

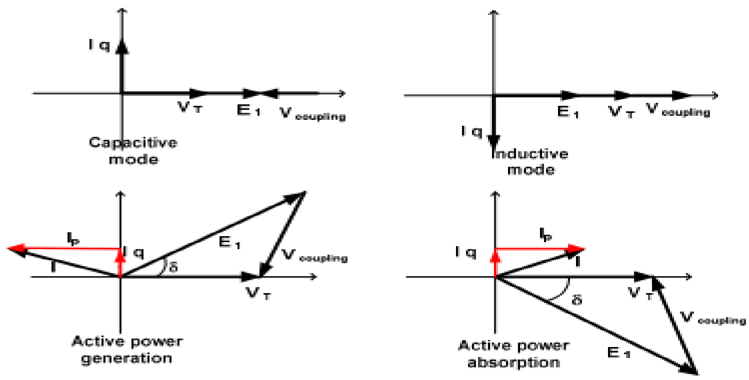


Figure 2.24. STATCOM operating in inductive and capacitive modes.

The V-I features of a STATCOM are depicted in Figures 2.23 and 2.24. Regardless of the AC system voltage, a STATCOM can correct for both capacitive (IC) and inductive (IL) losses and regulate its output current over the rated maximum capacitive (ICmax) or inductive range (ILmax). The STATCOM has a basic benefit over the SVC in that it may deliver full capacitive output current at any voltage of system, even near zero. The SVC, on the other hand, can only provide diminishing output current when the system voltage decreases, as its supreme equal admittance designates. As well as, this means that the maximal capacitive or inductive reactance provided by STATCOM diminishes linearly with voltage at continuous current [48].

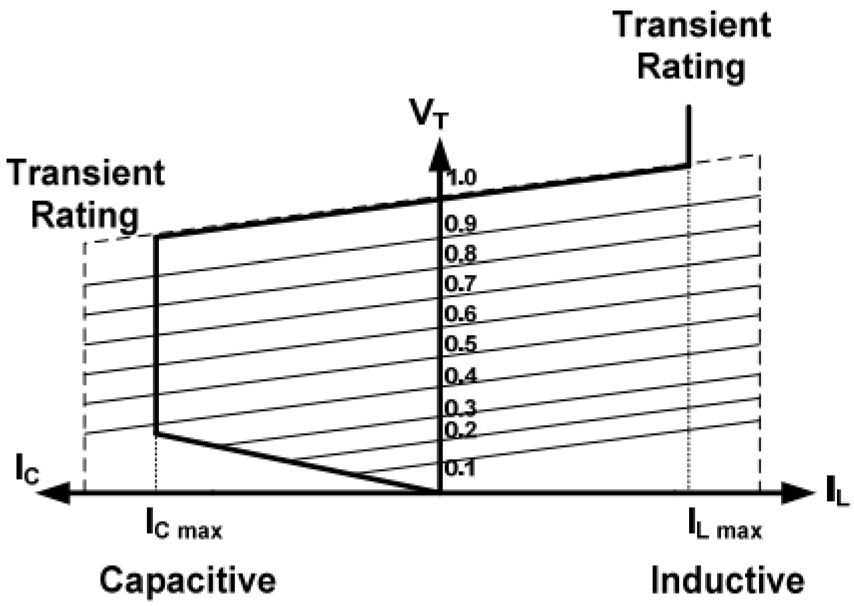


Figure 2.25. V-I Characteristics of STATCOM.

2.11.2. The Basic Operating Principle of STATCOM

As illustrated in Figure 2.25, the system is directly connected to the STATCOM, one of the most significant fellows of the FACTS family that is progressively used in modern power systems. It's a three-voltage system that can generate as well as absorb reactive power. When the voltage of the system is low, the STATCOM supplies reactive power (STATCOM capacitive). When the voltage of the system is high, the reactive power is absorbed (STATCOM inductive). This system is made up of the dc-link capacitor, measuring system, controller, coupling transformer and inverter/converter circuit. The fundamental operating belief of the STATCOM is to couple inductance between two AC sources (System and STATCOM) with the same frequency by altering the amplitude of the VSC output voltage. This allows for the interchange of reactive power among the system and STATCOM (Vout). If the amplitude of the VSC output voltage is larger than the voltage of the system, the STATCOM creates capacitive reactive power (Vac). On the other side, the STATCOM absorbs inductive reactive power. If the amplitude of the VSC output voltage is equivalent to the voltage of the system, the reactive power exchange between the STATCOM and the system is zero.[49, 50].

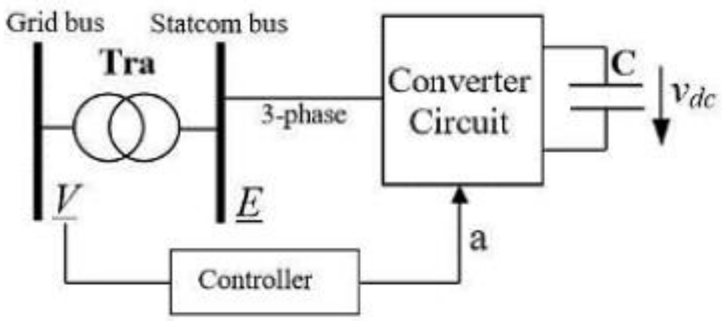


Figure 2.26. STATCOM in power system.

The voltage through the dc capacitor is proportional to the ac voltage output's fundamental component:

$$Vout = kVdc \tag{2.4}$$

The amount of switching pulses, converter constitution, and converter settings all influence the coefficient k. The important module of the converter voltage output, i.e. Vout, which is reliant on Vdc, may be affected by changing the dc voltage through the capacitor that can be implemented by modifying the phase angle of the converter switching. Whether reactive power flows from the system to the join modifier or from the coupling modifier to the system is determined by the variance between the converter voltage output and the ac system bus voltage [49]. The reactive power which is exchanged is calculated by the following equation:

$$Q = \frac{Vac^2 - Vout\,Vac}{X} cos\propto \tag{2.5}$$

The true power exchange among the voltage source converter and the ac system is shown below.:

$$P = \frac{Vac\,Vout}{X} sin\propto \tag{2.6}$$

Where:

$Vout$- output voltage of the converter,
Vac - magnitude of the ac system voltage.
X – the coupling transformer's leakage reactance
α - The angle between the converter output voltage and the system voltage is called the phase angle.

2.11.3. Functioning of the STATCOM

The STATCOM that has been created in MATLAB works in a similar way to the theoretical functioning of the STATCOM that we have seen in the circuit. The STATCOM is made up of an VSC and consists of six pairs of switches. The inverter circuits are arranged to form the inverter circuits, and the inverter circuits are controlled by the PWM pulse in response to the system voltage demand to create the basic value we have taken care of the proper dc source for the magnitude of the voltage set s of the three phase sets. The system is being supplied with voltage and pulse widths.

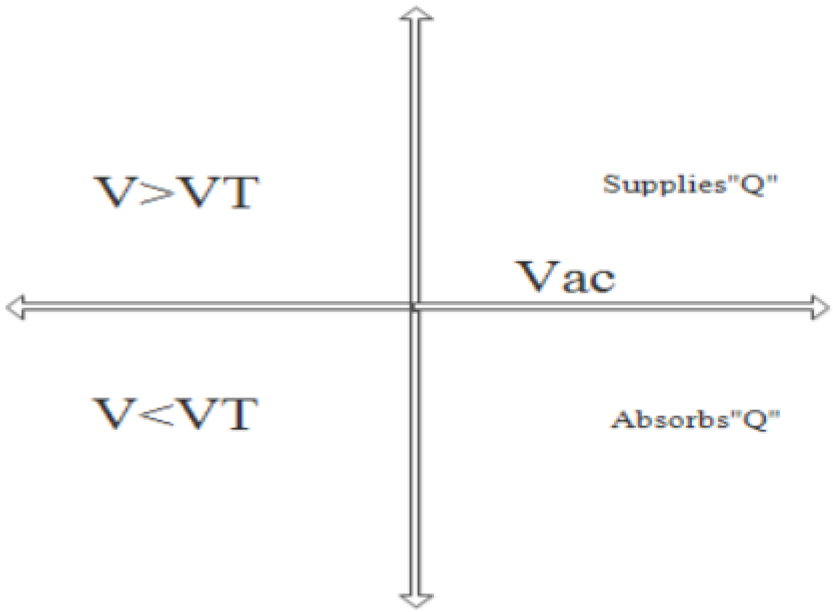


Figure 2.27. The reactive power supplied.

The STATCOM's reactive power is calculated as follows:

$$Q = \frac{Vstatcom - Vs}{X} Vs \tag{2.7}$$

Where:

Q represents the reactive power.

$V\ STATCOM$ represents the magnitude of STATCOM output voltage.

VS represents s the system voltage magnitude.

Between STATCOM and the system, X represents the equivalent impedance. The STATCOM provides reactive power to the system when Q is positive. Otherwise, the STATCOM consumes the system's reactive power. The compensator current is 90 degrees displaced from the ac bus voltage and may be either leading (creates reactive power) or lagging (does not generate reactive power) (absorbs reactive power). Finally, a coupling capacitor is utilized to make the inverter's dc voltage persistent. To keep the capacitor charged all the time, an uncontrolled diode bridge is connected to it. The diode bridge gets its power from the bus's primary supply voltage [39].

2.11.4. Comparison of Shunt Compensators (STATCOM vs SVC Devices)

Although the functional capabilities of STATCOM and SVC are extremely similar, the essential working principles are fundamentally different, as detailed in earlier sections. The functional comparison among the two types of shunt compensators (thyristor / converter types) is presented in Table 2.3.

Table 2.2. Functional details of converter and thyristor type shunt compensating devices are compared.

STATCOM (Voltage source convertor based shunt compensator)	SVC is an acronym for "Supporting (traditional thyristor based shunt compensator)
STATCOM is a synchronous voltage source with a shunt connection. The STATCOM's have many features such as greater application flexibility, stronger functional qualities and greater flexibility of application over an SVC are due to this distinction.	An SVC is a regulated reactive admittance that is coupled to a shunt.
The V-I features and functional adjustment capacity are like the SVC in linear range of operation.	The V-I features and functional adjustment capacity are like to that of an SVC in the linear range of operation.
The STATCOM can adjust its output current over the rated maximum capacitive or inductive range in the non-linear working range, regardless of the AC system voltage.	The SVC's maximum compensatory current drops linearly as the AC voltage rises.
Beside the reactive compensation of power, STATCOM may deliver active compensation of power.	The active power adjustment feature of an SVC is not available.

STATCOM has improved functional qualities for better performance and higher flexibility of application comparing with SVC are due to these distinctions. STATCOM improves power system performance and flexibility by providing real-time data. When a voltage disruption is detected, it quickly compensates by injecting leading voltage or reactive power that is sluggish STATCOM assists utilities in regaining system voltage with the capacity to alleviate stability-related power transfer limits, collapse events are no longer a problem controls that are advanced. More importantly, it is a low-cost option with few drawbacks footprint [34].

According to the above-mentioned literature survey, researchers have frequently studied STATCOM controllers using a simple system model (source, transmission line, and inductive load). Clearly, the model should replicate the actual system as closely as possible in order to provide more accurate findings. It is possible to get insight into the system and a better knowledge of the events that occur during disruptions in this scenario [33].

STATCOM is being adopted and installed in an increasing number of countries throughout the world. There will come a day when Iraq's power grid will accept the idea of incorporating such gadgets into the national grid system. Before that, preliminary research of the advantages of adopting this approach should be conducted.

This was the motivating factor behind the decision to carry out the current project. The Diyala City Ring System has been chosen as the study platform.

2.12. LITERATURE REVIEW RELATED TO STATCOM IMPLEMENTATION

The study in [51] conducted power-flow study by the use of Newton-Raphson method. A modified power flow model of the STATCOM attempted to examine the influence of STATCOM on the power system. The modified load flow program was utilized to assess the impact of STATCOM on the system, which is installed in various locations in various bus systems. MATLAB was used to run the simulation. The voltage profile of the system was found to be enhanced. when a load flow study of all three buses (IEEE 5, IEEE 14, and IEEE 30-bus) is considered. It was also clear that the voltage magnitude of the bus on which STATCOM is installed is kept constant at 1 p.u.

In [52] the authors used the artificial neural network and after incorporating the STATCOM into the Mosul city ring system, researchers looked into the performance of the system. However, the focus of the research was on steady-state settings. The ideal position for the STATCOM was determined by a load flow study, which was also utilized to establish the appropriate value of reactive power required under various load circumstances. When STATCOM is added to the network, however, harmonics are formed in the system. Some STATCOM components, such as leakage reactance, pulse number, and triggering frequencies, have been investigated. A total harmonic distortion (THD) of significantly less than 5% has been achieved using appropriately chosen components. Within the Mosul ring, an artificial neural network was utilized to organize the operation of the STATCOM under many load levels. It is advised that a combined STATCOM and capacitor banks technology are used to further reduce THD to less than the permissible standard amount (2.5%) [29].

In [53].the researchers simulated an 8-bus system, and D-STATCOM was utilized to eliminate voltage sag resulting from rapid changes in loads. A series impedance model is utilized to represent the transmission lines in the circuit model of an 8-bus system. The line's shunt capacitance is ignored, and there is no feedback in a STATCOM controller.

The study in [54]used Newton Raphson’s method for load flow analysis, where they compared two algorithms, a direct and an indirect algorithm for three studies; they adopted the principle of the number of iterations and the total time spent in implementation. The authors mentioned that the required accuracy is 0.0001 and used IEEE 5-bus, 14-bus and 30-bus systems for comparison. It was reported that the direct algorithm is good and is better than the indirect algorithm in terms of the rate of convergence of Newton Raphson.

The authors in [55] used the genetic algorithm and compared it with the case where the network is without a statcom device. Basic transmission line parameters including line impedance, voltage magnitude and phase angles are also controlled to keep things running smoothly. By optimizing the voltage profile and ensuring that there are no active or reactive power losses, active and reactive power losses can be reduced.

In [56] it was reported that when the system exposes to load increments or turbulences, the voltage dips induce voltage profile decay. Variation in load caused by unscheduled accessions, making the system difficult to operate and perhaps causing a cascading trip throughout the system. Close monitoring of load difference may assist to alter the system to operate at its highest capabilities in this way. Special strategies, including reactive power compensation, the installation of FACTs devices, and the placement of capacitors, can be used to overcome this issue.

The researchers in [57] were able to achieve the modeling, operation, and various control strategies of STATCOM, have been investigated in this study to accomplish good dynamic response. The performance of various shunt FACTS controllers has been compared. A brief discussion of STATCOM operation and uses has been presented, as well as the determination of suitable STATCOM locations. Three STATCOM models for power systems have been presented. The use of STATCOM has been utilized used to discuss control options for damping power oscillation.

In [58] This study looks at the impact of STATCOM on enhancing the transient steadiness of a multimachine power system in terms of Fault Clearing Time. The STATCOM is utilized to control the power flow of the power system by injecting a suitable reactive power through the dynamic condition. According to computer modeling data, STATCOM not only enhances the transient stability but also adjusts for reactive power in the stable state. As a result, STATCOM may raise the reliability and capabilities of the AC transmission system. For the 9-bus system, the most likely location of the STATCOM for boosting transient steadiness is also discovered to be varied, depending on the fault location.

The study in [34] used the IEEE 14-bus test system to assess STATCOM's performance in terms of decreasing the power losses and enhancing the system voltage stability limits. The results showed that the device controller simultaneously reduces power consumption. Losses are decreased, and the voltage system profile is enhanced. The system was then simulated by performing a power flow study using the load flow program based on Newton-Raphson equations. Voltage magnitude profile quantities and voltage was shown to be affected by both active and reactive power losses.

At steady-state operating circumstances, the system's stability and power transfer prior and post to the addition of STATCOM to the system and new power flow analysis was run to get the voltage profile, active and reactive power losses, and other information. The process was repeated, this time raising the maximum loading factor by 10% increments up to 40%. The obtained data was compared to determine the device's effects on system quantities. The voltage profile and power transfer on the transmission line improved sufficiently with STATCOM; active and reactive power losses were reduced by 17.73 percent and 24.8 percent correspondingly, when STATCOM was introduced in the system at normal load.

According to [59] the voltage is subjected to significant transient disturbances as long as the defect remains in the system. When STATCOM is installed first in the system, however, the voltage disturbance is eliminated from the system during a fault state. In addition, there is a decrease in active power and a significant increase in reactive power in the system when it is malfunctioning. As a result, by creating the right control strategy for STATCOM operation, the stability is improved. In the case of Rotor Angle Stability, a similar result is observed. When a system experiences a malfunction, it experiences transitory instability. When STATCOM is connected to the system, however, this instability improves and can be stabilized.

In [60] SVC was utilized to improve the load ability and voltage profile of a transmission line in Jordan. The average line-to-line voltage has reached its maximum level. The FACTS controller was determined by keeping a close eye on the system situation. All of the 110 system load buses have minimal voltage dips.

The MATLAB/Simulink was utilized to model the specified power system. To increase the power, an SVC and its placement were considered to determine the transmission capacity of a given transmission line and to avert the projected overload. The increase in loading has been calculated to be 14.35 %. The use of STATCOM in a power system results in a higher voltage. The results obtained after installing the SVC in its optimal location were compared to the results obtained after improving the transmission capabilities of the same power system by installing a STATCOM in its optimal location. When compared to SVC, employing STATCOM results in a better voltage profile for the given power supply.

PART 3

MATHEMATICAL MODELING

3.1. INTRODUCTION

The load/power flow analysis gives information for line and transformer loads (and other losses) across the system, in addition to actual and reactive power levels. It also shows voltages at various places across the system for the purposes of evaluating and regulating power system performance. Power flow is also necessary for power system control and future system expansion planning. In this sense, the approaches used to assess the quality and performance of a power system are critical [61].

A variety of methodologies, including Gauss-Seidel [62], NR [62] and Fast-Decoupled [63] can be used to determine the load flow for a specific power system. In recent years, there were breakthroughs in discovering the solutions of digital computer for load flows of power system. This provided accuracy improvement and fast convergence of numerical solution methodologies. In this regard, the NR approach is the most extensively employed in practice for this task [64].

For this reason, in this study, the NR approach is used to maintain a safe voltage profile across a variety of buses and to maintain optimal performance condition of the power system. The R/X ratio of the transmission system is low since it is looped. The variables used in load flow analysis in the electricity transmission system differ from those used in load flow analysis in distribution systems. The distribution systems are characterized with a high R/X ratio. The NR method has been used successfully in high voltage transmission system load flow analyses [64].

3.2. THE RATIONALE OF LOAD FLOW STUDY

The main goal of load flow solution is to calculate individual phase voltages at each busbar connected to the network based on system data. The load flow analysis ensures that the bus voltage is near to rated and that the generator operates inside real and reactive power limits. Each bus has active and reactive powers, as well as voltage magnitudes and angles. The four unknown parameters must be solved using four independent constraints. The two most common bus types are load and generator buses. The slack bus is a type of generator bus that functions as a reference bus. The restrictions vary depending on the type of bus [65, 66].

When sparse network equations are addressed, the NR procedure is the most popular load flow method because it has powerful convergence properties comparing with substitute methods and much lower processing time [67].

Utility planning, operation, population and economics, and power exchange all require a load flow study of the power system. Load flow analysis can be utilized to determine the best location and optimum capability of a proposed generating station or substation design during the development stages of new network/generation assets or adding/removing a new line to a present substation.

Numerical analysis techniques are used in power flow studies. Iterative approaches are utilized to carry out these assessments because there is no acknowledged analytical approach for solving the nonlinear nature of the power flow problem. According to load flow studies, electrical power transfer from generators to consumer during the electricity network must be steady, reliable, and cost-effective. During the last few decades, a lot of research has gone into progress of computer code for load flow analysis of large power systems [68]. Depending on its formulation and use, the process can be accurate or estimated have modified or unadjusted data, and be used on-line or off-line.

For power flow studies, load is expected to be a continuous amount in a power system. Nonlinear algebraic equations are used in power flow analysis to express steady state active and reactive powers [69].The bulk of load flow studies use simpler notation including per unit system and one-line diagrams, and they concentrate on different types of AC power (irritable, real, and deceptive) instead of voltage and current [70].

3.2.1. Analysis on Load Flow by Using Newton Raphson Method

The load flow study, in addition to providing real and reactive power, also offers information regarding line and transformer loading (also losses) through the system, as well as voltages at various points in the system, to evaluate and manage of power system performance.

In evaluating the power system operation and performance, the state of the system and the methods for determining it are critical control of the power system, and determining the system's future expansion Any electricity system's current condition load flow analysis, which analyzes the power flowing during the system's lines, can be used to identify this. The load flow for a given system is determined using many approaches, including Gauss-Seidel, Newton Raphson Load, and the Fast-Decoupled method. There were advancements in identifying the solutions of digital computer for power-system load flows over the last few years. This entails improving the numerical-solution approaches' accuracy and speed of convergence. Even a few failures to provide first-time convergence for physically practicable problems is uneconomical in frequent use. As a result, the Newton-Raphson (NR) method is the most widely used. Transmission lines have a wide range of characteristics and performance, which is mostly determined by their system. As a result, the NR technique is utilized to maintain a safe voltage profile across a variety of buses with different power flows. Because the transmission system is looped, it has a low R/X ratio. As a result, the variables used in transmission system load flow analysis differ from those used in distribution systems with a high R/X ratio. As a result, dissimilar to the distribution systems, the NR approach is successfully applied in transmission system load flow studies [64]. The load-flow solution's main goal is to calculate individual phase voltages at every bus bars, buses linked to the network based on defined system parameters. Because each bus involves active and reactive powers, voltage magnitudes, and angles, four separate constraints are necessary to solve for the four unknown parameters listed above. Load and generator buses are the two main types of buses. The slack bus is a specific sort of generator bus that is used as a reference bus. The limitations differ for different types of buses [65, 66]. Because of its many benefits, the Newton-Raphson approach is considered one of the most common load flow method. When the sparse network equations are solved by the use of the sparsely-programmed well-ordered elimination technique, it provides strong merging characteristic and significantly lower computing times comparing with substitute operations [67].

3.3. CREATING AND BUILDING A POWER SYSTEM

Load flow analysis is a crucial criterion for designing and constructing a power system. Utility planning, operation, economic scheduling, and electricity exchange all require it. The main purpose of power system analysis is to figure out the magnitude and phase angle of voltage at every bus, as well as the quantity of active and reactive power flowing through every transmission line. The power flow analysis is an effective way for developing a power system that uses numerical analytical approach. Since there is no recognized analytical approach to solve the problem, iterative procedures are used to carry out these analyses. Electrical power transfer from the generator to consumer throughout the grid system must be constant, consistent, and cost-effective, according to load flow studies. The most common methods to solve load flow problems are Newton-Raphson or Gauss-Seidel. The analysis of load flow is a precondition for power system studies [68].

Much research has gone into developing computer programs for load flow analysis of big power systems during the last few decades. To solve load flow challenges, a variety of solutions have been devised. A process can be accurate or imprecise have modified or unadjusted values which can be used on-line or off-line, and be designed for application with single-case or multiple-case depending on its formulation. Engineers are always associated with decreasing the products and services cost, therefore effective maximum economic planning and process engineering is necessary[67].

3.3.1. Power Flow Analysis

Power flow analysis is critical in power network research. It looks at actual power, reactive power, voltage magnitude, and phase angle, among other things. Load flow analysis is used to ensure that generating satisfies load and loss requirements. The load flow analysis ensures that the bus voltage is near to rated and that the generator operates inside the real and reactive power limits. The overloading requirements to transmit and distribute lines are similarly violated by the analysis of load flow. Load flow analysis is utilized in the planning phases of new networks, as well as the adding and removing a new line from a present substation. It delivers node voltage and phase angles, as well as injected power in the entire buses in a connected network, allowing us to identify the best location and capability of the proposed generating station or substation design. In a power system network, overvoltage or overload circumstances can occur, and power flow analysis is a useful technique for dealing with these problems. [71].

The steady-state behavior of the system, including the active and reactive powers generated and absorbed, as well as line losses, is also included in the load flow study. Trippers prefer to refer to these investigations as Power Flow Studies rather than Load Flow Studies because load is a continuous quantity in a power system while power flows along transmission lines. Lone flow can also be utilized to determine whether conditions are overloaded or under loaded. Nonlinear algebraic equations are used in power systems to express steady-state active and reactive powers. Load flow analysis, which employs traditional iterative methods such as Newton-Raphson or Gauss-Seidel, is used to perform all of these duties of planning, operation, data conservation, and cost-effective dispatching. [69]. The majority of load flow studies employ simpler notation including per unit system and one line diagrams, and they focus on different types of AC power (reactive, actual, and apparent) instead of the voltage and current [70].

3.4. MODELING OF POWER SYSTEM WITH STATCOM

For analyzing challenges in power system management and control, power flow calculations are required [70].These computations can result in a balanced steady-state functioning condition. In terms of the STATCOM power flow analysis, the following are specific goals:

- To determine appropriate STATCOM locations and ratings.
- To offer information about the system condition.

Active and reactive power flows are important to develop baseline information for stability research in both normal and contingency system settings. The symbolic depiction of a power system with many generators, numerous loads, and a STATCOM is depicted in Figure 3.1.

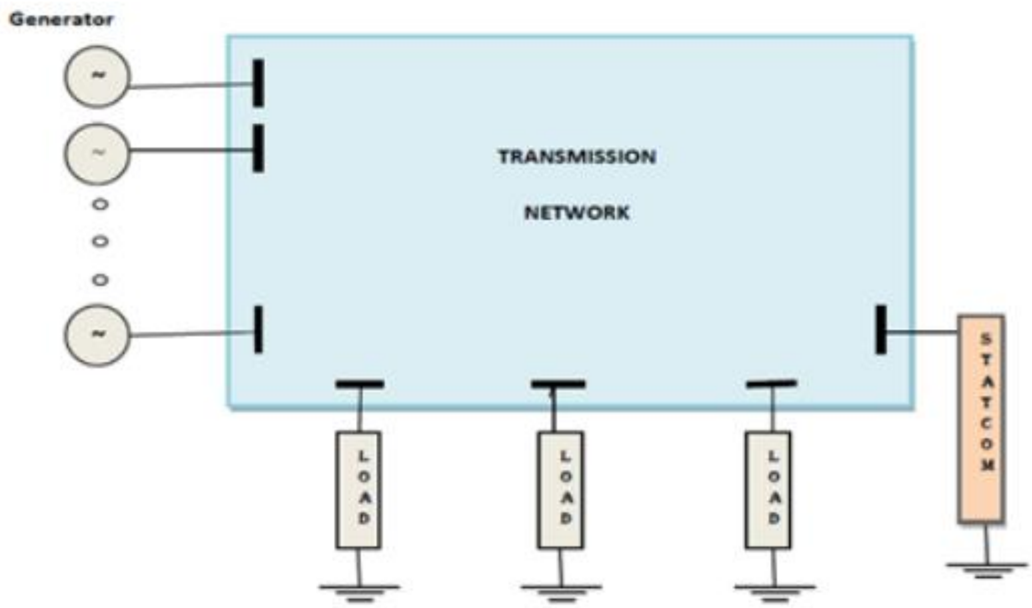


Figure 3.1. Symbolic representation of a power system.

The admittance matrix (Y matrix) can be used to simulate the interconnection of different components in a transmission network. It is worth noting that the system's power flow model connects each bus's net injected active/reactive power to all other bus voltages (both magnitude and angles) [71]. Furthermore, any power flow algorithm, particularly the NR power flow algorithm, can simply incorporate such a model. Without a FACTS controller, the usual power flow equations for a generic bus (bus i) of the power system are as follows:

$$P_i = P_{Gi} - P_{Li} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \, cos \ (\theta ij + \delta j + \delta i) \tag{3.1}$$

$$Q_i = Q_{Gi} - Q_{Li} = \sum_{j=1}^{N} |V_i||V_j||Y_{ij}| \, sin \ (\theta ij + \delta j + \delta i) \tag{3.2}$$

If i = 2, 3...N, with bus 1 being the first bus and N being the total number of buses. Eq. (3.1) is adjusted as follows when FACTS devices are included at buses k and t, respectively, as shown in Figure 3.2.

$$P_k = P_{Gk} - P_{Lk} + P_{kinject} = \sum_{j=1}^{N} |V_i||V_j||Y_{kj}| \, cos \ (\theta kj \text{ - } \delta j - \delta k) \tag{3.3}$$

$$Q_k = Q_{Gk} - Q_{Lk} + Q_{kinject} = \sum_{j=1}^{N} |V_k||V_j||Y_{kj}| \delta k) \quad sin \ (\theta kj \text{ - } \delta j - \tag{3.4}$$

$$(3\text{-}P_t = P_{Gi} - P_{Li} + P_{tinject} = \sum_{j=1}^{N} |V_t||V_j||Y_{tj} \, co(\theta tj\text{-}\delta j - \delta t \tag{3.5}$$

$$Q_t = Q_{Gt} - Q_{Lt} + Q_{tinject} = \sum_{j=1}^{N} |V_t||V_j||Y_{tj}| \, sin \ (\theta tj \text{ - } \delta j \delta t) \tag{3.6}$$

The buses t and k, as well as the rest of the network's buses, can be renamed PV or PQ buses. The linearized Jacobian equation (3-7) is used to iteratively solve the power flow equations stated in (3-1). It is formulated as:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta|V| \end{bmatrix} \qquad (3-7)$$

$$J_2 = \frac{\partial P}{\partial |V|} \quad , J_3 = \frac{\partial Q}{\partial \delta} \quad , \quad J_4 = \frac{\partial Q}{\partial |V|} \text{ are the sub} - \text{Jacobian matrices, respectively.}$$

The main purpose of this project is to use FACTS controllers (STATCOM) to address the power flow problem for the system under load increases and line disruptions. Equations (3-2) and (3-3) accommodate the presence of FACTS controllers. The Jacobian equation (3-7) is consequently expanded and modified.

It is vital to model the STATCOM within power flow problem to have a vision into the benefits of STATCOM in terms of improved system voltage profile and power transfer capability. This necessitates accurate STATCOM representation in steady state. Figures 3.2 (a) and (b) show a diagram illustration of STATCOM and its equivalent circuit respectively [72].

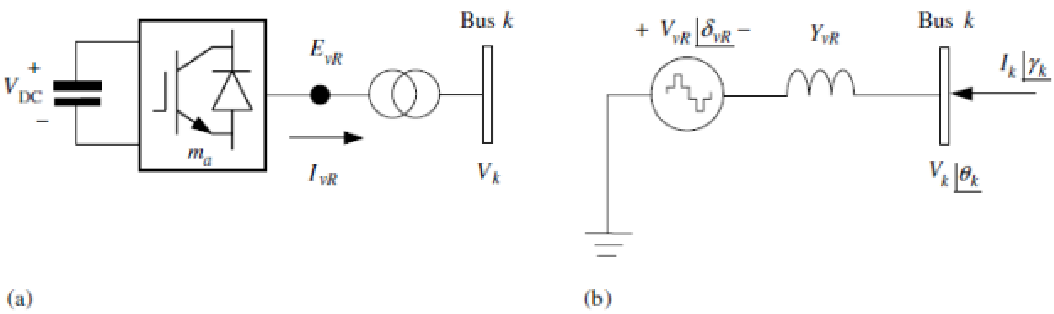


Figure 3.2. Equivalent circuit of STATCOM

STATCOM consists of a coupling transformer, a voltage converter, and a regulated DC voltage source, as shown in the schematic design. By absorbing or injecting reactive power to and from the connected bus, the device controls the connected bus voltage. Any sort of power inverter, including current source and voltage source inverters, can be utilized with STATCOM. The bus to which STATCOM is linked is designated as PV bus; however, it may convert to PQ bus if the limitations are exceeded. In this situation, the reactive power generated or absorbed would match to the limit that had been breached [71]. In order to solve steady-state problems, STATCOM performs the following functions tabulated in Table 3.3.

Table 3.1. Functioning mechanism of STATCOM.

No	Operating Problem	Corrective Action
1	Low voltage when a heavy load is activated	Reactive power should be supplied.
2	Low load, high voltage	Reactive power absorption
3	Following a power outage, a surge in voltage.	Prevent overload by absorbing reactive power.
4	Following a power outage, a drop in voltage.	By absorbing reactive power, avoid overload.

The power flow equations for the converter and bus k can be determined as follows using the equivalent circuit of the STATCOM shown in Figure 3.2:

$$P_{vR} = V_{vR}^2 G_{vR} + V_{vR} V_K[G_{vR} cos(\delta_{vR} - \theta_K) + B_{vR} sin(\delta_{vR} - \theta_K)] \quad (3-8)$$

$$Q_{vR} = - V_{vR}^2 B_{vR} + V_{vR} V_K[G_{vR} sin(\delta_{vR} - \theta_K) - B_{vR} cos(\delta_{vR} - \theta_K)] \quad (3-9)$$

$$P_K = V_K^2 G_{vR} + V_{vR} V_K[G_{vR} cos(\delta_{vR} - \theta_K) + B_{vR} sin(\delta_{vR} - \theta_K)] \quad (3-10)$$

$$Q_K = -V_K^2 B_{vR} + V_{vR} V_K[G_{vR} sin(\delta_{vR} - \theta_K) - B_{vR} cos(\delta_{vR} - \theta_K)] \quad (3-11)$$

3.5. CONSTRAINTS OF STATCOM

The STATCOM's power flow constraints are as follows:

$$P_{sh+jQ_{sh}}(V_{sh} \angle\theta_{sh}).\left(\frac{V_{sh} \angle Q_{i-V_{sh}} \angle\theta_{sh}}{Z_{sh}}\right) \quad (3.12)$$

Through Eq. (3-12) it is shown that the device is coupled to an n-bus power system of individual bus "i". The STATCOM includes two additional variables, V_{sh} and θ_{sh}, which help to absorb or deliver the appropriate amount of reactive power from or to the power system in order to make the voltage persistent to the entire power system loads inside a practical range [72]. where V is the STATCOM's controlled voltage source in equation (3-13) and (3-14). It can be adjusted to manage the voltage on the local bus. The STATCOM's operating limitation is active power exchange across the DC link, as indicated by:

$$PE= \mathrm{Re}(V_{sh}I_{sh}) = 0 \tag{3.13}$$

Also shown in (11) is the bus control constraint:

$$V_i - V_i ref = 0 \tag{3.14}$$

Where

$V_{sh}\angle\theta_{sh}$ is the STATCOM complex voltage
$P_{sh}+jQ_{sh}$ is the apparent power through STATCOM
Z_{sh} is shunt transformer impedance
The bus voltage control is defined by the $V_i ref$

3.6. INTEGRATION OF STATCOM INTO NEWTON-RAPHSON POWER FLOW SOLUTION

The MATLAB environment is used to program an algorithm for solving a power flow problem integrating a STATCOM device into the NR method for solving nonlinear algebraic problems. NR technique is a strong tool because of its quadratic convergence. It is effective for resolving load flow problems in large power networks despite its flaw of being needs large computer memory. However, the scale of the network to be solved, as well as the number and types of control equipment in the system, have no bearing on convergence., unlike other solutions. As a result, the NR approach is preferred in the proposed work [73, 74]. A STATCOM has only one degree of control because the active power exchange with the DC link must be zero in all times. The following is a concise NR power flow method with STATCOM:

$$F(X) = J\,\Delta X \tag{3.15}$$

Where X in equation (3-15) is the solution variable and J is the Jacobian matrix (the matrix of fractional derivatives of F(X) regarding X, and they are calculated as follows:

$$F(X) = \begin{bmatrix} \Delta P_K \\ \Delta Q_K \\ \Delta P_{vR} \\ \Delta Q_{vR} \end{bmatrix}, \quad \Delta X = \begin{bmatrix} \Delta \theta_K \\ \frac{\Delta V_K}{V_K} \\ \Delta \delta_{vR} \\ \frac{\Delta V_{vR}}{V_{vR}} \end{bmatrix} \tag{3.16}$$

$$J = \begin{bmatrix} \left(\frac{d\, p_K}{d\, \theta_K}\right) & \left(\frac{d\, P_K}{d\, V_K} V_K\right) & \left(\frac{d\, P_K}{d\delta_{VR}}\right) & \left(\frac{d\, P_K}{dV_{VR}} V_{VR}\right) \\ \left(\frac{d\, Q_K}{d\, \theta_K}\right) & \left(\frac{d\, Q_K}{d\, V_K} V_K\right) & \left(\frac{d\, Q_K}{d\delta_{VR}}\right) & \left(\frac{d\, Q_K}{\delta V_{VR}} V_{VR}\right) \\ \left(\frac{dP_{VR}}{d\, \theta_K}\right) & \left(\frac{dP_{VR}}{d\, V_K} V_K\right) & \left(\frac{dP_{VR}}{d\delta_{VR}}\right) & \left(\frac{dP_{VR}}{d\delta_{VR}} V_{VR}\right) \\ \left(\frac{dQ_{VR}}{d\, \theta_K}\right) & \left(\frac{dQ_{VR}}{d\, V_K} V_K\right) & \left(\frac{dQ_{VR}}{d\delta_{VR}}\right) & \left(\frac{dQ_{VR}}{d\delta_{VR}} V_{VR}\right) \end{bmatrix} \tag{3.17}$$

ΔP_K, ΔQ_K, ΔP_{vR}, and ΔQ_{vR}in equation (3-16) are the active and reactive power mismatches at the bus K and the converter, respectively. The sum of active and reactive power flows exiting the bus K and the converter is P_K, Q_K, P_{vR}, and Q_{vR}, respectively in equation (3-17). Because of the inclusion of STATCOM, the Jacobian matrix is modified in comparison to (3-16), and is hence referred to as "augmented Jacobian matrix." The augmented matrix's enhanced size is determined by the types of controllers used are the dimensions of such a matrix [75, 76].

3.7. ALGORITHM OF NR-POWER FLOW WITH STATCOM

The following is a step-by-step description of the algorithm for solving NR-power flow with STATCOM.

Step1: STATCOM and power system data are ready. Read load data primitive matrix, slack bus voltage, real and reactive bus power ،etc.

Step2: Formed δ_{vR} and V_{vR} the STATCOM for the first time.

Step 3: Formulate Y matrix using load flow data

Step 4: Make initial assumption Vi and θi for I = 1,2,…,n

Vi= Vi, spec.∠0˚ (at all PV buses)

Vi= 1∠0˚ (at all PQ buses)

Step4: Using (3-8) & (3-9) to calculate the STATCOM's P_{vR} and Q_{vR} .

Step5: Compute Pi and Qi for I = 1,2,..,n using power flow equation and Find the power differences ΔPi and Δ Qi for all i=1, 2, 3… (n-1);

Step 6: Choose the tolerance values.

Step7: Calculate the power mismatch limitations for active and reactive power.

Step8: Using the STATCOM, compute and alter the elements of the Jacobian matrix to generate a complete reinforced Jacobian matrix (3-17).

Step9: Matrix inversion is used to update the state variables.

Step10: Steps 3–9 should be repeated until all mismatch vectors are smaller than a predetermined tolerance.

Step 11: Report the result

Step 12: Stop the iteration if all ΔP_K, ΔQ_K are within the tolerance values.

3.7.1. Flow Diagram for the Newton Raphson Load Flow Method

The following thorough flowchart has been prepared in relation to the many processes required in conducting load flow studies using the Newton Raphson approach as shown in Figure 3.3 [77].

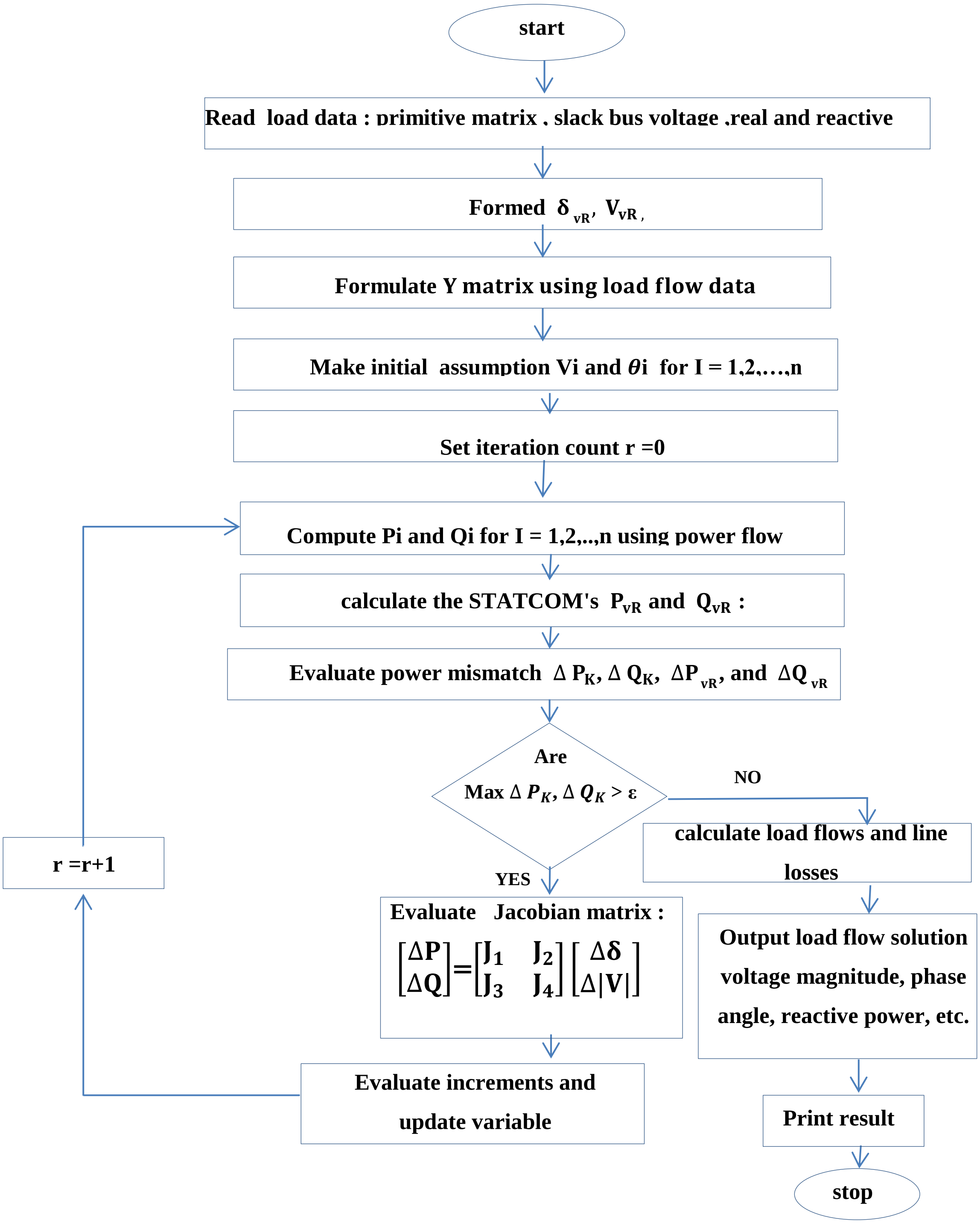


Figure 3.3. Flowchart Algorithm for NR-power flow with STATCOM [77].

3.8. DIYALA ELECTRIC POWER SYSTEM

On a geographical basis, the Iraqi National Grid (ING) is divided into sub-grids. One of these sub-grids is the Iraqi Middle Region National Grid (INRNG). The city of Diyala makes up the majority of it. There are eight 132 kV substations in this section which consists of 11 bus bars. Two-generation plants are included in the Diyala ring, as seen in Figure 3.4.

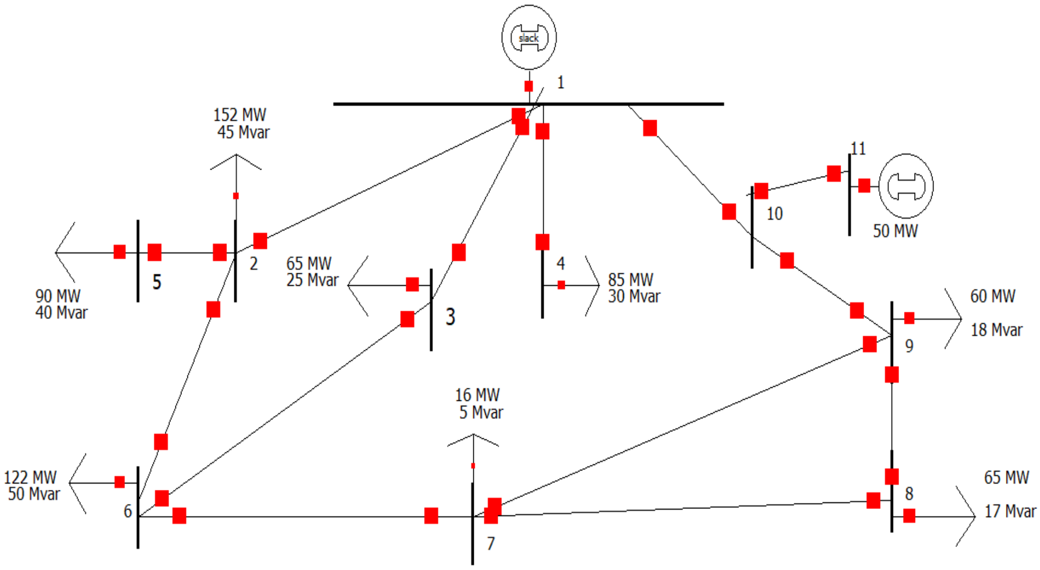


Figure 3.4. Single line diagram for the electrical network of Diyala city.

Table 3.4 shows data about the power network of Diyala city that contains sending and receiving buses. It contains 11 bus bar and 13 lines with their Per Unit (PU) resistance (R), reactance (X), and half susceptance (B/2) values.

Table 3.2. Network data of Diyala city.

No.	Send. Bus	Receive. Bus	R (p.u.)	X (p.u.)	B (p.u.)
1	1	2	0.0044	0.0196	0.00414
2	1	3	0.04061	0.17395	0.03496
3	1	4	0.00279	0.01561	0.00737
4	2	5	0.01553	0.03520	0.00635
5	3	6	0.0372	0.1596	0.032
6	6	7	0.0879	0.1782	0.0313
7	7	8	0.0528	0.2263	0.0454
8	9	10	0.0356	0.1525	0.0306
9	11	10	0.00639	0.0274	0.0055
10	10	1	0.03170	0.13583	0.2729
11	7	9	0.01641	0.07029	0.01412
12	9	8	0.0267	0.1143	0.0229
13	2	6	0.01553	0.03520	0.00635

Busbar no. (1) is the main feeder and is called slack, and bus bar No. (11) is the generator in addition to a total of 9 bus bars representing load buses (2,3,4,5,6,7,8,9,10), as illustrated in Table 3.5.

Table 3.3. Busbar data for Diyala.

Bus No.	Bus Name	Active Load (MW)	Reactive Load (MVAr)	Notes
1	Diyala	0	0	Slack Bus
2	W.baquba	152	45	Load Bus
3	baladruz	65	25	Load Bus
4	khalis	85	30	Load Bus
5	S.baquba	90	40	Load Bus
6	E.baquba	122	50	Load Bus
7	himreen	16	5	Load Bus
8	khanaqeen	65	17	Load Bus
9	muqdadya	60	25	Load Bus
10	Gen.hemreen	58	13	Load Bus
11	Mansorya	21	12	Gen. Bus

3.9. SUMMARY

There are many reasons to choose Statcom in this thesis, including:

1. STATCOM is a synchronous voltage source with a shunt connection.
2. The STATCOM's have many features such as greater application flexibility.
3. The STATCOM can adjust its output current over the rated maximum capacitive or inductive range in the non-linear working range, regardless of the AC system voltage. Beside the reactive compensation of power, STATCOM may deliver active compensation of power.

PART 4

RESULTS AND ANALYSIS

4.1. INTRODUCTION

In power system studies, load flow analysis is still a common tool. Such computations are required in the design and operation of a power system in order to examine the power system's steady-state performance under various working situations and to assess the effects of changes in equipment configuration. Computer programs were used to examine load flow solutions created for these reasons. The primary goal of load flow performance is to generate load power utilization and voltage assessment at each bus in a specified electric power system. The numerical investigation of a power system is an important part of load flow analysis in electrical power engineering. The amplitude and phase angle of the voltage at each bus, as well as the active and reactive power flowing in each line, are essential data gained from the load flow research [78].The goal of a load flow study is to figure out the following:

- The magnitude of the voltage on all buses.
- Each section of the power system has a line flow of active power, reactive power, current, and power factor which need to be within the specified limit.
- Every line section has a loss of power which needs to be minimized.

A bus is a node that connects one or more lines, loads, or generators. Each requirement in a power system is linked to electrical quantities such as voltage magnitude, active power, reactive power, and voltage phase angle [77]. In this study, the data were analyzed using a system rating of 100 MVA and bus number one as the reference bus. With the explicit goal of verifying the model and outlining the impact of STATCOM, to determine the loss mitigating effect of STATCOM on the grid in the event of unexpected increase or decrease in voltage. The power flow results for each example were acquired and compared to the initial power flow result of the system's base condition. A number of scenarios are described below. In this study, three cases for the voltage level were selected: the high voltage transmission network is at:

1. Under voltage with a value of 125 kV.
2. Normal voltage with a value of 132 Kv.
3. Over voltage with a value of 140 kV. For the three scenraios, the test method was carried out for all bus bars with and without STATCOM. The standard operating condition was a power system with typical loads on all load buses, and the Newton-Raphson load flow was carried out with a loading factor of one without STATCOM as the base case. The Newton- Raphson load flow study with and without STATCOM is applied.

4.2. SIMULATION OF DIYALA POWER NETWORK

In this study, Matlab R2020a was used to program the test system, and a load flow study was carried out for the network of Diyala city using the Newton-Raphson method. The case study is made up of 11 busbars, with the first busbar being slack, the eleventh busbar being a generator bus, and the remaining busbars being a load buses, as shown in Figure 4.1.

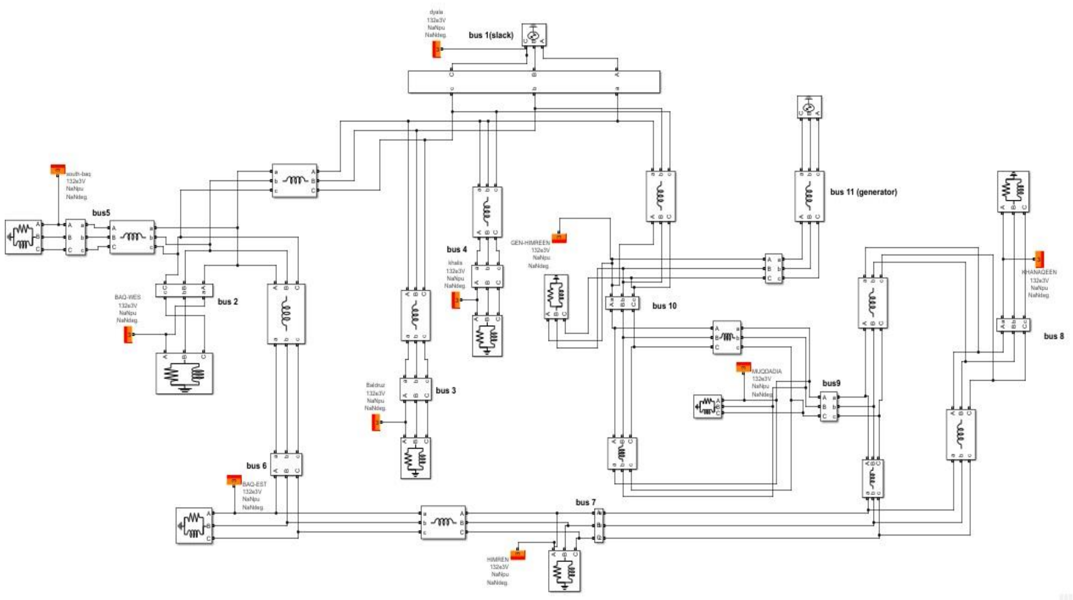


Figure 4.1. Simulated single line diagram for network of Diyala city.

4.3. VOLTAGE PROFILE

The Voltage magnitude profile of the bus bars 7, 8, and 9 are the focus due to their distance from the source and the large losses in the power transmission lines occur at those stations. In the same way, the voltage of the rest of the bus bars (2, 3, 4, 5, 6,10) were also calculated and all the values were reported later in Table 4.1.

4.3.1. Case 1: Under-Voltage (125 kV)

The test system is analyzed under below-normal voltage condition using Newton Raphson load flow method with and without STATCOM.

4.3.1.1. Installation of STATCOM at Bus Bar 7

The reactive power correction implemented by STATCOM improved the voltage profile of the system. Because the voltage magnitude of bus 7 was low (0.765) p.u., STATCOM injected reactive power into the system to compensate for the voltage drop on the affected buses, bringing their voltage magnitudes up to 1 p.u. A control for the voltage value was also present. Whether the voltage rises beyond 1 p.u or falls below 1 p.u, STATCOM sets the voltage to 1 p.u.

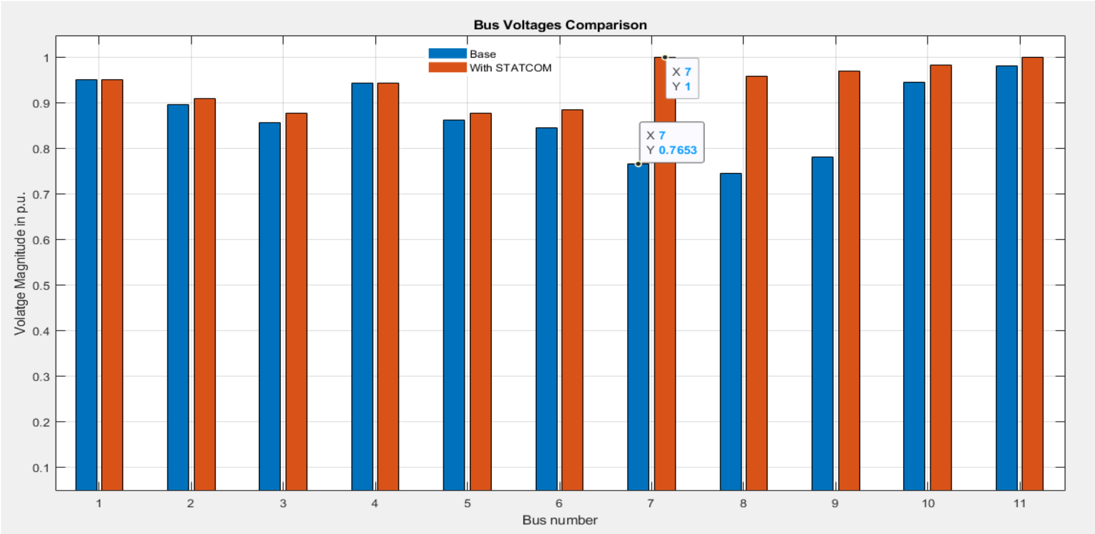


Figure 4.2. Bus voltage comparison without and with STATCOM at node 7, for under voltage scenario.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	0.950	-0.000	0.000	0.000	0.000	0.000
2	0.894	-5.438	152.000	45.000	0.000	0.000
3	0.855	-8.770	65.000	25.000	0.000	0.000
4	0.943	-0.797	85.000	30.000	0.000	0.000
5	0.862	-7.337	90.000	40.000	0.000	0.000
6	0.845	-10.152	122.000	50.000	0.000	0.000
7	0.765	-22.151	25.000	15.000	0.000	0.000
8	0.744	-27.951	65.000	17.000	0.000	0.000
9	0.781	-23.832	60.000	25.000	0.000	0.000
10	0.944	-15.897	58.000	13.000	0.000	0.000
11	0.980	-16.791	21.000	12.000	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	0.950	-0.000	0.000	0.000	0.000	0.000
2	0.909	-5.479	152.000	45.000	0.000	0.000
3	0.877	-8.883	65.000	25.000	0.000	0.000
4	0.943	-0.797	85.000	30.000	0.000	0.000
5	0.876	-7.318	90.000	40.000	0.000	0.000
6	0.884	-10.484	122.000	50.000	0.000	0.000
7	1.000	-24.008	25.000	15.000	0.000	0.000
8	0.958	-27.058	65.000	17.000	0.000	0.000
9	0.970	-24.239	60.000	25.000	0.000	0.000
10	0.983	-15.952	58.000	13.000	0.000	0.000
11	1.000	-16.541	21.000	12.000	0.000	0.000

Figure 4.3. Voltage profile without and with STATCOM at node 7, for under voltage scenario.

From the above figures i.e., Fig 4.2 and Fig 4.3, it is observed that bus 7 has a low voltage magnitude (0.765) p.u but when installing STATCOM device at bus 7, the STATCOM injects reactive power into the system to compensate for the voltage drop on the affected buses, stabilizing their voltage magnitude up to 1 p.u. It is also demonstrated that the installation effect of the STATCOM was not limited to bus bar

7, but rather affected the other buses 2, 3, 5, 6, 8, 9, 10, & 11, which caused the improvement and increase of their voltages too.

4.3.1.2. Installation of STATCOM at Bus Bar 8

In bus bar 8, there was a significant drop in the value of the voltage and it was less than the voltage of the bus bar 7due to its distance from the supply point. Hence, STATCOM injects reactive power into the system to compensate for the voltage drop on the affected buses, raising their voltage magnitude up to the desired value i.e., 1 p.u[79].

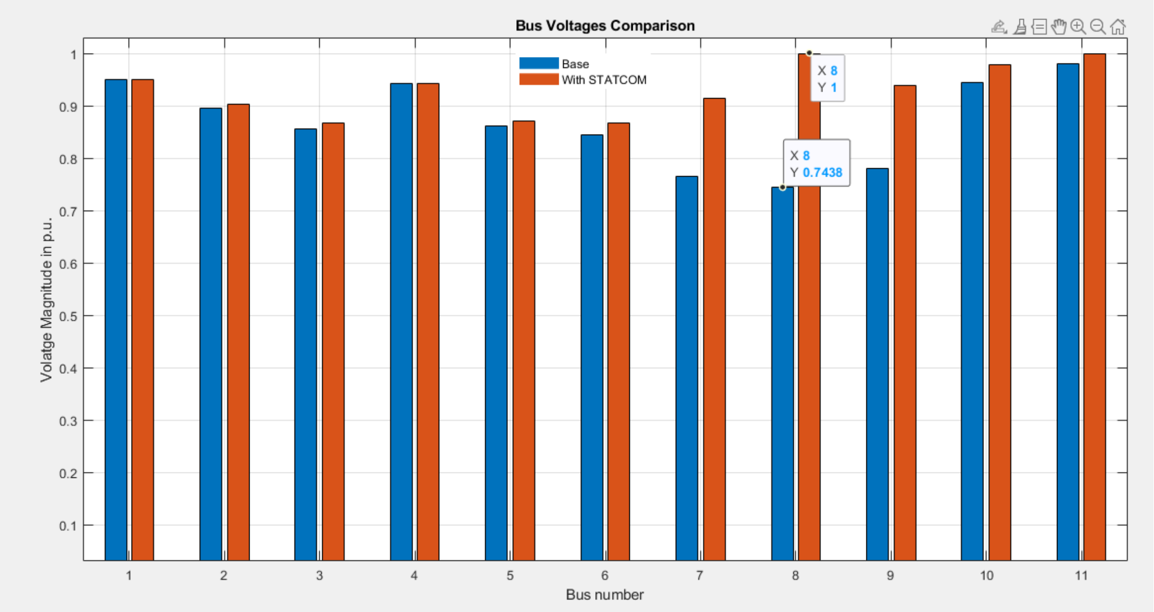


Figure 4.4. Bus voltage comparison without and with STATCOM at node 8, for under voltage scenario.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	0.950	-0.000	0.000	0.000	0.000	0.000
2	0.894	-5.438	152.000	45.000	0.000	0.000
3	0.855	-8.770	65.000	25.000	0.000	0.000
4	0.943	-0.797	85.000	30.000	0.000	0.000
5	0.862	-7.337	90.000	40.000	0.000	0.000
6	0.845	-10.152	122.000	50.000	0.000	0.000
7	0.765	-22.151	25.000	15.000	0.000	0.000
8	0.744	-27.951	65.000	17.000	0.000	0.000
9	0.781	-23.832	60.000	25.000	0.000	0.000
10	0.944	-15.897	58.000	13.000	0.000	0.000
11	0.980	-16.791	21.000	12.000	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	0.950	-0.000	0.000	0.000	0.000	0.000
2	0.902	-5.412	152.000	45.000	0.000	0.000
3	0.867	-8.756	65.000	25.000	0.000	0.000
4	0.943	-0.797	85.000	30.000	0.000	0.000
5	0.870	-7.276	90.000	40.000	0.000	0.000
6	0.867	-10.188	122.000	50.000	0.000	0.000
7	0.914	-22.864	25.000	15.000	0.000	0.000
8	1.000	-27.633	65.000	17.000	0.000	0.000
9	0.939	-23.955	60.000	25.000	0.000	0.000
10	0.979	-15.854	58.000	13.000	0.000	0.000
11	1.000	-16.498	21.000	12.000	0.000	0.000

Figure 4.5. Voltage profile without and with STATCOM at node 8, for under voltage scenario.

From the above figures, Figure 4.4 and Figure 4.5, it is observed that the bus 8 has originally low voltage magnitude (0.744) p.u and when STATCOM device is installed at bus 8, STATCOM injected reactive power into the system to compensate for the voltage drop on the affected buses, bringing their voltage magnitude up to 1 p.u. Furthermore, similar to the first case, the effect of installation the STATCOM was not limited to the bus bar 8, but rather affected the other buses 2, 3, 5, 6, 7, 9, 10, & 11, which caused the improvement and increase of voltages as well.

4.3.1.3. Installation of STATCOM at Bus Bar 9

From Figure 4.6 and Figure 4.7, it is observed the bus 9 has reportedly a low voltage magnitude (0.781) p.u and when installing STATCOM device at bus 9 STATCOM injects reactive power into the system to compensate for the voltage drop on the affected buses, improving their voltage magnitude up to the set level. Likewise, the effect of installation the STATCOM was not limited to the bus bar 9 but indeed affected the other buses 2, 3, 5, 6, 7, 8, 10, & 11, which caused the improvement and increase of voltages too.

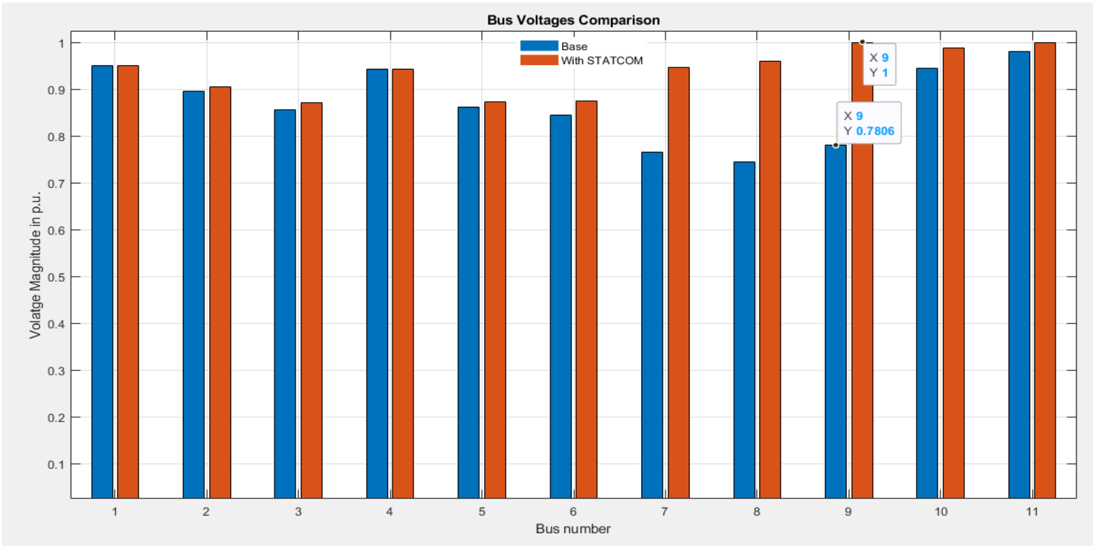


Figure 4.6. Bus voltage comparison without and with STATCOM at node 9, for under voltage scenario.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	Load MW	Load Mvar	Generation MW	Generation Mvar
1	0.950	-0.000	0.000	0.000	0.000	0.000
2	0.894	-5.438	152.000	45.000	0.000	0.000
3	0.855	-8.770	65.000	25.000	0.000	0.000
4	0.943	-0.797	85.000	30.000	0.000	0.000
5	0.862	-7.337	90.000	40.000	0.000	0.000
6	0.845	-10.152	122.000	50.000	0.000	0.000
7	0.765	-22.151	25.000	15.000	0.000	0.000
8	0.744	-27.951	65.000	17.000	0.000	0.000
9	0.781	-23.832	60.000	25.000	0.000	0.000
10	0.944	-15.897	58.000	13.000	0.000	0.000
11	0.980	-16.791	21.000	12.000	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	Load MW	Load Mvar	Generation MW	Generation Mvar
1	0.950	-0.000	0.000	0.000	0.000	0.000
2	0.905	-5.383	152.000	45.000	0.000	0.000
3	0.871	-8.720	65.000	25.000	0.000	0.000
4	0.943	-0.797	85.000	30.000	0.000	0.000
5	0.872	-7.237	90.000	40.000	0.000	0.000
6	0.874	-10.136	122.000	50.000	0.000	0.000
7	0.946	-22.526	25.000	15.000	0.000	0.000
8	0.960	-26.261	65.000	17.000	0.000	0.000
9	1.000	-23.780	60.000	25.000	0.000	0.000
10	0.987	-15.677	58.000	13.000	0.000	0.000
11	1.000	-16.207	21.000	12.000	0.000	0.000

Figure 4.7. Voltage profile without and with STATCOM at node 9, for under voltage case.

4.3.2. Case 2: Overvoltage (140 kV)

The test system is analyzed in case of over-voltage scenario using Newton Raphson load flow method with and without STATCOM.

4.3.2.1. Installation of STATCOM at Bus Bar 4

In the case the transmission network experiences an overvoltage of 140 kV, an increase in voltage is observed in the bus bar 4 due to its proximity to the main voltage source and the absence of branch bars connected to it [80]. The reactive power correction implemented by STATCOM improved the voltage profile of the system. Since the voltage for bus bar 4 was high (1.053) p.u, STATCOM in this case absorbs reactive power from the system to reduce the high voltage on the affected buses, bringing the voltages down to 1 p.u, as shown in Fig. 4.9. Voltage value control was also present. Whether the voltage rises above 1 p.u or falls below 1 p.u, STATCOM sets the voltage to 1 p.u.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.012	-4.318	152.000	45.000	0.000	0.000
3	0.979	-6.907	65.000	25.000	0.000	0.000
4	1.053	-0.639	85.000	30.000	0.000	0.000
5	0.983	-5.791	90.000	40.000	0.000	0.000
6	0.966	-7.976	122.000	50.000	0.000	0.000
7	0.873	-17.064	25.000	15.000	0.000	0.000
8	0.850	-21.618	65.000	17.000	0.000	0.000
9	0.877	-18.440	60.000	25.000	0.000	0.000
10	0.989	-11.848	58.000	13.000	0.000	0.000
11	1.000	-12.342	21.000	12.000	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.008	-4.295	152.000	45.000	0.000	0.000
3	0.973	-6.855	65.000	25.000	0.000	0.000
4	1.000	-0.087	85.000	30.000	0.000	0.000
5	0.979	-5.778	90.000	40.000	0.000	0.000
6	0.957	-7.852	122.000	50.000	0.000	0.000
7	0.867	-17.147	25.000	15.000	0.000	0.000
8	0.844	-21.762	65.000	17.000	0.000	0.000
9	0.872	-18.542	60.000	25.000	0.000	0.000
10	0.989	-11.903	58.000	13.000	0.000	0.000
11	1.000	-12.408	21.000	12.000	0.000	0.000

Figure 4.8. Voltage profile without and with STATCOM at node 4, for overvoltage scenario.

4.3.2.2. Installation of STATCOM at Bus Bar 7

From Figure 4.10 , it is obvious that the bus 7 has a low voltage magnitude (0.873) p.u but when STATCOM device is installed at bus 7 STATCOM injects reactive power into the system to compensate for the voltage drop on the affected buses, raising their voltage magnitude up to 1 p.u and, similarly, the effect of installation the STATCOM was not limited to the bus bar 7 but rather affected the other buses 2, 3, 5, 6, 8, 9, 10, & 11, which caused the improvement and increase of voltages too [81].

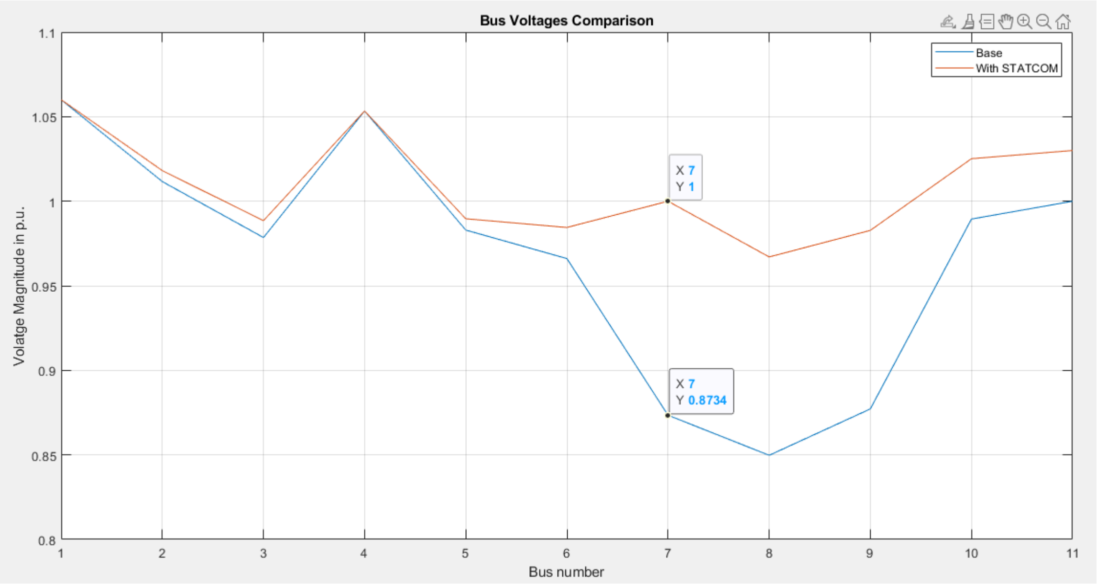


Figure 4.9.Curve voltage comparison without and with STATCOM at node 7, for overvoltage scenario.

4.3.2.3. Installation of STATCOM at Bus Bar 9

From Figure 4.11 and Figure 4.12, it is clear that the voltage at bus 9 is violated; it has a low voltage magnitude (0.877) p.u but as STATCOM device is installed at bus 9 STATCOM injected reactive power into the system to compensate for the voltage drop on the affected buses, bringing their voltage magnitude up to 1 p.u. The impact of installation of the STATCOM was not limited to the bus bar 9 but rather extended to the other buses 2, 3, 5, 6, 7, 8, 10, & 11, which yielded the improvement and increase of voltages either.

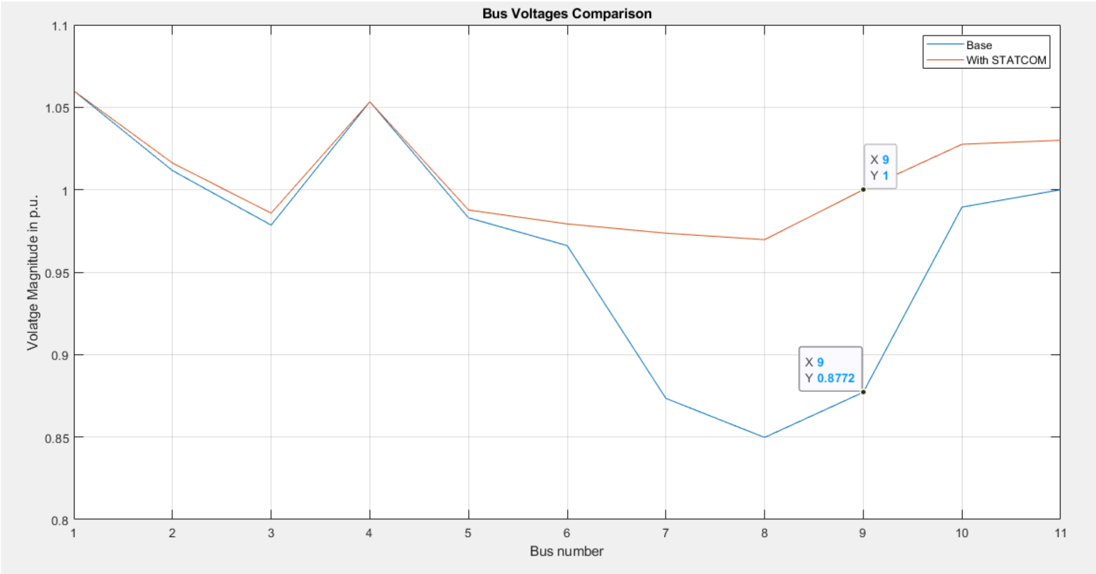


Figure 4.10. Curve voltage profile without and with STATCOM at node 9, for 140 kV scenario.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.012	-4.318	152.000	45.000	0.000	0.000
3	0.979	-6.907	65.000	25.000	0.000	0.000
4	1.053	-0.639	85.000	30.000	0.000	0.000
5	0.983	-5.791	90.000	40.000	0.000	0.000
6	0.966	-7.976	122.000	50.000	0.000	0.000
7	0.873	-17.064	25.000	15.000	0.000	0.000
8	0.850	-21.618	65.000	17.000	0.000	0.000
9	0.877	-18.440	60.000	25.000	0.000	0.000
10	0.989	-11.848	58.000	13.000	0.000	0.000
11	1.000	-12.342	21.000	12.000	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.016	-4.254	152.000	45.000	0.000	0.000
3	0.986	-6.831	65.000	25.000	0.000	0.000
4	1.053	-0.639	85.000	30.000	0.000	0.000
5	0.988	-5.714	90.000	40.000	0.000	0.000
6	0.979	-7.851	122.000	50.000	0.000	0.000
7	0.974	-17.134	25.000	15.000	0.000	0.000
8	0.970	-20.715	65.000	17.000	0.000	0.000
9	1.000	-18.252	60.000	25.000	0.000	0.000
10	1.028	-11.745	58.000	13.000	0.000	0.000
11	1.030	-12.106	21.000	12.000	0.000	0.000

Figure 4.11. Voltage profile without and with STATCOM at bus bar 9 for overvoltage case.

4.3.3. Case 3: Normal Voltage (132 kV)

The test system is further analyzed at rated voltage condition using Newton Raphson load flow method with and without STATCOM.

4.3.3.1. Installation of STATCOM on Bus Bar 7

From Figure 4.13. it is experienced that the bus 7 has a low voltage magnitude (0.811) p.u. However, when STATCOM device is installed at bus 7, it injects reactive power into the system to compensate for the voltage drop on the affected buses, improving their voltage magnitude to reach 1 p.u. Likewise, the effect of installing the STATCOM was not limited to the bus bar 7 but rather affected the other buses 2, 3, 5, 6, 8, 9, 10, & 11, which caused the improvement and increase of voltages too. On the other hand, Figure 4.13 illustrates that the system's bus voltage profile has been considerably improved. The bus voltage at which the STATCOM is installed has been restored to 1 p.u and the system's overall voltage profile has been enhanced, whenever installing a STATCOM device on any bus, the value of the bus voltage is restored to 1 p.u.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.000	0.000	0.000	0.000	0.000	0.000
2	0.948	0.085	152.000	45.000	0.000	0.000
3	0.911	0.137	65.000	25.000	0.000	0.000
4	0.993	0.013	85.000	30.000	0.000	0.000
5	0.917	0.115	90.000	40.000	0.000	0.000
6	0.900	0.158	122.000	50.000	0.000	0.000
7	0.811	0.343	25.000	15.000	0.000	0.000
8	0.788	0.434	65.000	17.000	0.000	0.000
9	0.820	0.370	60.000	25.000	0.000	0.000
10	0.957	0.241	58.000	13.000	0.000	0.000
11	0.980	0.254	21.000	12.000	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.000	0.000	0.000	0.000	0.000	0.000
2	0.959	0.085	152.000	45.000	0.000	0.000
3	0.928	0.138	65.000	25.000	0.000	0.000
4	0.993	0.013	85.000	30.000	0.000	0.000
5	0.928	0.114	90.000	40.000	0.000	0.000
6	0.930	0.162	122.000	50.000	0.000	0.000
7	1.000	0.369	25.000	15.000	0.000	0.000
8	0.960	0.424	65.000	17.000	0.000	0.000
9	0.973	0.377	60.000	25.000	0.000	0.000
10	0.992	0.243	58.000	13.000	0.000	0.000
11	1.000	0.251	21.000	12.000	0.000	0.000

Figure 4.12. Voltage profile without and with STATCOM at node 7, for normal voltage scenario.

4.3.3.2. Installation of STATCOM on Bus Bar 8

From Figure 4.14, it can be noticed that bus 8 has a low voltage magnitude (0.787) p.u., it is lower than the bus bar 7. However, when the STATCOM device is installed at bus 8 the bus bar voltage is increased to the desired level i.e., 1 p.u. The effect of installation the STATCOM was not limited to the bus bar 8 but obviously affected the other buses 2, 3, 5, 6, 7, 9, 10, & 11, which caused the improvement and increase of voltages too.

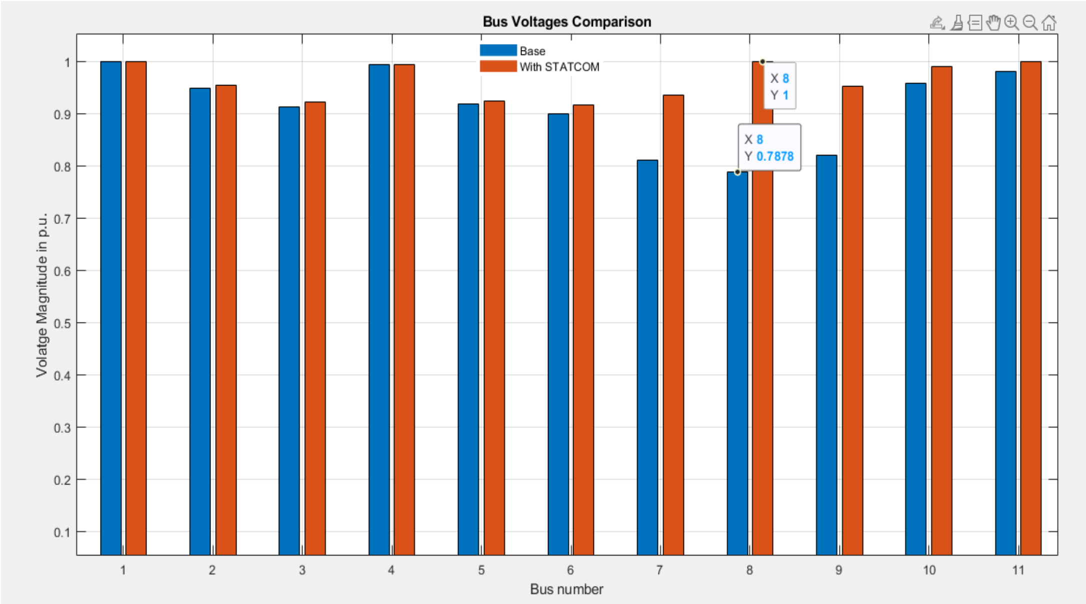


Figure 4.13. Bus voltage comparison without and with STATCOM at node 8, for normal voltage scenario.

4.3.3.3. Installation of STATCOM on bus bar 9

From Figure 4.15, it is observed from the curve that the bus 9 has a weak voltage magnitude (0.820) p.u but when installing STATCOM device at bus 9 the bus bar voltage increased to a value of 1 p.u; the effect of installation the STATCOM was not limited to the bus bar 9 but rather extended to the other buses within the network i.e., 2, 3, 5, 6, 7, 9, 10, & 11, which contributed to the improvement and enhancement of voltages.

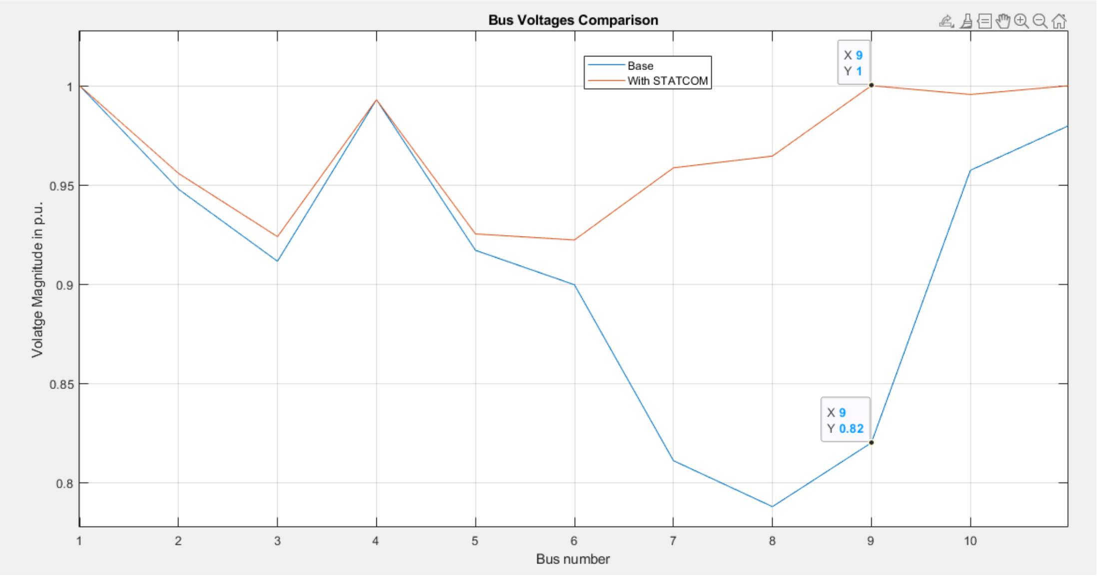


Figure 4.14. Curve bus voltage comparison without and with STATCOM at node 9, for normal voltage scenario.

Table 4.1, on the other hand, shows the bus voltages with and without STATCOM for all buses in the three cases. It is considerably observed that buses before connecting STATCOM possess a weak voltage of less than 1 per unit, but when the STATCOM is connected to the bus bar, it brings the voltage up to 1 per unit. Moreover, it raises the values of all other bus bar voltages, as shown in the Figures for each of the three cases [81].

Table 4.1. Summarized comparison of voltag.

Bus no.	**Without STATCOM (p.u)**			**With STATCOM (p.u)**		
	125 kV	**132 kV**	**140 kV**	**125 kV**	**132 kV**	**140 kV**
2	0.894	0.948	1.012	1	1	1
3	0.855	0.911	0.979	1	1	1
4	0.943	0.993	1.052	1	1	1
5	0.862	0.917	0.983	1	1	1
6	0.845	0.900	0.966	1	1	1
7	0.765	0.811	0.873	1	1	1
8	0.744	0.788	0.850	1	1	1
9	0.781	0.820	0.877	1	1	1
10	0.944	0.945	0.982	1	1	1

4.4. ACTIVE AND REACTIVE POWER LOSSES

The increasing voltage instability problem in Iraq's power infrastructure is posing a severe operating challenge for the utilities. The impact of adopting STATCOM for reactive power compensation in the energy grid was investigated in this study, which used an 11-bus power network as a case study. Because the quality of power supply for any given system is determined by voltage at the buses and transmitted power, it is critical to keep bus voltage within the specified voltage constraints and minimize transmission active power loss, and to do so, effective reactive power compensation in the electricity grid must be improved [82]. The STATCOM regulates voltage at the terminal by controlling the amount of reactive power brought into or absorbed by the power system network. When the system voltage is low, the STATCOM delivers reactive power (STATCOM capacitive), and when the system voltage is high, reactive power is absorbed (STATCOM inductive).

4.4.1. Case 1: Under-Voltage (125 kV)

As mentioned earlier, the active and reactive power of the bus bars (7, 8, 9) are the focus due to their distance from the source and the large losses that occur in the power transmission lines at those stations. In the same way, the voltage of the rest of the bus bars (2, 3, 4, 5, 6,10) were also calculated and all the values were reported later in Table 4.10.

4.4.1.1. Installation of STATCOM at Bus Bar 7

Table 4.2 reports line flow and losses with and without STATCOM for bus 7 under voltage of 125 kV. It is clearly observed from the result that the total real power losses are 53.298 MW and total reactive power loss are 110.734 Mvar. Interestingly, after installing STATCOM at bus 7 it is found that the total real power loss is reduced to 53.273 MW and total reactive power loss is reduced to 86.758 Mvar. It is also observed that STATCOM reduced the active and reactive power losses in all buses and not only bus 7.

Table 4.2. Line flow and losses without and with STATCOM at bus 7.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	Mvar	**From bus**	**To bus**	MW	Mvar
1	2	11.700	51.415	1	2	10.474	45.941
1	3	3.560	9.538	1	3	3.225	7.973
1	4	0.254	0.101	1	4	0.254	0.101
2	5	2.021	3.602	2	5	1.954	3.417
3	6	0.074	-4.307	3	6	0.090	-4.569
6	7	7.690	11.524	6	7	13.904	22.610
7	8	0.616	-2.535	7	8	0.437	-6.835
9	10	5.899	20.681	9	10	2.914	6.648
11	10	1.255	4.365	11	10	0.325	0.310
10	1	11.178	-1.029	10	1	11.890	-0.038
7	9	0.236	-0.675	7	9	0.294	-1.482
9	8	0.844	0.950	9	8	0.462	-2.278
2	6	7.971	17.104	2	6	7.050	14.960
Total losses		**53.298**	**110.734**			**53.273**	**86.758**

When comparing the system with STATCOM to the system without, it can be seen that the active power loss has decreased. Table 4.2 demonstrates how the reactive power loss decreased in the same manner. When STATCOM was connected to the system, both active and reactive power losses in the transmission line fell significantly, which is indeed an effective way to reduce power system losses [83].

4.4.1.2. Installation of STATCOM at Bus Bar 8

Table 4.3 shows line flow and losses with and without STATCOM at bus 8 under voltage of 125 kV. Upon installing STATCOM at bus 7 it is found out that total real power loss is reduced from 53.298 MW to 50.662 MW and total reactive power loss is reduced from 110.734 Mvar to 88.335 Mvar. From the attained results tabulated in Table 4.3, it is observed that STATCOM reduces the active and reactive power losses in all buses and not only bus 8.

Table 4.3. Line flow and losses without and with STATCOM at bus 8.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	Mvar	**From bus**	**To bus**	MW	Mvar
1	2	11.700	51.415	1	2	10.807	47.430
1	3	3.560	9.538	1	3	3.312	8.401
1	4	0.254	0.101	1	4	0.254	0.101
2	5	2.021	3.602	2	5	1.983	3.498
3	6	0.074	-4.307	3	6	0.065	-4.533
6	7	7.690	11.524	6	7	9.107	13.494
7	8	0.616	-2.535	7	8	1.335	-2.616
9	10	5.899	20.681	9	10	2.892	6.755
11	10	1.255	4.365	11	10	0.460	0.894
10	1	11.178	-1.029	10	1	11.663	-0.804
7	9	0.236	-0.675	7	9	0.293	-1.171
9	8	0.844	0.950	9	8	1.463	1.951
2	6	7.971	17.104	2	6	7.028	14.935
Total losses		**53.298**	**110.734**			**50.662**	**88.335**

4.4.1.3. Installation of STATCOM on Bus Bar 9

Table 4.4 shows line flow and losses with and without STATCOM for bus 9 under voltage 125 kV. It is clear from the results that as soon as STATCOM is installed at bus 9 the total active power losses are reduced from 53.298 MW to 49.256 MW and a decrease in total reactive power losses are also obtained, from 110.734 Mvar to

80.08 Mvar. From Table 4.4, it is observed that STATCOM reduces the active and reactive power losses in all other buses.

Table 4.4. Line flow and losses without and with STATCOM at bus 9.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	Mvar	**From bus**	**To bus**	MW	Mvar
1	2	11.700	51.415	1	2	10.493	46.029
1	3	3.560	9.538	1	3	3.223	7.999
1	4	0.254	0.101	1	4	0.254	0.101
2	5	2.021	3.602	2	5	1.971	3.466
3	6	0.074	-4.307	3	6	0.065	-4.592
6	7	7.690	11.524	6	7	9.731	14.536
7	8	0.616	-2.535	7	8	0.397	-6.546
9	10	5.899	20.681	9	10	2.885	6.319
11	10	1.255	4.365	11	10	0.206	-0.202
10	1	11.178	-1.029	10	1	11.589	-1.555
7	9	0.236	-0.675	7	9	1.065	1.885
9	8	0.844	0.950	9	8	0.658	-1.585
2	6	7.971	17.104	2	6	6.719	14.225
Total losses		**53.298**	**110.734**			**49.256**	**80.08**

4.4.2. Case 2: Over-Voltage (140 kV)

4.4.2.1. Installation of STATCOM at Bus Bar 7

Table 4.5 shows line flow and losses without and with STATCOM at bus 7 in case of over voltage (140 kV). It is clear from the results that before installing STATCOM at bus bar 7 the total real losses were 39.737 MW while the total reactive loss was 41.355 Mvar. On the contrary, after installing STATCOM at bus 7 it is found that the total real power losses are reduced to 36.355 MW while the total reactive power loss is reduced to 20.650 Mvar. From Table 4.5, it is observed that STATCOM reduced both the active and reactive power losses in all buses and not only bus 7.

Table 4.5. Line flow and losses without and with STATCOM at bus 7 (overvoltage).

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	Mvar	**From bus**	**To bus**	MW	Mvar
1	2	9.192	40.056	1	2	8.536	37.131
1	3	2.761	4.550	1	3	2.587	3.738
1	4	0.203	-0.510	1	4	0.203	-0.510
2	5	1.551	2.254	2	5	1.530	2.189
3	6	0.067	-5.763	3	6	0.052	-6.003
6	7	6.628	8.127	6	7	6.648	7.313
7	8	0.513	-4.543	7	8	0.420	-6.987
9	10	3.496	9.627	9	10	2.249	3.463
11	10	0.149	-0.449	11	10	0.059	-0.908
10	1	8.092	-22.707	10	1	7.894	-25.520
7	9	0.144	-1.549	7	9	0.138	-2.185
9	8	0.590	-0.891	9	8	0.432	-2.507
2	6	6.351	13.153	2	6	5.607	11.436
Total losses		**39.737**	**41.355**			**36.355**	**20.650**

4.4.2.2. Installation of STATCOM at Bus Bar 8

In the same manner, Table 4.6 shows line flow and losses without and with STATCOM installation at bus 8 in case of over voltage i.e., 140 kV. It is found that as soon as installing STATCOM at bus 7 the total real power loss is reduced from 39.737 MW to 36.255 and a reduction in total reactive power loss is also observed, from 41.355 Mvar to 22.434 Mvar.

Table 4.6. Line flow and losses without and with STATCOM at bus 8.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	Mvar	**From bus**	**To bus**	MW	Mvar
1	2	9.192	40.056	1	2	8.710	37.906
1	3	2.761	4.550	1	3	2.630	3.949
1	4	0.203	-0.510	1	4	0.203	-0.510
2	5	1.551	2.254	2	5	1.539	2.215
3	6	0.067	-5.763	3	6	0.052	-5.930
6	7	6.628	8.127	6	7	5.816	5.906
7	8	0.513	-4.543	7	8	0.607	-6.146
9	10	3.496	9.627	9	10	2.276	3.639
11	10	0.149	-0.449	11	10	0.072	-0.853
10	1	8.092	-22.707	10	1	7.829	-25.734
7	9	0.144	-1.549	7	9	0.144	-2.031
9	8	0.590	-0.891	9	8	0.641	-1.718
2	6	6.351	13.153	2	6	5.736	11.741
Total losses		**39.737**	**41.355**			**36.255**	**22.434**

4.4.2.3. Installation of STATCOM at Bus Bar 9

Table 4.7 reports power flow and losses without and with implementing the STATCOM at bus 9 in case over voltage of 140 kV is experienced. After the insertion of the STATCOM at bus 9, it is found out that the total real power loss is reduced from 39.737 MW to 34.949 MW while the total reactive power loss is reduced from 41.355 Mvar to 17.352 Mvar. From the table below, it is observed that the STATCOM has a positive effect on the whole system in terms of a reduction in the active and reactive power losses.

Table 4.7. Line flow and losses without and with STATCOM at bus 9.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	Mvar	**From bus**	**To bus**	MW	Mvar
1	2	9.192	40.056	1	2	8.564	37.255
1	3	2.761	4.550	1	3	2.589	3.765
1	4	0.203	-0.510	1	4	0.203	-0.510
2	5	1.551	2.254	2	5	1.536	2.207
3	6	0.067	-5.763	3	6	0.048	-5.971
6	7	6.628	8.127	6	7	5.567	5.317
7	8	0.513	-4.543	7	8	0.362	-7.021
9	10	3.496	9.627	9	10	2.032	2.413
11	10	0.149	-0.449	11	10	0.039	-0.999
10	1	8.092	-22.707	10	1	7.603	-26.899
7	9	0.144	-1.549	7	9	0.336	-1.312
9	8	0.590	-0.891	9	8	0.525	-2.196
2	6	6.351	13.153	2	6	5.545	11.303
Total losses		**39.737**	**41.355**			**34.949**	**17.352**

4.4.3. Case 3: Normal voltage 132 kV

As mentioned previously, the active and reactive power of the bus bars (7, 8, 9) are the focus due to their distance from the source and the large losses that occur in the power transmission lines at those stations. In the same way, the voltage of the rest of the bus bars (2, 3, 4, 5, 6,10) were also calculated and all the values were reported later in Table 4.10.

4.4.3.1. Installation of STATCOM at Bus Bar 7

Table 4.8 shows line flow and losses without and with STATCOM insertion at bus 7 in case the network is at a voltage condition of 132 kV. It is demonstrated from the results that after inserting the STATCOM the total real power loss is reduced from 46.134 MW to 43.966 MW whereas the total reactive power loss is reduced from 75.710 Mvar to 52.324 Mvar. From the below table, it can clearly be seen that the STATCOM will reduce the active and reactive power losses in all buses and not only bus 7.

Table 4.8. Line flow and losses without and with STATCOM at bus 7.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	MVAR	**From bus**	**To bus**	MW	MVAR
1	2	10.471	45.856	1	2	9.484	41.454
1	3	3.166	7.159	1	3	2.904	5.922
1	4	0.229	-0.184	1	4	0.225	-0.184
2	5	1.784	2.938	2	5	1.742	2.814
3	6	0.071	-4.942	3	6	0.068	-5.233
6	7	7.257	10.121	6	7	9.961	14.354
7	8	0.573	-3.345	7	8	0.442	-6.830
9	10	4.610	14.885	9	10	2.554	5.038
11	10	0.525	1.219	11	10	0.106	-0.635
10	1	9.350	-12.238	10	1	9.495	-13.447
7	9	0.180	-1.108	7	9	0.252	-1.670
9	8	0.717	0.110	9	8	0.444	-2.376
2	6	7.201	15.239	2	6	6.285	13.117
Total losses		**46.13**	**75.710**			**43.966**	**52.324**

4.4.3.2. Installation of STATCOM at Bus Bar 8

Table 4.9 shows line flow and losses without and with STATCOM at bus 8 in case of normal voltage condition of 132 kV. Installing STATCOM at bus 7 would bring the total real power loss down, from 46.134 MW to 42.874MW and the total reactive power loss from 75.710 Mvar to 54.722 Mvar. Likewise, it is also experienced that STATCOM will reduce the active and reactive power losses in the whole system.

Table 4.9. Line flow and losses without and with STATCOM at bus 8.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	MVAR	**From bus**	**To bus**	MW	MVAR
1	2	10.471	45.856	1	2	9.766	42.711
1	3	3.166	7.159	1	3	2.973	6.273
1	4	0.229	-0.184	1	4	0.225	-0.184
2	5	1.784	2.938	2	5	1.759	2.868
3	6	0.071	-4.942	3	6	0.057	-5.158
6	7	7.257	10.121	6	7	7.333	9.504
7	8	0.573	-3.345	7	8	0.984	-4.284
9	10	4.610	14.885	9	10	2.551	5.164
11	10	0.525	1.219	11	10	0.157	-0.420
10	1	9.350	-12.238	10	1	9.378	-13.805
7	9	0.180	-1.108	7	9	0.199	-1.661
9	8	0.717	0.110	9	8	1.100	0.346
2	6	7.201	15.239	2	6	6.388	13.368
Total losses		**46.134**	**75.710**			**42.87**	**54.722**

4.4.3.3. Installation of STATCOM at Bus Bar 9

Line flow and losses without and with STATCOM at bus 9 in case of normal voltage 132 kV are tabulated in Table 4.10. It is clearly visualized that when inserting STATCOM at bus 9 the total active power loss is reduced from 46.134 MW to 41.415 MW and the total reactive power loss is reduced from 75.710 Mvar to only 47.613 Mvar. Similarly, the STATCOM will reduce the active and reactive power losses the entire power system.

Table 4.10. Line flow and losses without and with STATCOM at bus 9.

Line Flow and Losses without STATCOM				Line Flow and Losses with STATCOM			
From bus	**To bus**	MW	MVAR	**From bus**	**To bus**	MW	MVAR
1	2	10.471	45.856	1	2	9.517	41.600
1	3	3.166	7.159	1	3	2.904	5.958
1	4	0.229	-0.184	1	4	0.229	-0.184
2	5	1.784	2.938	2	5	1.752	2.845
3	6	0.071	-4.942	3	6	0.054	-5.219
6	7	7.257	10.121	6	7	7.469	9.604
7	8	0.573	-3.345	7	8	0.376	-6.783
9	10	4.610	14.885	9	10	2.477	4.518
11	10	0.525	1.219	11	10	0.057	-0.850
10	1	9.350	-12.238	10	1	9.203	-14.902
7	9	0.180	-1.108	7	9	0.676	0.188
9	8	0.717	0.110	9	8	0.590	-1.893
2	6	7.201	15.239	2	6	6.111	12.731
Total losses		**46.134**	**75.710**			**41.415**	**47.613**

The Newton-Raphson load flow program was conducted on the model without and with the STATCOM device for all load conditions of the system to study the impact of STATCOM in minimizing power losses in the system. The outcome is summarized in Table 4.11. It is clear from the findings that after STATCOM was integrated into the system, the losses in the system were decreased for all the three considered cases.

Table 4.11. Summary of line flow and losses without and with STATCOM for the three cases.

N0.bus	Line flow and losses Without STATCOM						Line flow and losses With STATCOM					
	125 KV		132KV		140KV		125 KV		132KV		140KV	
	MW	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**	**MW**	**Mvar**
2	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**50.92**	**95.18**	**42.0**	**54.2**	**41.1**	**47.3**
3	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**51.83**	**103.2**	**44.2**	**66.7**	**39.3**	**39.5**
4	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**57.78**	**132.8**	**45.9**	**75.2**	**39.5**	**41.1**
5	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**54.54**	**101.6**	**44.0**	**62.2**	**38.6**	**37.0**
6	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**49.03**	**75.58**	**39.4**	**41.1**	**34.9**	**21.8**
7	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**53.27**	**86.75**	**41.4**	**41.4**	**34.9**	**17.3**
8	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**50.66**	**88.33**	**42.8**	**54.7**	**36.2**	**22.4**
9	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**49.25**	**80.08**	**41.4**	**47.6**	**34.9**	**17.3**
10	**53.2**	**110.7**	**46.1**	**75.7**	**39.7**	**41.3**	**52.31**	**104.2**	**45.2**	**70.4**	**39.8**	**41.4**

4.5. IMPLEMENTATION OF THE DEVELOPED MECHANISM ON IEEE 30-BUS TEST SYSTEM

To improve the voltage profile and performance of the IEEE 30-bus system we discovered (with load flow study) two weak buses, busbar 26 that had a voltage level (prior to STATCOM placement) 0.955, and busbar 30 that had a value of 0.951. Figure 4.16 shows the complete voltage profile of the IEEE 30-bus system that has been obtained using the developed program in two cases i.e., without and with STATCOM. Because buses 26 and 30 are designated as weak buses in the system, so STATCOM devices are installed on both buses, making the voltage magnitude improved as compared to the case without STATCOM. The voltage magnitudes are kept at 1 p.u. with the presence of FACTS Device.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.010	-4.353	21.700	12.700	40.000	48.822
3	0.997	-6.723	2.400	1.200	0.000	0.000
4	0.984	-8.111	7.600	1.600	0.000	0.000
5	0.980	-13.388	94.200	19.000	0.000	35.975
6	0.981	-9.646	0.000	0.000	0.000	0.000
7	0.972	-11.740	22.800	10.900	0.000	0.000
8	0.980	-10.428	30.000	30.000	0.000	30.826
9	0.998	-10.774	0.000	0.000	30.000	0.000
10	0.995	-13.281	5.800	2.000	0.000	0.000
11	1.000	-10.774	0.000	0.000	0.000	16.119
12	1.001	-13.345	11.200	7.500	0.000	0.000
13	1.000	-13.345	0.000	0.000	0.000	10.423
14	0.986	-14.242	6.200	1.600	0.000	0.000
15	0.982	-14.265	8.200	2.500	0.000	0.000
16	0.991	-13.630	3.500	1.800	0.000	0.000
17	0.988	-13.618	9.000	5.800	0.000	0.000
18	0.974	-14.692	3.200	0.900	0.000	0.000
19	0.972	-14.730	9.500	3.400	0.000	0.000
20	0.977	-14.431	2.200	0.700	0.000	0.000
21	0.982	-13.847	17.500	11.200	0.000	0.000
22	0.983	-13.856	0.000	0.000	0.000	0.000
23	0.974	-14.576	3.200	1.600	0.000	0.000
24	0.971	-14.603	8.700	6.700	0.000	0.000
25	0.973	-14.567	0.000	0.000	0.000	0.000
26	0.955	-15.026	3.500	2.300	0.000	0.000
27	0.984	-14.254	0.000	0.000	0.000	0.000
28	0.979	-10.306	0.000	0.000	0.000	0.000
29	0.963	-15.587	2.400	0.900	0.000	0.000
30	0.951	-16.547	10.600	1.900	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus No.	Voltage Mag.	Angle Degree	------Load------ MW	Mvar	---Generation--- MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.000	-4.218	21.700	12.700	40.000	48.822
3	1.001	-6.824	2.400	1.200	0.000	0.000
4	0.987	-8.232	7.600	1.600	0.000	0.000
5	1.000	-13.638	94.200	19.000	0.000	35.975
6	0.990	-9.830	0.000	0.000	0.000	0.000
7	0.986	-11.937	22.800	10.900	0.000	0.000
8	1.000	-10.773	30.000	30.000	0.000	30.826
9	0.993	-10.816	0.000	0.000	30.000	0.000
10	0.981	-13.295	5.800	2.000	0.000	0.000
11	1.000	-10.816	0.000	0.000	0.000	16.119
12	0.998	-13.552	11.200	7.500	0.000	0.000
13	1.000	-13.552	0.000	0.000	0.000	10.423
14	0.982	-14.447	6.200	1.600	0.000	0.000
15	0.978	-14.437	8.200	2.500	0.000	0.000
16	0.983	-13.754	3.500	1.800	0.000	0.000
17	0.976	-13.668	9.000	5.800	0.000	0.000
18	0.966	-14.822	3.200	0.900	0.000	0.000
19	0.962	-14.833	9.500	3.400	0.000	0.000
20	0.966	-14.512	2.200	0.700	0.000	0.000
21	0.969	-13.879	17.500	11.200	0.000	0.000
22	0.970	-13.889	0.000	0.000	0.000	0.000
23	0.968	-14.720	3.200	1.600	0.000	0.000
24	0.964	-14.707	8.700	6.700	0.000	0.000
25	0.990	-15.168	0.000	0.000	0.000	0.000
26	1.000	-16.688	3.500	2.300	0.000	0.000
27	1.000	-14.663	0.000	0.000	0.000	0.000
28	0.991	-10.555	0.000	0.000	0.000	0.000
29	0.979	-15.952	2.400	0.900	0.000	0.000
30	0.968	-16.879	10.600	1.900	0.000	0.000

Figure 4.15. Bus voltage comparison for the IEEE 30-bus test system without and with STATCOM bus 26.

voltage profile with out statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus	Voltage	Angle	------Load------		---Generation---	
No.	Mag.	Degree	MW	Mvar	MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.010	-4.353	21.700	12.700	40.000	48.822
3	0.997	-6.723	2.400	1.200	0.000	0.000
4	0.984	-8.111	7.600	1.600	0.000	0.000
5	0.980	-13.388	94.200	19.000	0.000	35.975
6	0.981	-9.646	0.000	0.000	0.000	0.000
7	0.972	-11.740	22.800	10.900	0.000	0.000
8	0.980	-10.428	30.000	30.000	0.000	30.826
9	0.998	-10.774	0.000	0.000	30.000	0.000
10	0.995	-13.281	5.800	2.000	0.000	0.000
11	1.000	-10.774	0.000	0.000	0.000	16.119
12	1.001	-13.345	11.200	7.500	0.000	0.000
13	1.000	-13.345	0.000	0.000	0.000	10.423
14	0.986	-14.242	6.200	1.600	0.000	0.000
15	0.982	-14.265	8.200	2.500	0.000	0.000
16	0.991	-13.630	3.500	1.800	0.000	0.000
17	0.988	-13.618	9.000	5.800	0.000	0.000
18	0.974	-14.692	3.200	0.900	0.000	0.000
19	0.972	-14.730	9.500	3.400	0.000	0.000
20	0.977	-14.431	2.200	0.700	0.000	0.000
21	0.982	-13.847	17.500	11.200	0.000	0.000
22	0.983	-13.856	0.000	0.000	0.000	0.000
23	0.974	-14.576	3.200	1.600	0.000	0.000
24	0.971	-14.603	8.700	6.700	0.000	0.000
25	0.973	-14.567	0.000	0.000	0.000	0.000
26	0.955	-15.026	3.500	2.300	0.000	0.000
27	0.984	-14.254	0.000	0.000	0.000	0.000
28	0.979	-10.306	0.000	0.000	0.000	0.000
29	0.963	-15.587	2.400	0.900	0.000	0.000
30	0.951	-16.547	10.600	1.900	0.000	0.000

voltage profile with statcom

Maximum Power Mismatch = 0.0001
No. of Iterations = 100

Bus	Voltage	Angle	------Load------		---Generation---	
No.	Mag.	Degree	MW	Mvar	MW	Mvar
1	1.060	-0.000	0.000	0.000	0.000	0.000
2	1.000	-4.218	21.700	12.700	40.000	48.822
3	1.001	-6.824	2.400	1.200	0.000	0.000
4	0.987	-8.233	7.600	1.600	0.000	0.000
5	1.000	-13.638	94.200	19.000	0.000	35.975
6	0.990	-9.833	0.000	0.000	0.000	0.000
7	0.986	-11.938	22.800	10.900	0.000	0.000
8	1.000	-10.776	30.000	30.000	0.000	30.826
9	0.993	-10.804	0.000	0.000	30.000	0.000
10	0.980	-13.280	5.800	2.000	0.000	0.000
11	1.000	-10.804	0.000	0.000	0.000	16.119
12	0.998	-13.550	11.200	7.500	0.000	0.000
13	1.000	-13.550	0.000	0.000	0.000	10.423
14	0.981	-14.438	6.200	1.600	0.000	0.000
15	0.977	-14.416	8.200	2.500	0.000	0.000
16	0.983	-13.745	3.500	1.800	0.000	0.000
17	0.975	-13.655	9.000	5.800	0.000	0.000
18	0.965	-14.805	3.200	0.900	0.000	0.000
19	0.961	-14.818	9.500	3.400	0.000	0.000
20	0.965	-14.496	2.200	0.700	0.000	0.000
21	0.968	-13.849	17.500	11.200	0.000	0.000
22	0.969	-13.855	0.000	0.000	0.000	0.000
23	0.966	-14.662	3.200	1.600	0.000	0.000
24	0.961	-14.597	8.700	6.700	0.000	0.000
25	0.983	-14.862	0.000	0.000	0.000	0.000
26	0.965	-15.313	3.500	2.300	0.000	0.000
27	1.006	-14.712	0.000	0.000	0.000	0.000
28	0.991	-10.574	0.000	0.000	0.000	0.000
29	0.998	-16.349	2.400	0.900	0.000	0.000
30	1.000	-17.644	10.600	1.900	0.000	0.000

Figure 4.16. Bus voltage comparison for the IEEE 30-bus test system without and with STATCOM bus 30.

PART 5

CONCLUSION

5.1. CONCLUSION

Flexible AC Transmission System (FACTS) controllers are capable of controlling both active and reactive power, making them a useful tool for optimizing power system dynamics. STATCOM is a FACTS, synchronous voltage source, device used for generating or absorbing reactive power that is connected to the network as a shunt device. Generally, The STATCOM provides reactive power (STATCOM capacitive) when the system voltage is low, and when the system voltage is high, reactive power is absorbed (STATCOM inductive).

The ideal operating state of a power system network is determined through a power flow study. The power-flow equation in this study was solved using the Newton-Raphson load flow method. A modified power flow model of the STATCOM is attempted to study the effect of STATCOM on the power system. The modified load flow program was used to assess the impact of STATCOM on the power system, which is installed in various buses for the network of Diyala city that is made up of 11 bus bars, and 13 lines.

The findings of this study revealed that the voltage profile and power transfer in transmission lines improved considerably with STATCOM; active and reactive power losses were also reduced when installing STATCOM at weak buses that are distant from the feeding point. As far as the integration of STATCOM device in Diyala electrical network is concerned, three scenarios were assumed: the buses have a stable voltage of 132 kV which is the standard voltage magnitude of the Diyala high voltage transmission network, under voltage of 125 kV, and another case assuming the buses are at overvoltage condition of 140 kV. Implementing STATCOM at bus 9 of the simulated Diyala power system (in case of under voltage 125 kV) showed that the total real power loss is reduced from 53.298 MW (prior to STATCOM installation) to 49.256 MW while the total reactive power loss is reduced from 110.734 Mvar to 80.08 Mvar. In this case, bus 9 had a low voltage magnitude of 0.781 p.u., yet when installing STATCOM device at the specified bus STATCOM generates reactive power and eventually raised the voltage magnitude to 1 p.u. The voltage of the remaining bus bars also improved.

In the case of overvoltage, an increase in voltage is observed in the bus bar 4 due to its proximity to the main voltage source and the absence of branch bars connected to it. The voltage for bus bar 4 was 1.053 p.u., and upon installing the STATCOM, it absorbs reactive power from the system to reduce the high voltage on the affected buses, bringing the voltage down to 1 p.u. As a result, it turns out that despite the increase in the voltage up to 140 kV, the operation of the STATCOM device has absorbed the reactive power and reduced the high voltage to the desired value of 1 p.u.

At overvoltage condition, when inserting STATCOM at bus 9 it was found that the total real power loss is reduced from 39.737 MW to 34.949 MW and the total reactive power loss is also reduced from 41.355 Mvar to 17.352 Mvar. it was observed that bus 9 had the lowest voltage magnitude (0.877 p.u.) due to its location of being far, but when STATCOM device was placed at bus 9, it generates reactive power in order to keep the voltage magnitude at 1 p.u. The voltage at the rest of the bus bars also increased. Generally, whenever installing a STATCOM device on any bus bar, voltage improvement occurs and a reduction in active and reactive power losses.

At normal voltage condition of 132 kV, when STATCOM was inserted at bus 9 it was experienced that the total real power loss is reduced from 46.134 MW to 41.415 MW while the total reactive power loss is further reduced from 75.710 Mvar to 47.613 Mvar. It was also observed that the low voltage magnitude of bus 9 (0.820

p.u.) has been upgraded to 1 p.u. when STATCOM device was installed at bus 9. The whole busbars were affected positively by this solution.

Impact of STATCOM installation was also evaluated in the IEEE 30-bus test system. The results obtained confirmed the effectiveness of the developed algorithm in the sense that the developed mechanism has improved the weakest buses in the system which were the buses 26 and 30.

To conclude, when STATCOM is connected to the system specifically at the weakest buses, the voltage profile of the whole system is improved and maintained at 1 p.u. Furthermore, both active and reactive power losses in the transmission lines fell significantly.

5.2. RECOMMENDATIONS

This research has demonstrated that STATCOM is important and necessary equipment that utility and service providers must investigate in order to provide consumers with high-quality power. The performance analysis of the device under various fault scenarios should be considered in future STATCOM development. Also, voltage stability margin of the system with the presence of STATCOM needs to be investigated.

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RESUME

Mohammad Kadhim Mohammad was born in Diyala Governorate, Iraq in 1975. He started his Bachelor in the Department of Computer Science and graduated in 1999 from the University of Technology. Then in 2009, he started Bachelor in the Department of Electrical Engineering and graduated in 2013 from Al-Mustansiriya University, and worked as Head of the Planning Department at the General Electricity Transmission Company in Iraq in 2010 and is currently a maintenance engineer for stations in the electrical power transmission network in Diyala Governorate