UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

USING DISTRIBUTED STATIC COMPENSATOR IN POWER QUALITY IMPROVEMENT

MASTER THESIS

HUSSEIN ALI MISHBAK

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
MASTER OF SCIENCE IN
ELECTRICAL AND ELECTRONICS ENGINEERING

ANKARA, 2017

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Supervisor: Prof. Dr. Doğan ÇALIKOĞLU

Hussein Ali Hussein Mishbak, having student number 1406030042 and enrolled in the Master Program at the Institute of Science and Technology at the University of Turkish Aeronautical Association, after meeting all of the required conditions contained in the related regulations, has successfully accomplished, in front of the jury, the presentation of the thesis prepared with the title of: Using Distributed Static Compensator In Power Quality Improvement.

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Thesis Defense Date: 21 September 2017

UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION
INSTITUTE OF SCIENCE AND TECHNOLOGY

I hereby declare that all the information in this study I presented as my Master's Thesis, called: “Using Distributed Static Compensator in Power Quality Improvement” has been presented in accordance with the academic rules and ethical conduct. I also declare and certify with my honor that I have fully cited and referenced all the sources I made use of in this present study.

21.09.2017
Hussein Ali MISHBAK

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LIST OF ABBREVIATIONS

AC	Alternating Current
BJT	Bipolar Junction Transistor
DSTATCOM	Distribution Static Compensator
DSP	Digital Signal Processor
DVR	Dynamic Voltage Restorer
DSO	Distribution System Operator
DPG	Double Phase to Ground
IEEE	“Institute of Electrical and Electronics Engineers”
IEC	“International Electrotechnical Commission”
IGBT	Insulated Gate Bipolar Transistor
ME	Ministry of Electricity
MOSFET	Metal-Oxide Semiconductor Field-Effect Transistor
PQ	Power Quality
P.F	Power Factor
PCC	Point of Common Coupling
PFC	Power Factor Correction
PI	Proportional–Integral
SVC	Static Var Compensator
SLG	Single Line to Ground
SIT	Static Induction Thyristor
THD	Total Harmonic Distortion
UPQC	Unified Power-Quality Conditioner
VSC	Voltage Source Converter
ICT	Information and Communication Technology
PQR	Power Quality and Reliability
UF	Unbalance factor
UPQC	Unified Power Quality Conditioner
CSC	Current Source Converters
PWM	Pulse Width Modulation
ASD	Adjustable Speed Drive
KCL	Kirchhoff’s Law
CPD	Custom Power Device
BPT	Power balance theory
CSD	Current Synchronous Detection
IRPT	Instantaneous Reactive Power Theory
SRF	Synchronous Reference Frame Theory
EPLL	Enhanced Phase Locked Loop
FC	Flying Capacitor
CHB	Cascaded H-bridge
EMI	Electromagnetic Interference

ABSTRACT

USING DISTRIBUTED STATIC COMPENSATOR IN POWER QUALITY IMPROVEMENT

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This thesis investigates and simulates one of the modern power electronics devices Distributed Static Compensator (DSTATCOM) for improvement power quality. DSTATCOM is a shunt connected power electronic device that can quickly mitigate power quality disturbances in the system. The performance of proposed DSTATCOM has been tested in a part from the Iraqi distribution power system. The study also consists of demonstration the power quality problems, their characteristics, the most common power quality problems that effect to the Iraqi distribution system such as voltage regulation, voltage unbalances, voltage sag, voltage swell, and power factor correction. The appropriate location for testing DSTATCOM has been chosen in one of the distribution substations (33/11KV). The evaluation of DSTATCOM is calculated by using the voltage - reactive power curve, and the synchronous reference frame theory is applied as a control algorithm of the D-STATCOM, which can use for maintaining the desired PCC voltage and correcting power factor. A ±10 Mvar/11KV DSTATCOM is implemented and simulated in MATLAB/ SIMULINK using SIMPOWER SYSTEM TOOLBOX program.

The results indicate that using the synchronous reference frame theory improves power quality in voltage control mode and reactive power compensation mode such as voltage regulation, voltage unbalances, voltage sag, voltage swell, and power factor correction. Moreover, the results demonstrate how the installation of DSTATCOM in the system can increase the capability of power transmit and decrease the transmission losses.

Keywords: Power quality, power factor, DSTATCOM, Iraqi distribution system.

ÖZET

STATİK DAĞITIM KOMPANSATORÜ KULLANIMI İLE GÜÇ KALİTESİNİN İYİLEŞTİRİLMESİ

MISHBAK, Hussein
Yüksek Lisans, Elektrik ve Elektronik Mühendisliği
Tez Danışmanı: Prf. Dr. Doğan ÇALIKOĞLU
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Bu tez güç kalite gelişimi açısından modern güç elektroniği araçlarının statik kompansatör dağıtımını araştırmakta ve simülasyonunu yapmaktadır. DSTATCOM sistemdeki güç kalite bozukluklarını seribir şekilde azaltabilen şönt (paralel) bağlantılı bir elektroniği aracıdır.Teklif edilen DSTATCOM Irak güç dağıtım sisteminde test edilmiştir. Çalışma,güç kalite problemlerini ve onların karakteristik özelliklerini,gerilim ayarlama,gerilim dengesizliklerini,gerilim sarkmasını,gerilim artışını ve güç faktörünün düzeltilmesi gibi Irak dağıtım sistemini etkileyen en yaygın güç kalite problemlerinin ortaya koyulmasını kapsamaktadır. DSTATCOM'un testi için uygun yer dağıtım trafo istasyonlarının (33/11 KV) biri olarak seçilmiştir. DSTATCOM'un oranı gerilim reaktif güç eğrisi kullanılarak hesaplanmış ve istenilen PCC gerilim ve güç faktörünün düzeltilmesi devamının sürdürülmesi için kullanılan eş zamanlı referans çerçeve teorisi DSTATCOM'UN kontrol algoritması olarak testte kullanılmıştır. A±10 Mvar/11KV DSTATCOM SIMPOWER SYSTEM TOOLBOX programı kullanılarak MATLAB/ SIMULINK'de simülasyonu yapılmış ve uygulanmıştır.

Irak şebeke dağıtımında kullanılan unsur olan DSTATCOM gerilim ayarlama, gerilim dengesizlikleri, gerilim sarkmasını, gerilim artışını ve güç faktörünün düzeltilmesi gibi güç kalite problemlerini başarıyla geliştirdiğini göstermektedir.

Ayrıca, sonuçlar DSTATCOM’un sisteme yükleniminin güç transferini nasıl artırabilme ve transmisyon kayıplarını azaltabilme kapasitesini göstermiştir.

Anahtar Kelimeler: Güç kalite, güç faktörü, DSTATCOM, Irak dağıtım sistemi.

CHAPTER ONE

INTRODUCTION

1.1 Presentation of The Work

In this work, the usage of Distributed Static Compensator for power quality improvement is investigated. The Thi-Qar region a part from the Iraqi distribution network is taken as a study case. DSTATCOM is one of the shunts connected custom power devices. It is widely used to control voltage, decrease harmonic, minimize voltage trouble and load compensation.

In the beginning, the study consists of demonstration the power quality definitions, their characteristics and problems and different types of mitigation techniques, which have developed to enhance PQ in the distribution system. After that, the distributed static compensator is presented. The principle of DSTATCOM's work and its control strategies are illustrated. In addition, the work consists of choice the appropriate location in one of the distribution substations (33/11KV) in Iraqi network and the proposed design of DSTATCOM to enhance the PQ and the synchronous reference frame theory is applied as a control algorithm of the D-STATCOM, which can work in voltage control and reactive power compensation modes. Finally, a ±10 Mvar DSTATCOM is associated with the system, simulated to present its influences to the performance of the scheme, and shown the results.

The results indicate that using the synchronous reference frame theory improves power quality in voltage control mode and reactive power compensation mode. Moreover, the results demonstrate how the installation of DSTATCOM in the system can increase the capability of power transmit and decrease the transmission losses.

1.2 Overview of Power Quality

The term power quality recently has become one of the most common expressions not only in the commercial and industrial sectors but in residences too. In the past, the loads were typically motors, heating, and lighting, which in general are not very sensitive to the different power quality issues like voltage variation. Furthermore, the most of the loads were more separated from each other. Recently utility companies have evaluated that over 30% of the power as of now being pulled by sensitive equipment such as semiconductor components, which are extremely sensitive to voltage variation and other waveform distortions [1].

Power quality can be defined as any power problem shown in voltage/current or leading to failure or disoperation of customer equipment. Power quality term has many numbers of phenomena observed in electric power systems for instance voltage surges, short power disturbances and dips, harmonics, poor P.F and other distortions. Since electricity as a invention should be accepted the appropriate quality desires, several organizations for instance IEEE ("Institute of Electrical and Electronics Engineers") and IEC ("International Electrotechnical Commission") have developed a number of standards and guidelines that are accomplished on the consumers, systems, and constructers to reduce or to exclude the PQ problems [2].

There are some explanations for poor PQ in power utilities, counting natural ones for instance flashover, lightening, equipment failure and forced things such as faults (around 60%), voltage distortions and notches (about 40%)[2 and 3]. Low level of PQ causes disaster of capacitor banks, enlarged losses in the distribution network and electric machines, vibrations, noise, overvoltage and too much current caused by resonance [2]. Also, PQ problems lead to negative sequence currents in motors, dielectric failure, interference with communication systems, signal interference and relay and incorrect measurement, incorrect metering, breaker failures, obstructions to the motor controls and digital regulators [2] [4].

The reliability of the electricity distributed by utilities should be considered, and the utilities are aware of the significance of transporting to their customers with "good quality" in order to satisfy and consequently retain them. Nowadays, power quality is one of the most important issues that affected in the electricity market when the consumers request a certain level of power quality, adapted to their activity, at an attractive price [5][6].

In the power system, the responsibilities of each part should be defined in term of power quality, because PQ improvements are very expensive. The responsibility of the distribution system operator (DSO) is in charge of the operation, maintenance and development of grid and this part of the grid, traditionally in a radial topology, connects the end consumers of electricity at lower voltages. Therefore, limits for some PQ problems have to be defined in the distribution system at the point of connection between the transmission system and the distribution system, this point of common coupling (PCC), in the substations[5]. Most of the PQ problems in this PCC are concerning voltage variation, unbalance, and voltage sags, poor P.F where voltage sags can be caused by faults in both the transmission system and the distribution system while reactive power causes high losses in transmission and distribution lines.

Iraqi network suffers from different types of PQ problems; reactive power is the biggest challenge in it. In addition, Iraqi network has quite high levels of losses[7][8]. Reactive power and high losses in transmission line cause a voltage drop to the end user. This powerless in the voltage level makes voltage sags most happened in distribution grid, which can be caused by switching action and the faults in both the transmission system and the distribution system. Objectives of the Ministry of Electricity (ME) in distribution network are an improvement the voltage quality and loss reduction[9][10]. Therefore, it is more efficient to study improvement PQ in the Iraqi distribution grid by modern devices.

1.3 Distributed Static Synchronous Compensator (DSTATCOM)

1.3.1 The Importance of DSTATCOM and Its Applications

Different types of mitigation techniques have been developed to enhance PQ in the distribution system, and the power semiconductor technology has qualified a very fast development to improve PQ [2 and 4]. Until the beginning of the nineties, the single semiconductor device realistic to high power applications was the thyristor, engaged in High Voltage Direct Current (HVDC) transmission systems and Static Var Compensators (SVC)[6]. Lately, new equipments, such as custom power devices established on power electronic concepts, have been improved [4].

Commonly, CPD are divided into three groups such as static series compensator such as the DVR, static shunt compensator such as a distributed static synchronous compensator, and static series and shunt compensator such as the UPQC [4]. The difference between them results from the power quality problems in the distribution network, the operation and requirements of distribution systems. The distributed static compensator is utilized for mitigating the voltage, current, or the two sorts of PQ problems [11].

DSTATCOMs are shunt controllers used in distribution uitilities, and their major purposes are regulating voltage and compensating load [4]. When working with an energy-storing method, DSTATCOM is susceptive for compensating active power oscillations in the system [4]. DSTATCOM has frequently been used since the 1990s to specifically regulating voltage, improving voltage level, decrease harmonic, decrease transient instabilities and load compensation [2 and 4]. Relatively, using traditional capacitor and inductor mutual with electrical switches, DSTATCOM customs a power electronic converters to reject or observe the reactive power in PCC, power factor correction (PFC), reducing losses, neutral current compensation and load balancing [12 and 13].

1.3.2 The Types of DSTATCOM and Its Properties

DSTATCOM is designed and classified regarding various structures, control schemes, and solid-state devices. Also, it may be categorized based on the kind of used converter, and the total of phases [14 and 15]. The advance in DSPs (digital signal processors) has made it potential to use various control algorithms such as PI controller, variable structure control, fuzzy logic control, and neural network control for making better dynamic and steady state execution of DSTATCOMs [4, 19].

Power quality problems in distribution power systems are one of the biggest challenges. Notably, the DSTATCOM has demonstrated suitable effective in order to mitigate those great problems. In various conditions, DSTATCOM is considered significant to protect the load terminal voltage the same to the AC mains voltage by using it at the load end. It means to recover the voltage drop in the distribution feeder. Finally, DSTATCOM has the following advantages [2 and 6]:

a. Avoids the voltage swells caused by capacitor switching.

b. Reduces the voltage sags due to common feeder faults.

c. Controls the voltage fluctuations and unbalances caused by customer load variations.
d. Reduces the frequency of mechanical switching operations in load tap changing (LTC) transformers and mechanically switched capacitors for a reduction in their maintenance.
e. Enhances the load ability of the system.
f. For improving the stability of the load such as an induction motor under major disturbances.
g. Reactive power compensation.

1.4 Literature Survey

Beginning from 1990, many structures of DSTATCOM have been established for many applications [2]. Primarily, BJTs and power MOSFETs have been used to improve D-STATCOMs. Later, GTOs and SITs have been engaged to advance D-STATCOMs. With the definition of IGBTs, the DSTATCOM equipment has became a real enhancement [2]. DSTATCOM has been used for different purposes to mitigate and improve PQ [11,13 and 14]; it has been used as a custom power device for voltage regulation and load compensation in the distribution system [4 and 15].

The DSTATCOM has been installed in various locations in distribution network depend on the PQ problem in the grid. In April 2004, a ±250 Kvar DSTATCOM was installed in distribution substation in Tehran. The aim of this installation was a voltage regulation for voltage regulation, with a particular work on reduction of unbalance issue [20].

In TURKEY, April 2007, the design of a ±750 Kvar DSTATCOM has been implemented (A. Çetin, 2007). The aim of this design was for reactive power compensation of Coal Preparation System in Kemerköy Thermal Power Plant at medium voltage [21].

Power Systems Testing has validated a ±3 Mvar DSTATCOM. Simulation Laboratory of Hydro-Quebec, a utility lab situated in Canada (Rehan Abidi, Dr. Mutasim Nour, 2014). The DSTATCOM was tested by varying different parameters like the voltage, load and from readings, at various time intervals, the inductive, capacitive and no load mode was seen. Many other factors that affect power quality are also described from the simulation, which production and reduction of active and reactive power, changes in the modulation index. The DSTATCOM's fast and efficient response was confirmed through the simulations [22].

DSTATCOM is very popular for harmonic mitigation voltage sag, balanced and unbalanced loads in PCC [16 and 17]. On June 30th of 2015, DSTATCOM used to improve one of the most common power quality disturbances in electrical facilities, voltage sag, this study presented the effect on voltage sags characteristics by the attendance of twelve-pulse DSTATCOM in the modified IEEE-13 distribution system[18].

DSTATCOM has been developed using cascaded multilevel VSCs to enhancement PQ issues associated with 11kV distribution system[23]. This study (Tapesh Vishnoi. 2011) has been designed multilevel PWM control for the multilevel inverter to maintain the reactive power and THD under control by keeping all the voltage and current waveforms as per their standard sinusoidal forms.

DSTATCOM has been used to mitigate all types of PQ problem associated with faults such as “Single Line to Ground (SLG) fault” and “multiple Phase to Ground (DPG) fault” (Manpreet Singh et al.2015a). In this study, Design and Simulation of DSTATCOM with PI controller have been presented to improve the quality of power in PCC such as voltage sags/dips, swells, and harmonics. Also, the results are proved by the simulation under different atypical conditions such as a SLG fault, multiple lines to earth fault in distribution networks with linear loads [15]. In 2016. Sharon Rosy. S, N. Shobana and KR.Vairamani have used DSTATCOM for mitigating voltage sags and harmonics. A PWM-based control scheme has been implemented to control the electronic valves in the two- level VSC used in the DSTATCOM. The simulations carried out and observed that the capacity for power compensation and voltage regulation of DSTATCOM depends on the rating of the dc storage device [14].

1.5 Significance of The Study

The purpose of this thesis is using the synchronous reference frame theory as a control algorithm of the DSTATCOM, which be able to work in voltage control and reactive power compensation modes. The performance of proposed design of DSTATCOM has been tested in a part from the Iraqi distribution power system for improving power quality. DSTATCOM is not installed in Iraqi network yet.

Therefore, it is more important to study improvement PQ in Iraqi system by this device.

Many studies have operated on using DSTATCOM to enhance power quality that related with voltage or to compensate reactive power. Our work investigates these advantages to improve PQ issues, which associated with voltage and improve power factor in the distribution network. This task has been achieved by using the appropriate control strategy. It is synchronous reference frame theory (Cristian A. Sepulveda et al...2013b). This control algorithm of the DSTATCOM is used for maintaining the desired PCC voltage and correcting power factor.

Moreover, this study represents a completed work of installation and test DSTATCOM. It consists of a selection of the proper location by choosing the critical bus in the distribution system. The rating of DSTATCOM is calculated by using voltage - reactive power curve (VQ curve). Finally, this work answers the following question:

a) What is the suitable way to select location, size, control strategy and procreate design of DSTATCOM for improving PQ in the distribution utilities?

1.6 Organization of The Dissertation

After a preliminary part (chapter 1) where the background, literature survey, aim, and outline of the study are introduced, the structure and organization of dissertation of this thesis are as follows:

Chapter 2 defines the power quality standers and some definitions, which related to the power quality issue used along the thesis. The causes and characteristics properties of the PQ problems are analyzed, and the mitigation methods of problems are discussed. After that, the most reasons that affected in power quality in the grid are presented. In addition, the chapter shows an overview of Iraqi power system especially the distribution system.

Chapter 3.This chapter explains on the structures, classifications, working principle, forming, and applications of DSTATCOMs. The heart of the DSTATCOM used for compensation of the power system is its control system; it is presented in this chapter also.

In Chapter 4, this chapter contains two main sections; the first section presents a description of the particular area from Iraqi distribution grid. This area includes single sub-transmission station (132/33/11KV) which feeds a number of distribution substations (33/11KV). Whereas, the second section provides selection the proper size, proposed control strategy, and design of DSTATCOM for the particular area. The equations derived in other chapters are adopted for this design. A two-level multi-pulses voltage source converter (VSC) is proposed to develop the model of 3-phase bridge DSTATCOM for line voltage 11kV. The power system parameters of the particular area and the DSTATCOM components are designed in MATLAB/ SIMULINK using SIMPOWER SYSTEM TOOLBOX program for simulation situations.

Chapter 5, this chapter studies the performance of the particular area without and with DSTATCOM at different power quality problems, which have been shown in chapter 2. Simulation results are realized for identifying the worthiness of the proposed design and control technique to enhancement the power quality in Iraqi distribution grid such as voltage regulation with different types of load, voltage sag, voltage swell, voltage unbalance, and power factor correction.

In Chapter 6, the important conclusions of the study and the benefits of using DSTATCOM and effectiveness to improve PQ in Iraqi distribution grid are illustrated in this chapter. In addition, the future work topics on DSTATCOM and PQ improving are presented.

CHAPTER TWO

ELECTRIC POWER QUALITY

2.1 Introduction

This chapter is opening with the little definition of electric PQ. It designates, in summarized, the sources of poor P.Q, poor P.F, and effectiveness of PQ problems in distribution power system. The power quality standards are also offered in short in this chapter. In addition, the custom power devices that are used for improving and compensating in distribution systems are shown. Moreover, Overview on Iraqi power system and power quality in Iraqi distribution system are presented.

2.2 Definition of Electric Power Quality

The PQ has come to be an issue lately, it does not denote that it was not significant in previous times. For decades, services have operated on the enhancement of what is now identified as power quality. The word “electric power quality” is usually used to evaluate and preserve the high quality at the standard of generation, distribution, and transmission [24]. The oldest indicating of the word "power quality" recognized to the author was in a paper put out in 1968 [25]. The article exhaustive a study by the U.S. Navy after qualifications for the power necessary by electronic tools.

Currently, the development of the digital economy indicates a common use of electronic tools not only in the manufacturing and marketable areas but the local flexible environment too [4]. Likewise, this won't just convey a more noteworthy interest for control, however, a larger amount of energy quality and dependability (PQR). It has been assessed that over 30% of the power presently being drawn from the utilities is currently drawing for sensitive equipment, and this is increasing [26]. It is significant to consider PQ at the terminals of end consumers in distribution networks because the pollution of electric supply networks is considerably critical at the consumption level [2]. There are various causes for contamination of the AC supply utility, comprising natural ones for example lightning, equipment failure, flashover, and and enforced things for instance notches (around 40%) faults (round 60%)and voltage distortions [2].

There are various calculations to the term “power quality”. The word “power quality” refers to a wide-ranging of electromagnetic events that describe voltage and current at a specified location and at a specified time in the power grid [4]. It is conceivable to interface it with control supply dependability, benefit quality, and supply quality. Commonly, it has been suitable to separate between “voltage quality” and “continuity of supply” [4][27].

Voltage quality (globally used term: “power quality”) is interested with the technical properties of the electricity at a specified location on an electrical grid, calculated compared to a established of reference technical limitations [28]. In this term, the variation of the voltage (or the current) from the perfect are investigated [4].

2.3 Power Quality Problem Classifications

There are various of PQ issues in the current day quick changing electrical grids. These possibly will be categorized based on the quantity like current, voltage, and frequency, or the load and supply systems, events for instance steady state and transient [2].

The transient sorts of P.Q issues comprise greatest of the phenomena happening in temporary (e.g.,oscillatory or impulsive), for instance swell, sag (dip), short-duration voltage deviations, power frequency variants, and voltage oscillations [29]. The steady-state categories of PQ problems comprise long-interval voltage deviations, unbalanced voltages, notches, waveform distortions, poor P.F, flicker, excessive neutral current and unbalanced load currents [2].

The second cataloguing can be completed based on quantity like current, frequency, and voltage [29]. In place of the voltage, these contain flicker, sag, notches, swell, voltage distortions unbalance, under voltage, and over voltage; correspondingly the current; these contain harmonic currents, unbalanced currents, reactive power component of current and extreme neutral current [2].

The third cataloging of PQ problems is established on the supply system or the load [2]. Generally, PQ problems as a result of nature of the load (e.g., fluctuating loads for example furnaces) are load current [29]. The PQ issues caused by the supply system comprise frequency and voltage associated problems for example unbalance, sag, swell, flicker, voltage distortion, and notches [2]. These could also include a combination of both voltages and current-based PQ issues in the grid. This study deals with power quality related with voltage quality so that the power quality problems associated with this team are presented.

2.4 Overview of Voltage Magnitude Events

The plurality of events currently of attention are related to either a decrease or an growth in the voltage level. It will be referred to these as "voltage level events."

A voltage magnitude event is a substantial deviation from the standard voltage magnitude for a limited period. The level can be found by taking the r.m.s of the voltage over a multiple of one half-cycle of the power-system frequency [5 and 24].

$$V_{r.m.s} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} V^2\left(k\Delta t\right)} \tag{2.1}$$

Where *V(t)* is the voltage as a function of time, sampled at equidistant points t = (kΔt).

The r.m.s value is taken over a period NΔt, mentioned to as the "window length." Alternatively, the magnitude can be determined from the peak voltage or from the fundamental-frequency component of the voltage. Most power quality monitors determine the r.m.s voltage once every cycle or once every few cycles.

Knowing the duration and magnitude of an event, it can be characterized as one point in the magnitude-duration plane. All events documented by a monitor over a given period can be denoted as a scattering of points [29]. Different underlying reasons may lead to events in various regions of the plane. Several standards provide diverse terms to events at various sections of the plane. A simple classification is set in Figure (2.1). The voltage level is divided into three areas [30]:

1) Interruption : the voltage amplitude is under 10% or zero.
2) Under voltage : the voltage magnitude is below its nominal value.

3) Overvoltage : the voltage level is above its nominal rate.

In the period, a distinction is completed between [30]:

1) Very short: matching to transient and self-restoring actions.
2) Short : conforming to automatic restoration of the pre-event situation.
3) Long : corresponding to the manual repair of the pre-event condition.
4) Very long: corresponding to repair or change of faulted components.

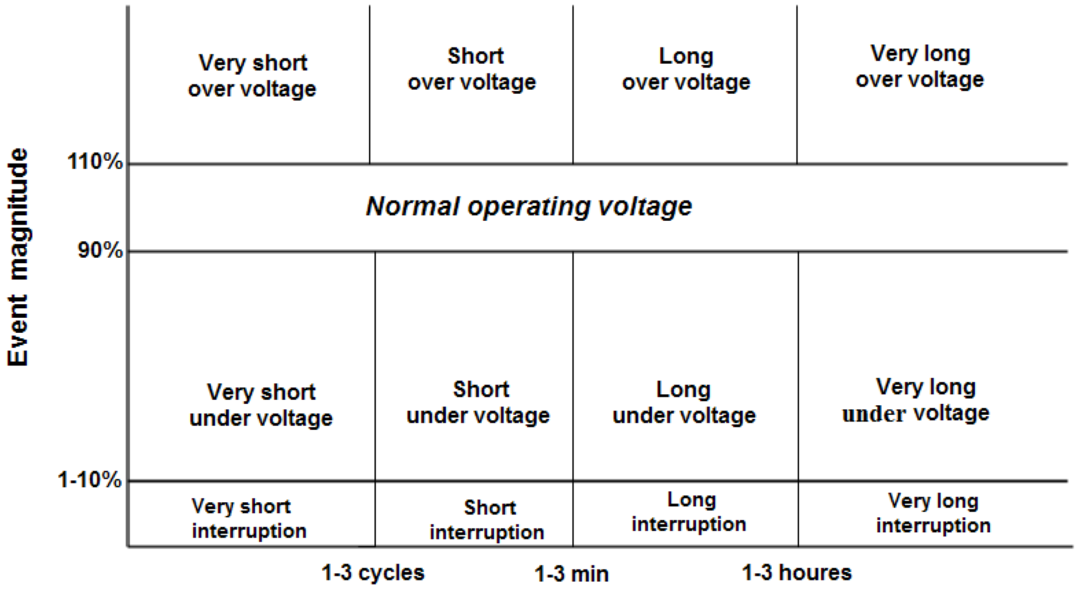


Figure 2.1: Classification of voltage magnitude events [30].

The different limitations in Figure (2.1) are somewhat arbitrary; some of the indicated values (1-3 minutes, 1-10%, 90%, and 110%) are those used in existing IEC and IEEE standards. The classification in this figure is only pointed at clarifying the different types of events: the terms mentioned in the figures are not all used in practice [29]. Different terms for events in some of the areas of the level-period plane are given by both IEC and IEEE. The IEC definitions are abbreviated in Figure (2.2) and the IEEE definitions in Figure (2.3). The IEC explanations were achieved from CENELEC document EN 50160 [31], the IEEE classifications from IEEE Std.1159-1995. The method of classifying events through one magnitude and one duration has been presented to be very useful and has resulted in a lot of information and knowledge about power quality.

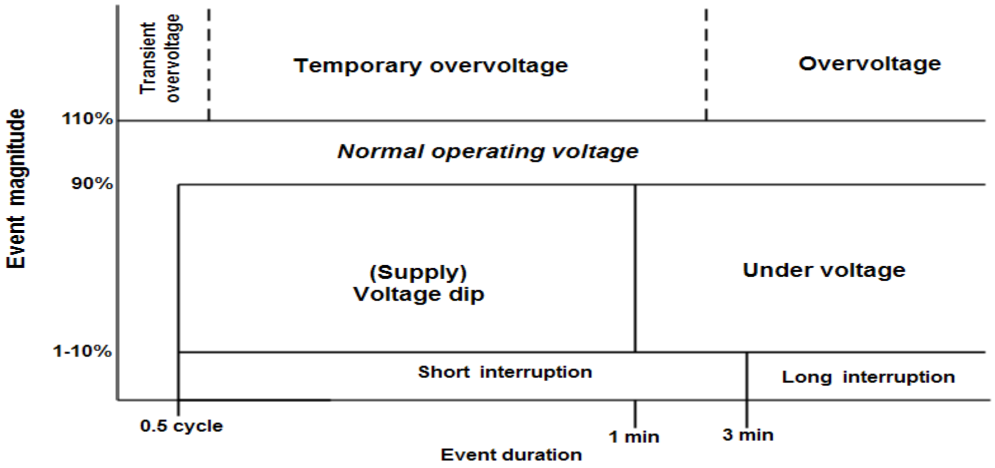


Figure 2.2: “Definitions of voltage magnitude events as used in EN 50160” [30].

European standard 50160 designates electricity as a product [31], comprising its shortcomings. It provides the main features of the voltage at the consumer's supply terminals in public low-voltage and medium-voltage systems under typical working situations.

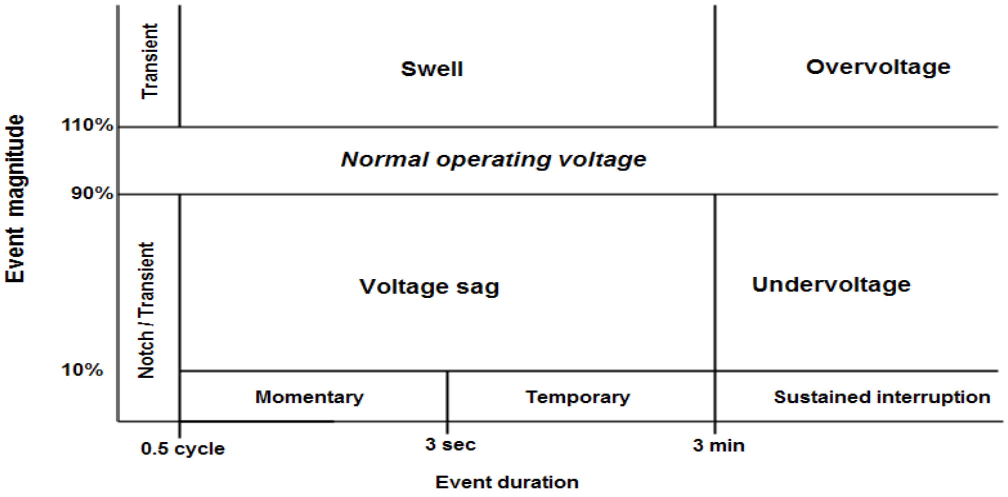


Figure 2.3: “Definitions of voltage level events as used in IEEE Std. 1159-1995” [30].

2.4.1 Voltage Variations

Limits for some variations are provided by standard IEEE Std. 1159-1995. For each of these variations, the amount must be completed with a specified averaging space. The following boundaries for the low and medium voltage supplies are given in the document [29 and 30]:

1) “Voltage magnitude variation”: “Increase and decrease of the voltage level, due to”:

a) “Variation of a total load of the distribution system or part of it”.

b) “Actions of transformer tap changers”.

c) “Switching of capacitor banks or reactors”.

2) Voltage fluctuation: Systematic deviations of the voltage envelope or a series of random voltage changes, the level of which does not usually exceed the voltage ranges of 0.95 to 1.05 p.u [32].

3) Voltage unbalances: “Unbalance, or three-phase unbalance, is the phenomenon in a three-phase system, in which the r.m.s values of the voltages or the phase angles between consecutive phases are not equal”. One way of calculating the degree of unbalance is “computing the ratio of the negative (or zero) sequence component to the positive sequence component” [5], which is defined as an unbalance factor (UF). It is calculated by [32 and 33]:

$$UFV = \frac{V_-}{V_+} \tag{2.2}$$

V+ and V− represent the root mean square (RMS) voltages of the positive and negative sequence components, respectively. The unbalance factor should not exceed 2% [33].

2.4.2 Voltage Characteristics For Events

Standard IEEE Std. 1159-1995 gives voltage qualities to occasions. It characterizes greatest worthy levels at the client's supply terminals for medium (≤ 35 kV) and low (≤ 1 kV) voltage power dissemination frameworks under typical working conditio [4]. For completeness, a list of events mentioned in IEEE Std. 1159-1995is reproduced below:

1) Long-duration voltage variations: “Measured voltage having a value greater or less than the nominal voltage for a period greater than 3 min. The first one is called overvoltage, typical values are 1.1 to 1.2 pu, and the second one undervoltage, typical values are 0.8 to 0.9 pu” [4].

2) Voltage sags: A decrease in r.m.s voltage at the frequency between 0.1 and 0.9 pu, and for periods of 0.5 cycle to 3 min [4].

3) Short interruptions: occur between a few tens and several hundred times per year. At the point the drop is to substantially zero volts (less than 0.1 pu), it is measured a "short interruption" [4].

4) Long interruptions of the supply voltage: their frequency may be less than 10 or up to 50 per year.

5) Voltage swells: "an increase in r.m.s voltage over a range of 1.1–1.8 pu for a period greater than 10 ms but less than 3 m" [4].

6) Transient: "A sudden, non-power frequency change in the steady-state condition of voltage. When unidirectional in polarity it is an impulsive transient when it includes both positive and negative polarity values it is an oscillatory transient" [4].

2.5 Sources and Sound effects of Power Quality Problems

The major reasons of the previous PQ problems can be divided into frequency, natural and man-made regarding voltage, and current. The natural sources of poor PQ are essentially lightning, faults, weather situations for instance storms and tools disaster. Conversely, the man-made reasons are mostly associated with system operations or loads [33].

The effects of PQ problems linked to system processes are interchanging of feeders, capacitors, heavy loads, and transformers [2]. The natural reasons effect in PQ problems that are usually transient in nature, for example voltage distortion, voltage swell, sag (dip), and oscillatory transients and impulsive [33]. Conversely, the human-made reasons product in both steady state and transient types of PQ problems.

The PQ problems disturb all interested systems, manufacturers, and customers directly or indirectly regarding significant economic losses as a result of equipment damage,interruption of a process, wastage of raw material, production loss and damage of significant data [2]. There are various cases and uses for instance automated industrial processes, pharmaceutical industries, semiconductor manufacturing, and banking, where even a slight voltage dip/sag gives rise to interruption of the progression for a number of hours, and waste of raw material [2].

Table 2.1: Causes and their Effects of Short-duration PQ problems.

Problems	Causes	Typical effects
Sag (dip)	-Fault in the network. -Energization of heavy loads. -Starting of large induction motors. -Single line-to-ground faults. -Line-line and symmetrical fault. -Inrush currents.	-Voltage stability because of reduction of bus voltage for a short period. -Failures of electrical low-voltage devices. -Malfunctions of uninterruptible power supply. -Malfunction of measuring and control equipment.
Swell	- Single-line ground failures (SLG). - Switching off a large load or switching on a large capacitor.	-Voltage stability because of reduction of bus voltage for short duration. - Malfunctions of electrical low-voltage devices.

The protection systems effect in protective devices are affected by some power quality problems. These distort several processes and operations in the manufacturing and other institutions [2]. These also disturb various kinds of measuring devices and metering of the numerous amounts like voltage, current, and power. Table 2.1 presents some of the PQ problems, causes, and the effects, which associated with short-duration voltage magnitude variations. While Table 2.2 shows the power quality problems, causes, and their Effects, which related with long-duration voltage magnitude variations [4 and 33].

Table 2.2: Causes and their effects of long-duration power quality problems.

Problems	Causes	Typical effects
Under-voltage	-Main causes of undervoltage are overload, less supply capability and fault.	- Voltage instability, draw of high current by motors, high reactive power demand.
Overvoltage	-Overvoltage generated by an insulation fault. - Ferroresonance. -Faults with the alternator regulator, tap changer transformer, or overcompensation. - Lightning overvoltage. - Switching overvoltage produced by rapid modifications in the network structure such as the opening of protective devices or the switching on of capacitive circuits.	- Overvoltage may cause overstress on insulation, problems of voltage instability, and demand for reactive power.

Table 2.2 (Continuation): Causes and their effects of long-duration power quality problems.

Problems	Causes	Typical effects
Voltage Unbalance	-Unbalanced single-phase loads on a three-phase circuit, -Capacitor bank anomalies such as a blown a fuse on one phase of a three-phase bank. -Severe (greater than 5%) can result from single phasing conditions.	-Power system stability problems. -The excessive draw of reactive power, mal-operation of equipment. -Mal-operation of measuring instruments and shortening of the life span of different appliances. -Negative sequence component performs. It rises net current in some phase and decreases the net current in another phase.

2.6 Poor Power Factor

Power factor is one of the essential aspects affecting significantly in distribution networks. For the explanation that, take into consideration a distribution grid in which an inductive load is supplying by a feeder. The resistance and the reactance of the feeder are Rs and Xs, *Is* is the feeder current, and V_L is the load voltage. The power factor of the load is lagging and its angle is indicated by θ_L. The system phasor drawing is displayed in Figure (2.4a). In this figure the load current is determined into a real part $Isp = |Is| \cos(\theta_L)$ and reactive part $Isq = |Is| \sin(\theta_L)$. The work completed based only on the P of these two components.

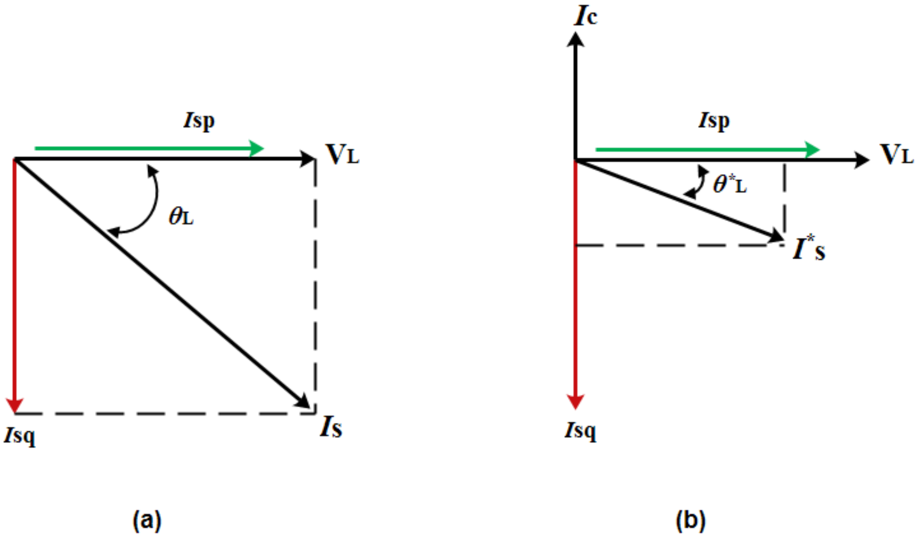


Figure 2.4: (a) "Poor P.F" and (b) improvement P.F by a shunt compensator.

Presently, assume the load P.F is poor, i.e., the load has a great X/R percentage. At that point, the P.F angle θ_L will be big. This infers that the reactive component of the current is larger and subsequently the extent of the load current |Is| is also larger. This will not just reason a huge drop in the feeder voltage, yet there will likewise be a lot of $|Is|^2$ R loss. This loss is related with great temperature dissemination in the feeder. Intemperate temperature may lessen the life expectancy of the feeder.

To rectify the great voltage drop in the feeder, a shunt compensator is connected in parallel at the end of the feeder. This compensator withdraws a current Ic which is in phase reciprocity to Isq. The consequential current pulled by the load collection is symbolized by I^*s. This is presented in Figure (2.4b). It can be realized that whereas the real component of the current keeps equal, the amount of the current drawn from the source has minimized substantially. This is because of the reducing of the reactive component significantly, therefore, the P.F angle has reduced. For that reason, to work the feeder in an ideal approach, the P.F at the load must be conserved proximate unity. In a best condition, the load P.F must be unity. Conversely, this possibly will permanently not be practical with the enhancement in the P.F; the feeder drop reduces resulting in superior voltage control at the load in addition.

CHAPTER THREE

DISTRIBUTED STATIC SYNCHRONOUS COMPENSATOR (DSTATCOM)

3.1 Introduction

This chapter concentrates on the structures, classifications, working principle, forming, and applications of D-STATCOM. The heart of the D-STATCOM used for compensating the power system is its control system; it is presented in this chapter also.

DSTATCOM is one of the shunts connected custom power devices and can perform load compensation, power factor correction, harmonic filtering, and load balancing (Cilona, 2010). DSTATCOM has been usually used subsequently the 1990s entirely to control voltage, enhance voltage level, decrease harmonic, decline transient voltage instabilities and for compensating load (Sumner et al., 2006) [4]. In this mode, it can hold the bus voltage constant against any unbalance or distortion in the distribution grid.

DSTATCOMs are utilized more frequently than STATCOM. Associated to STATCOM, DSTATCOMs have substantially lesser rated power (less than 30 Mvar)[36]. When the STATCOM is applied to the distribution network, it is called DSTATCOM (Distributed-STATCOM). Its configuration is the same or with small modifications of the STATCOM that is being implemented to the distribution grid at medium and low voltage. It operates in a similar manner as the STATCOM [36]. However, some of the control algorithms and applications of these devices are different. The STATCOM injects almost sinusoidal a balanced three-phase current, whereas the DSTATCOM must be able to insert a harmonically distorted and unbalanced current to balance and eliminate the harmonic distortion in the source current [35]. Therefore, the compensation algorithm and the control are significantly different between DSTATCOM and STATCOM.

There are two operating modes of the DSTATCOM associated to the control scheme and compensation algorithm. These operating modes are named voltage control mode (Kumar, Chandan et al. 2014c) and current control mode (Majumder, Ritwik. 2013a).

This chapter focuses on three-phase three-line since this type is designed and simulated with 11KV three-line. Substantially, work has been give an account on three-phase three-line DSTATCOM [2]. Beginning from 1984, various structures and control schemes for instance “synchronous detection theory”, “synchronous frame d–q method”, and “instantaneous reactive power theory” are used in the advance of D-STATCOMs [2] [4].

In the primary platforms, BJTs and power MOSFETs have been used to develop DSTATCOMs (YuFeng Qiu et al 2016). Later, SITs and GTOs have been employed to improve DSTATCOMs (Barry Brusso et al. 2014b). With the starter of IGBT the DSTATCOM has a growing, and it is presently take into account as an perfect device for DSTATCOMs [2][4].

3.2 Classification of D-STATCOMs

D-STATCOMs can be categorized based on the kind of topology, converter used and the amount of phases [2], below the different three categories:

1) Converter-Based Classification.
2) Topology-Based Classification.
3) Supply System-Based Classification.

3.2.1 Converter-Based Classification

There are two forms of converters are used to grow DSTATCOM. The first one is a DSTATCOM with a CSC and Figure (3.1) appearances a DSTATCOM based on a CSC, in this type to reverse voltage blocking; a diode is connected in series with the self-commutating scheme (IGBT) [2]. GTO-based DSTATCOM configurations have limited the frequency of converting [2]. However, they do not need the series diode. They have great losses and need high amounts of parallel AC capacitor, but considered reliable [36].

Figure (3.2) illustrates the additional converter used in a DSTATCOM is a VSC. This type has more advantages like it is cheap, light and expansible to multilevel and multistep topologies, to boost the act with lower converting frequencies so that it is more widely used [2][36]. VSC has a self-bolster DC voltage with a great DC capacitor.

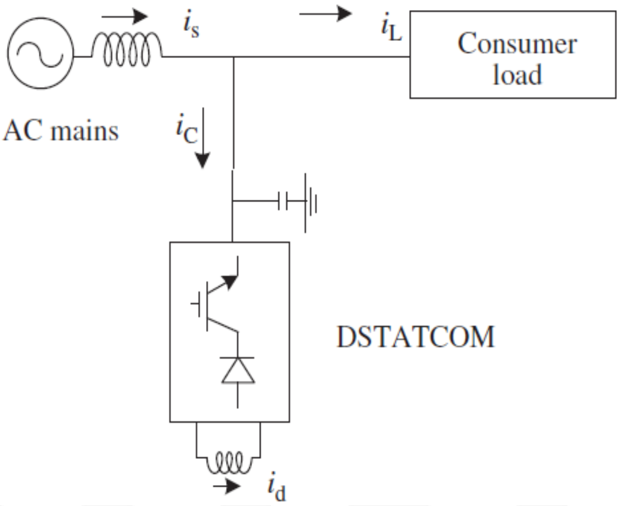


Figure 3.1: A CSC-based DSTATCOM [2].

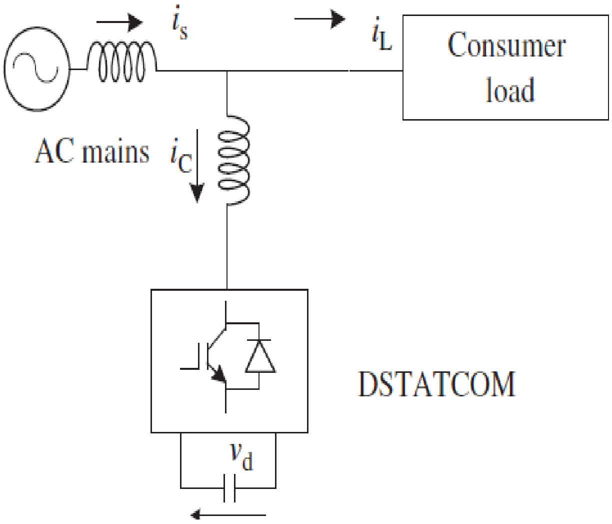


Figure 3.2: A VSC-based DSTATCOM [2].

3.2.2 Topology-Based Classification

D-STATCOMs may also be categorized based on the topology, for instance, VSC with non-isolated transformer and VSC with isolated transformer [2]. DSTATCOM is also used as developed static VAR generator in the power system grid for steadying and enhancing the voltage profile (J. C Das 2016a). Hence, a large amount of circuits of DSTATCOM with and without transformer is developed for meeting the particular necessities of the uses [2][36].

3.2.3 Supply System-Based Classification

DSTATCOMs can be classified on the supply and the load system, such as, single-phase two-line, three-phase three-line, and three-phase four-wire structures [2]. Figure (3.3) presents the sorting of three-phase three-line DSTATCOMs. DSTATCOMs may also be classified accordingly as two-wire, three-wire, and four-wire DSTATCOMs [2]. There are several variable loads for example domestic utilizations coupled to single-phase supply grids. Various three-phase loads are without neutral terminals, for example, traction, furnaces, and ASD served from three wire supply systems [4].

Since the Iraqi distribution network (11kv) is three-phase three-line, this thesis deals with three-phase three-line D-STATCOM. A three single-phase VSC-based three-phase three-line DSTATCOM shown in Figure (3.4).

One of the important benefits of the isolated VSC is that the voltage evaluation of the VSC can be optimally considered [2][35], since there is a connecting transformer.

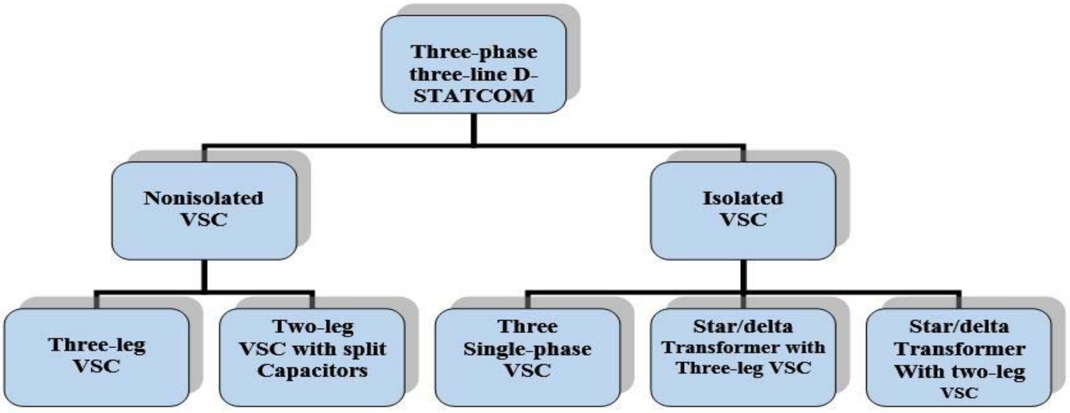


Figure 3.3: Categorization of three-phase three-line DSTATCOM [2].

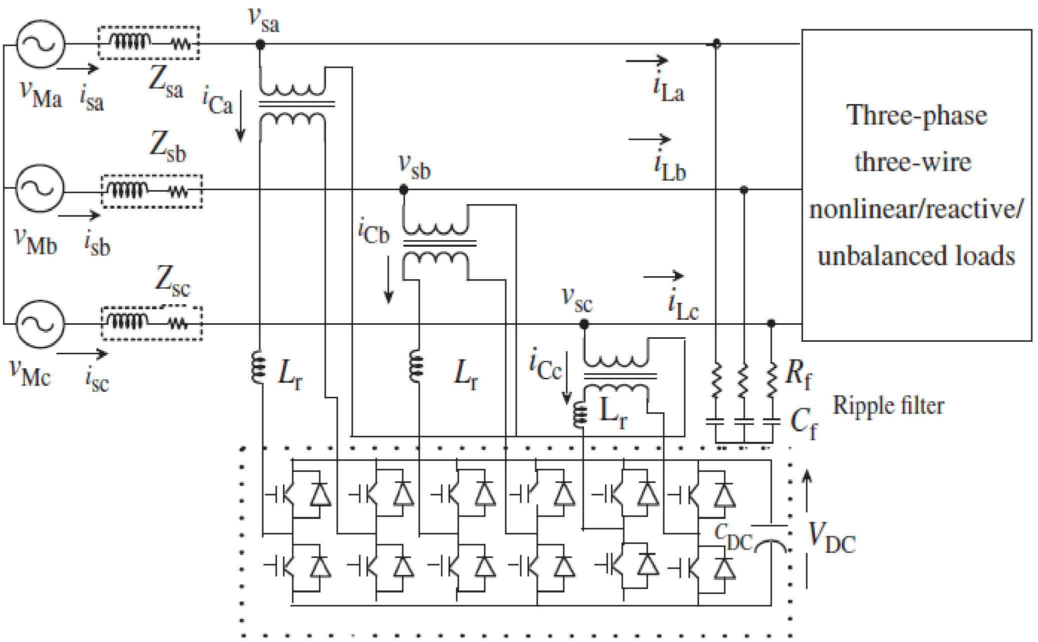


Figure 3.4: A Voltage source convertor-based three-phase three-line D-STATCOM. [2].

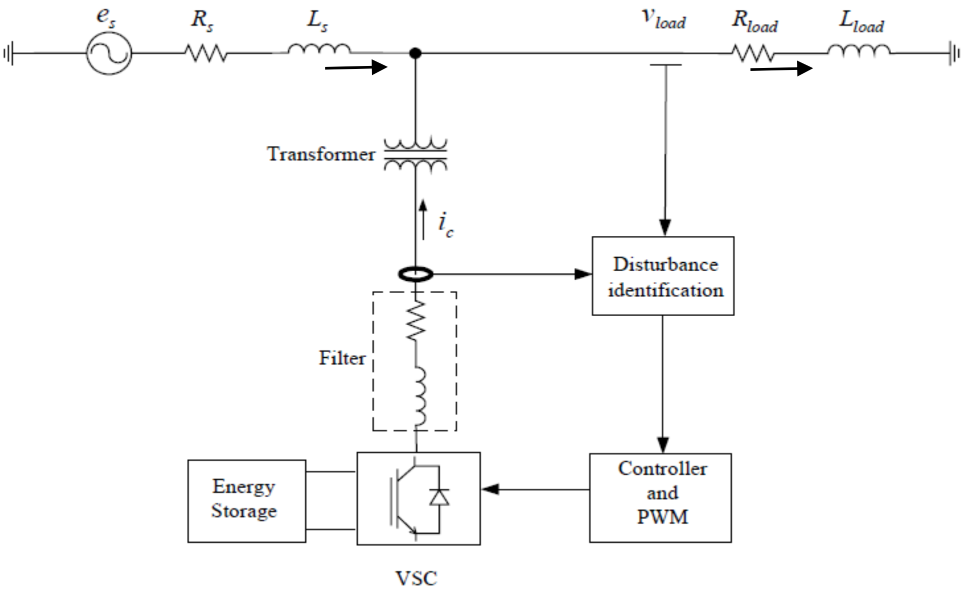


Figure 3.5: A VSC-based DSTATCOM [21].

3.3 DSTATCOM Configuration

In general, DSTATCOM can be divided into two segments as the power circuit and control unit. The VSC is the most important component in the power circuit of the DSTATCOM, and it can generate a sinusoidal voltage waveform with any desired amount, with any required phase angle and with any required frequency [12]. The DSTATCOM's AC side is typically attached in shunt across the PCC with or without a transformer, as shown in Figures (3.5) [2]. The PWM is used in VSC control; as a result, it involves small filters to soften converting ripples [2][21]. It needs hall Effect current and voltage sensors for feedback signals, and typically a DSP is used to perform the necessary control process to produce gating signals for the VSC [2]. Various passive components like an AC inductors, DC capacitor and isolation transformers are also needed [2][36].

3.4 Working Principle

DSTATCOM is one of consumer power devices, which has been commonly used, for adjusting the load bus voltage and mitigation of the voltage swells and sags [13]. The DSTATCOM is almost vastly used for eliminating current based distortion, power factor correction, and load balancing when connected to the load bus voltage [14]. The schematic diagram for load compensation using the DSTATCOM is presented in Figure (3.6). A current controlled VSC is supposed at the heart of the DSTATCOM. Hence for an ideal case, the DSTATCOM is replaced by an ideal current source i_f. Further, as in the case, the load is assumed to be reactive and unbalanced. First, assume the load is without a compensator. Hence, i_s flowing through the feeder is also unbalanced and distorted; subsequently, the voltage on PCC bus will also be unbalanced and distorted.

Ideally, the utility would like to see a load drawing unity P.F with fundamental and positive sequence current. Without the compensator, i_s will be the same as i_L i.e. reactive, unbalanced and distorted. For mitigating the problem, the compensator must inject current such that i_s becomes fundamental, positive sequence and in-phase with the PCC voltage

From Figure (3.6), applying KCL to the PCC that is:

$$i_s + i_f = i_L \tag{3.1}$$

Hence $i_s = i_L - i_f$

Thus, the compensator must generate a current i_f such that it cancels the reactive, harmonic and the unbalance components of the load current.

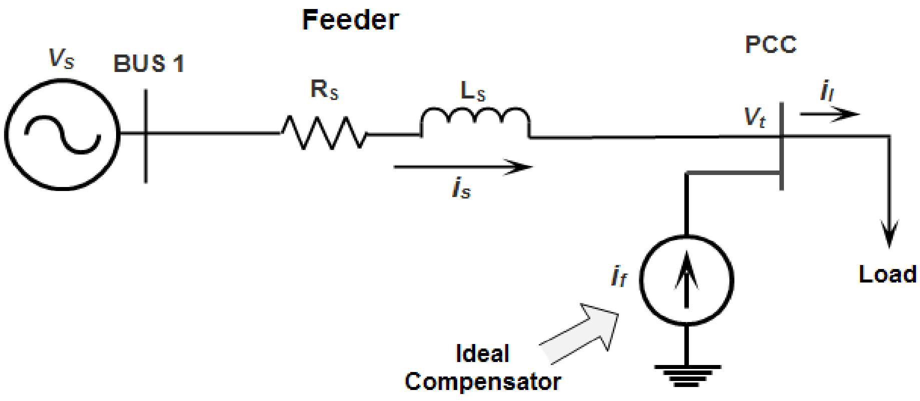


Figure 3.6: Distribution systems with the installed DSTATCOM [13].

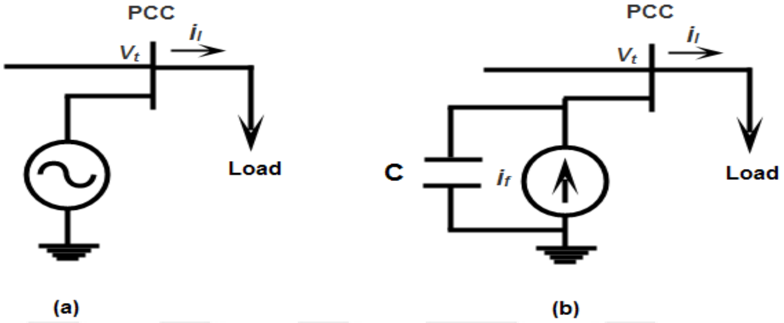


Figure 3.7: Schematic diagram of an ideal DSTATCOM acting as a voltage regulator [13].

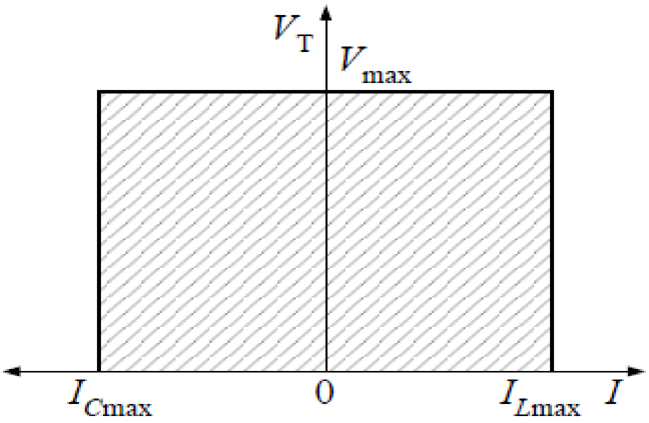


Figure 3.8: The V – I characteristic of D-STATCOM [2].

The schematic diagram of a perfect DSTATCOM acting as a voltage controller is presented in Figure (3.7a). In this, the ideal DSTATCOM is exemplified by a voltage source, and it is attached to the PCC. However, it is complicated to implement this circuit; the alternative structure is displayed in Figure (3.7b). It can be realized that this same construction as used for load compensation. However, it has the advantage that the filter capacitor *C* can bypass the harmonics.

The basic idea here is to inject the current i_f in such a way that the voltage v_t follows a detailed reference. The ideal DSTATCOM must be operated such that it does not inject or absorb any real power in the steady state. In practice, the operating region does not limit the maximum ratings of VSI semiconductors, so the static V – I characteristic of DSTATCOM reactive power is symmetrical Figure (3.8) [2]. The P is obsessive by the DSTATCOM only to boost inside losses.

In practice, the current source is implemented using the voltage source converter, which is schematically depicted in Figure (3.9). It corresponds to a three-phase voltage source converter, interfacing inductors, and a DC link capacitor. The VSC is connected to the system through the interfacing inductors and the transformer, which are used to nominate high-frequency components of compensating currents. The essential destination of DSTATCOM is to attain almost harmonic neutralized and controllable AC output voltage at the PCC and to regulate the reactive current flow by generation and absorption of controllable reactive power.

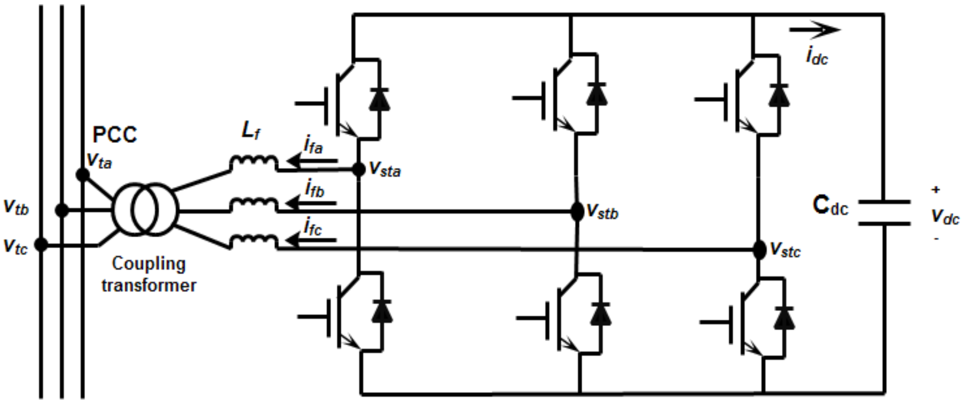


Figure 3.9: Basic two-level VSC bridge [6].

As DSTATCOM has inveterate characteristics of real power interchange with a sustenance of the proper energy storage system, the operation of such controller is possible in all four quadrants of QP plane, and the following power flow relation governs [6]:

$$S=\frac{V_t V_{st}}{X_f}\sin\delta-j\left[\frac{V_t V_{st}}{Xf}\cos\delta-\frac{V_t^2}{X_f}\right]=P-jQ \tag{3.2}$$

Where:

S = the apparent power flow.

P= the active power flow.

Q =the reactive power flow.

V_t =the terminal AC phase voltage to neutral (r.m.s) at PCC.

V_{st} =the DSTATCOM fundamental output AC phase voltage (r.m.s).

$X_f = (f\,\omega\, L$, where, $\omega = 2\pi f)$.

L =the leakage reactance.

f = the system frequency.

δ = the phase angle between V_t and V_{st}.

Active power flow is controlled by the alteration of δ, and reactive power flow is significantly changed with the magnitude of the voltage variation between V_t and V_{st}, and the AC voltage output (V_{st}) of DSTATCOM can be controlled through the PWM switching method. For δ= zero, the P is zero, and Q is derived from (3.2) as follows:

$$Q = \frac{V_t}{X_f}\left(V_{st} - V_t\right) \tag{3.3}$$

Functionally, DSTATCOM injects an almost sinusoidal current i_f in quadrature (lagging or leading) with the terminal voltage V_t. It also imitates as an inductive or a capacitive reactance at the point of connection with the system for reactive power control. The magnitude and phase angle of the injected current i_f are determined by the magnitude and phase difference δ between V_t and V_{st} across the leakage inductance L_f, which in turn controls reactive power flow and DC voltage V_{dc} across the capacitor.

The phasor diagrams on the working principle at the fundamental frequency for capacitive and inductive modes are shown in Figure (3.10). The terminal voltage V_t is equal to the sum of the converter AC output voltage V_{st} and the voltage across the coupling transformer, and interfacing inductor reactive V_{Lf} in both capacitive and inductive modes.

In case the output voltage of DSTATCOM (V_{st}) is in-phase with bus terminal voltage V_t, and V_{st} is greater than V_t ($V_{st} > V_t$), the DSTATCOM is taken into consideration to be working in a capacitive mode that it provides reactive power to the system. If V_{st} is smaller than V_t ($V_{st} < V_t$), it is working in an inductive mode that it absorbs reactive power from the electrical network. Also, for V_{st} is equal V_t ($V_{st} = V_t$), it is no reactive power give-and-take, and this is the no load mode.

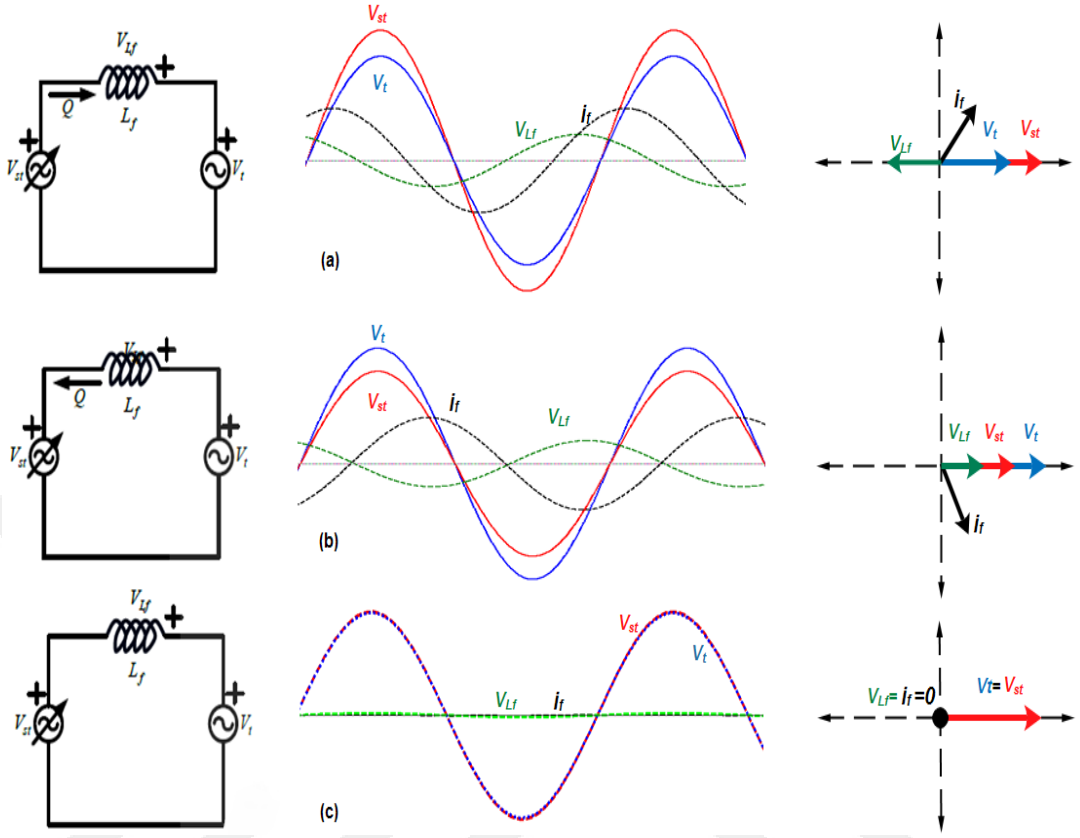


Figure 3.10: Phasor diagrams on the operating principle at the fundamental frequency for.

(a) Capacitive, (b) inductive and (c) no reactive power exchange modes [6].

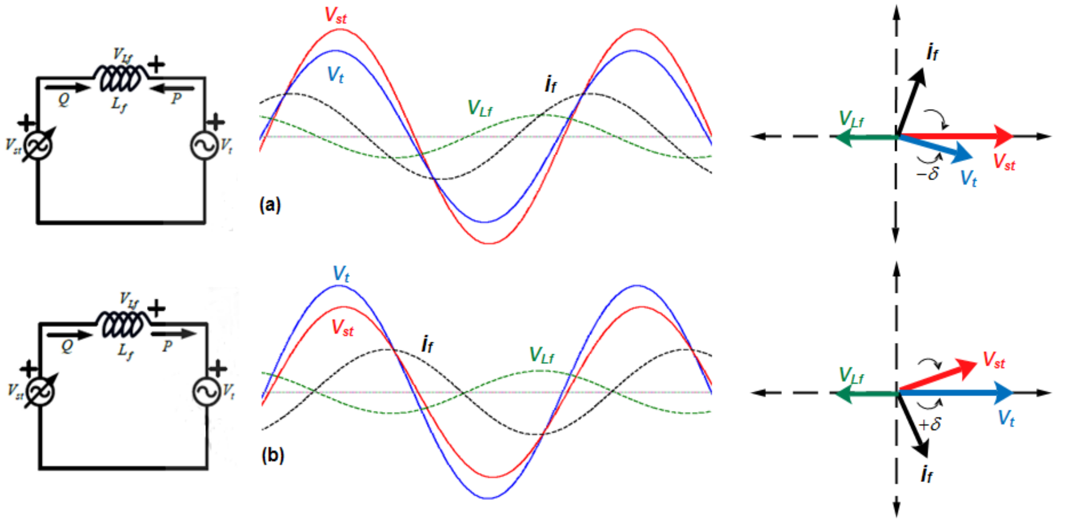


Figure 3.11: Phasor diagrams DSTATCOM consumes or produces active power (a) Capacitive and (b) inductive [6].

Ideally, V_t and V_{st} have the same phase, but they have a little phase difference to component the loss of the transformer winding, interfacing inductor, and inverter switching, so absorbs some active power from the system. Figure (3.11) shows DSTATCOM consumes or produces active power with V_t and V_{st} having phase lagging or leading ($\pm\delta$). For lagging ($-\delta$), power (P) flows from V_t to V_{st} that the active power is transferred from the AC side to the DC capacitor and causes the DC voltage to rise. For leading ($+\delta$), power (P) flows from V_{st} to V_t that the active power is transferred from the DC capacitor to the AC terminal and causes the DC voltage to reduce.

3.5 Modes of DSTATCOM in The Distribution System

In a distributed system, domestic and industrial loads induce harmonics, produce voltage dips, draw large reactive currents, cause an imbalance in the supply current [17]. The voltage of a particular bus can be distorted or unbalanced if the loads on any part of the network are nonlinear or unbalanced. The customers connected to that bus would be supplied by a set of unbalanced and distorted voltages, even when their loads are not contributing to the bus voltage pollution. The DSTATCOM has emerged as a promising CPD to provide not only for voltage sag mitigation (Molavi, H.ev al. 2013) but a host of other PQ solutions(Muppati Mahesh,ev. al. 2016). The large applications of it include voltage regulation, power factor correction, load balancing, harmonic filtering, and flicker reduction (Prakash Mahela et al.2016). DSTATCOM has two operation modes: “voltage regulation” and “load compensation” [2].

3.5.1 DSTATCOM Mode for Voltage Regulation

Since the nonzero of the internal impedance of the system, which is characterized by Zs (Ls, Rs), the voltage waveforms at PCC are not controlled and effect in a voltage drop. The D-STATCOM can recompense the negative-sequence currents and reactive power of the loads [2][18]. The DSTATCOM ought to adjust the PCC voltages with the aim of this voltage drop does not affect other loads connected at PCC. Therefore, it is required to control the working mode of the D-STATCOM for the voltage regulating. This mode can also be applied to mitigate voltage sag/swell, voltage flicker, and voltage fluctuations when connected to a distribution bus [2]. The possibility and effectiveness of compensation of a particular voltage-quality problem depended on the topology and rated power of the controller as well as on the capacity of the energy storage system connected at the DSTATCOM DC side [36].

In steady state analysis, the schematic diagram and the schematic diagram of the DSTATCOM for voltage regulation are shown in Figure (3.12) and (3.13) respectively [6]. In this diagram, the DSTATCOM injected current I_f, which regulates the voltage by adjusting the voltage drop across the system impedance Z_{th}. The injected current I_f can be written as [6]:

$$I_f = I_L - I_S = I_L - \frac{V_{th} - V_t}{Z_{th}}$$

$$or, I_f \angle \gamma = \left(I_l \angle -\theta\right) - \frac{V_{th} \angle \left(\alpha - \beta\right)}{Z_{th}} + \frac{V_t \angle -\beta}{Z_{th}} \tag{3.4}$$

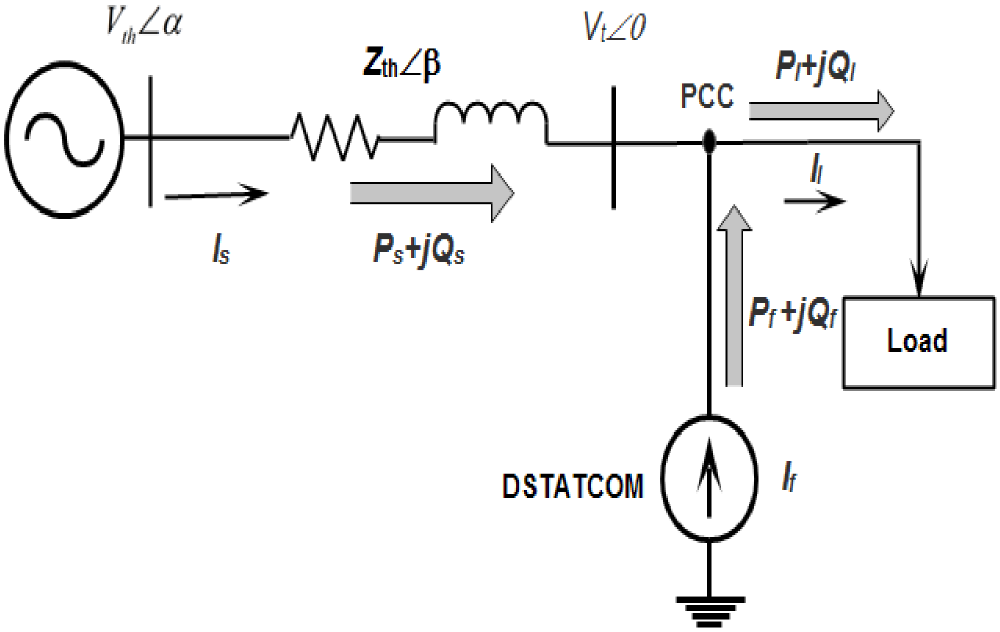


Figure 3.12: Schematic diagram of a DSTATCOM for voltage regulation [6].

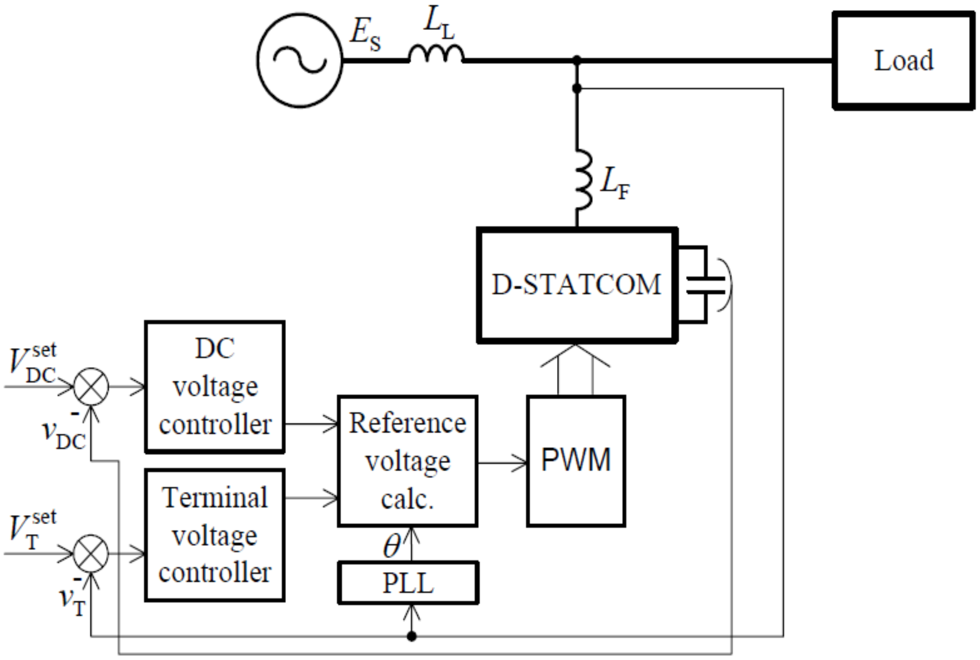


Figure 3.13: The diagram of the control system for voltage regulation [2].

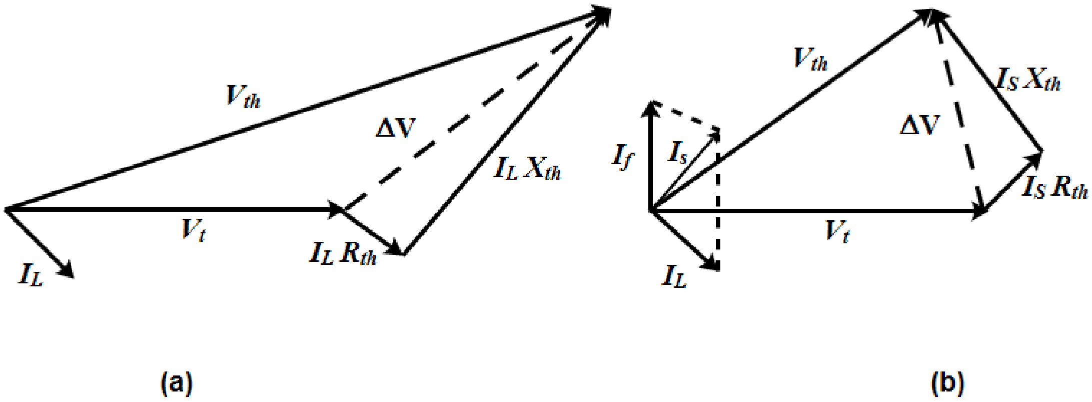


Figure 3.14: Phasor illustrations for VR mode of: (a) without a compensator and (b) with a compensator [2].

For maintaining a stable voltage at PCC, the DSTATCOM proceeds a leading current component (generally) because of lagging P.F loads, and it is described by phasor diagrams displayed in Figure (3.14). When the utility is working without a DSTATCOM, the voltage at PCC (V_t) is less than the supply voltage (V_{th}) caused by the drop in the impedance Z_{th} (L_{th}, R_{th}) as presented in Figure (3.14a). When a D-STATCOM coupled in the utility and with a leading current, the supply current and therefore the drop through the supply impedance can be organized so that the voltage at the PCC and at supply turn into equal ($|V_{th}| = |V_t|$) as shown in Figure (3.14b).

When the injected current I_f is kept in quadrature with V_t, the desired voltage regulation can again be achieved without injecting any active power into the system.

In this case, the entire load active power P_l must be provided by the system. The active power flow through the Thevenin impedance of Figure (3.12) (at load side) can be written as [6]:

$$P_l = \frac{V_{th} V_t}{Z_{th}} \cos(\beta - \alpha) - \frac{V_t^2}{Z_{th}} \cos \beta \tag{3.5}$$

From (3-5), the angle α can be expressed as:

$$\alpha = \beta - \cos^{-1} \left[\frac{V_t}{V_{th}} \cos \beta + \frac{Z_{th} P_l}{V_{th} V_t} \right] \tag{3.6}$$

For a possible value of α, the condition in (3.7) must be satisfied.

$$\frac{V_t}{V_{th}} \cos \beta + \frac{Z_{th} P_l}{V_{th} V_t} \leq 1 \tag{3.7}$$

The above constraint can be rewritten as:

$$V_{th} \geq \left(V_t \cos \beta + \frac{Z_{th} P_l}{V_t} \right) \tag{3.8}$$

Thus, when the system voltage magnitude satisfies as (3.8), the voltage can be regulated without interjecting any active power into the system by the DSTATCOM. The effectiveness of the DSTATCOM in regulating voltage respect on the value of Z_{th} or fault level of the PCC. However, the DSTATCOM can control the voltage with minimum apparent power injection into the system. The apparent power injection of the DSTATCOM can be expressed as:

$$S = V_t I_f^* \tag{3-9}$$

3.5.2 DSTATCOM Mode For Load Compensation

DSTATCOM, for the compensating load mode, is controlled by current mode [6]. The control utility of DSTATCOM has to produce reference currents, compensate harmonics, fundamental reactive components and unbalance of linear or nonlinear load [4]. The necessary rated power of DSTATCOM depends only on Q, harmonics distortion, and the power of the load [21]. In general, DSTATCOM is susceptible for compensating current instabilities from harmonic to long-period sound effects [4]. The schematic diagram for load compensation using DSTATCOM is shown in Figure (3.15). A current controlled voltage source converter is assumed at the heart of the DSTATCOM. Also, Figure (3.16) shows the diagram of the control system for compensating [4]. Hence for an ideal case, the DSTATCOM is replaced by an ideal current source i_c. Further, in this case, the load is assumed reactive, nonlinear and unbalanced. First, assume the load L is without a compensator.

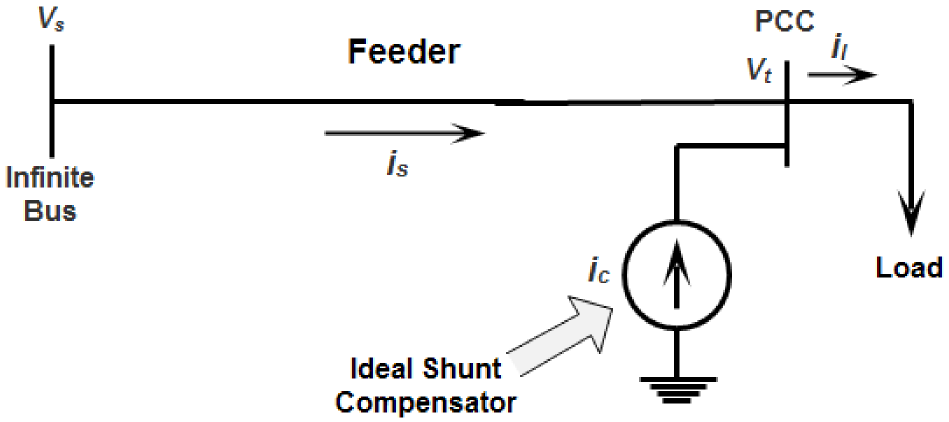


Figure 3.15: Schematic diagram of load compensation [6].

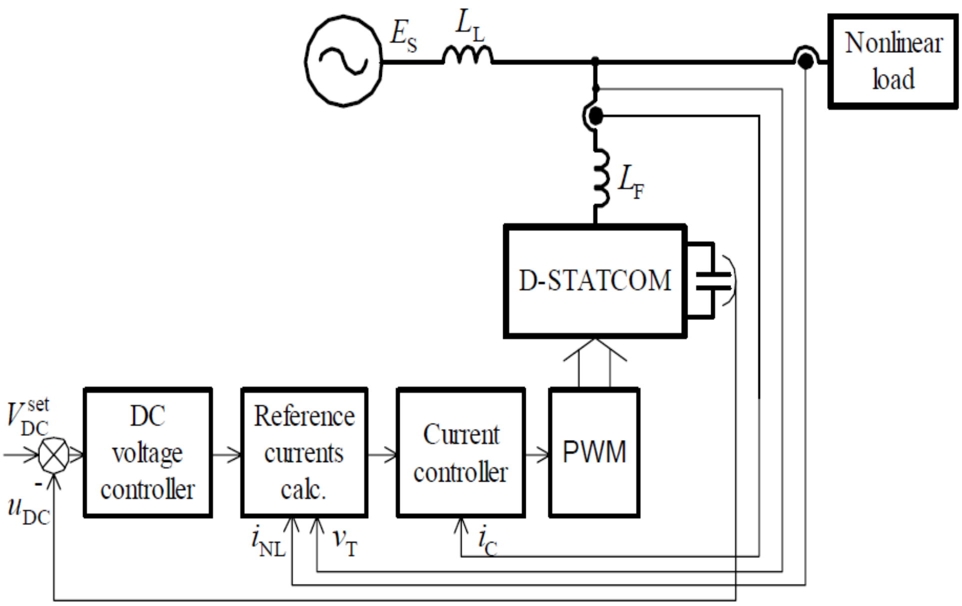


Figure 3.16: The diagram of the control system for compensating [4].

Hence, i_s flowing through the feeder is also unbalanced and distorted and consequently, the voltage at PCC bus will be unbalanced and distorted. Ideally, the utility would like to see a load drawing unity P.F with fundamental and positive sequence current. Without the compensator, i_s will be same as i_l reactive, unbalanced and distorted. For mitigating the problem, the compensator must inject current such that is becomes fundamental, positive sequence and in-phase with the PCC voltage. Applying KCL to PCC,

$$i_s + i_c = i_l$$

Hence,

$$i_s = i_l - i_c \tag{3.10}$$

3.6 Control algorithm of DSTATCOMs

The heart of the DSTATCOM used for compensation of the power system is its control system, and its response to the dynamic change of the load depends on the methodology used for its control [12]. Usually, the control of the DSTATCOM power circuit is firstly achieved by involving sensing, the essential AC and DC voltages and currents using PTs, CTs, and Hall-effect sensors to gather information about the dynamic condition of the load and the system. After that, the reference currents and voltages by using feedback signals are employed in PWM switches to determine PWM signals for switching devices (IGBTs) of the VSC [2][40]. Reference currents for the governor of DSTATCOM must be obtained accordingly, and these gating signals may be evaluated using some control procedures [2]. For the control of DSTATCOMs, there are many control algorithms reported. These algorithms are classified as Time-domain (Lu et al., 2012; Geddada et al., 2012 and Singh and Arya, 2014) and frequency-domain control algorithms (Shan et al., 2010; Singh, 1999 and Ghosh and Ledwich, 2003; Lu et al., 2012).

A few of time-domain control strategies that are accustomed for the controlling are as follows [2]:

1) "Unit template method or PI controller-based theory".
2) "Power balance theory (BPT)".
3) "Current synchronous detection (CSD) method".
4) "Instantaneous reactive power theory (IRPT), also known as PQ theory or α–β theory"

5) “Synchronous reference frame (SRF) theory, also known as d–q theory”.

6) “Enhanced phase locked loop (EPLL)-established control system”.

Similarly, some of the frequency-domain control algorithms as [2]:

1) “Fourier series theory”.

2) “Discrete Fourier transform theory”.

3) “Fast Fourier transform theory”.

4) “Kalman filter-based control algorithm”.

5) “Stockwell transformation (S-transform) theory”.

Most of the time-domain control systems have been applied for the switch of DSTATCOMs and additional compensating devices [2][3]. Most of the frequency-domain control algorithms are used for power quality monitoring for some purposes in the power analyzers, [2]. Several of these procedures have been applied for the control of D-STATCOM. Whilst, these algorithms are inactive and slothful [3]; for that reason, these control procedures are not too much desired for real-time control be as good as the time-domain control processes [2].

In this thesis, according to the purpose of using DSTSTCOM in this study, One of the widest control algorithms has been using is synchronous reference frame theory (Akagi et al., 1984; Akagi et al., 1986) and (Cristian A. Sepulveda et al..2013b). The control algorithm of the D-STATCOM control system to keep the required PCC voltage, are shown in Figure (3.17) [4]. The load currents (i_{La}, i_{Lb}, i_{Lc}), PCC voltages (v_{sa}, v_{sb}, v_{sc}), and DC bus voltage (V_{DC}) of the DSTATCOM are considered as feedback signals. The load currents in the three phases are converted into the dq0 frame using the Clarke and Park’s transformations (Appendix-A) as follows [2 and 56]:

$$\begin{bmatrix} i_{Ld} \\ i_{Lq} \\ i_{L0} \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta & -\sin\theta & \frac{1}{2} \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & \frac{1}{2} \\ \cos\left(\theta + \frac{2\pi}{3}\right) & \sin\left(\theta + \frac{2\pi}{3}\right) & \frac{1}{2} \end{bmatrix} \begin{bmatrix} i_{La} \\ i_{Lb} \\ i_{Lc} \end{bmatrix} \tag{3-11}$$

A three-phase locked loop is utilized to synchronize these signals with the load voltage. An LPF is also used to separate the DC components of i_{Ld} and i_{Lq} after bringing the d–q current components to it [2]. The d-component and q-component of currents components as:

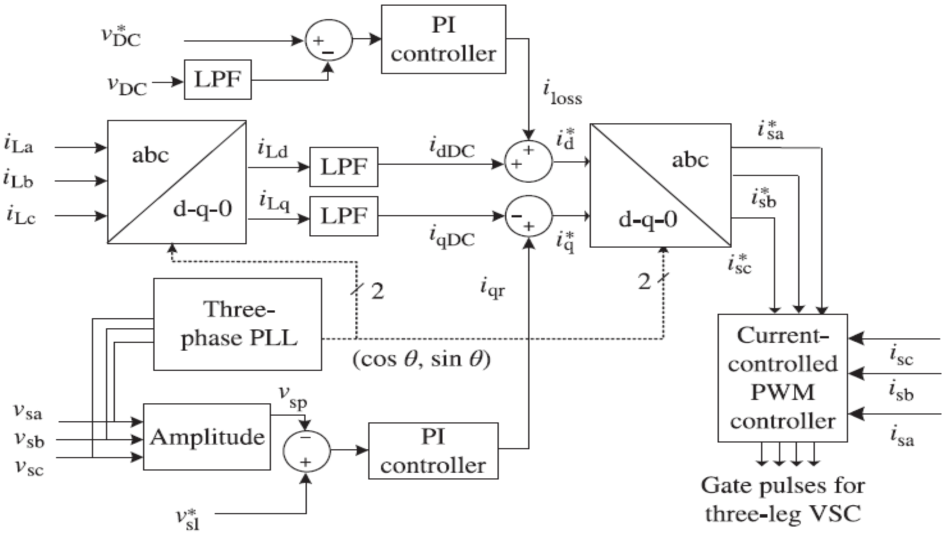


Figure 3.17: Block figure of SRF control system of DSTATCOMs [4].

$$i_{Ld} = i_{dDC} + i_{dAC} \tag{3-12}$$

$$i_{Lq} = i_{qDC} + i_{qAC} \tag{3-13}$$

An SRF can be worked in P.F correction and voltage regulation modes by controlling i_{Lq} [2].

3.7 Converters Based DSTATCOM

The converters used in DSTATCOM topologies are classified according to their multi-pulse or multilevel structures [36]. The multi-pulse converters are switched in line frequency where it consists of line-commutated devices. On the other hand, multilevel converters including widely known VSC topologies are commutated by pulse width modulation (PWM) or its improved methods [36].

3.7.1 Multi-pulse (Six-Pulse) Converter

The preliminary DSTATCOM applications are based on multi-pulse converters owing to its lower losses and lower harmonic contents [36]. An essential VSC DSTATCOM in the configuration of 6-pulse two-level is illustrated in Figure (3.18) that is constituted with six IGBT where several other self-commutated devices such as GTOs, MCT or IGCT could also be used [36].

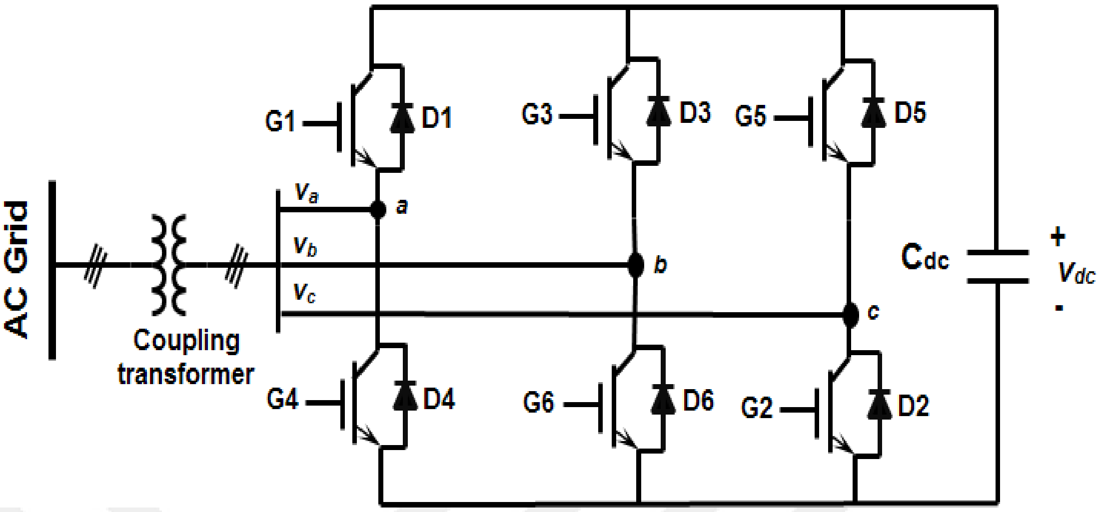


Figure 3.18: Basic 6-pulse two-level VSC DSTATCOM [36].

The IGBTs are the switching devices of the system, where the converter can generate balanced three-phase AC output voltages from a DC capacitor. The frequency of the output voltage is adjusted by the modulating frequency of IGBT switches, and the phase voltages are coupled to the AC grid through an interconnection reactor [37].The operating principle of the DSTATCOM is based on generating a staircase waveform by synthesizing the DC input voltage levels. The VSC can be operated with 120° or 180° switching sequences where it allows conducting two or three switches at any time, respectively [36]. Figure (3.19) illustrates the switching sequences; signals generated and applied to G1 and G4 switches, and output line voltage of v_{ab} in each axis.

The line voltage v_{ab} can be expressed in Fourier series as:

$$v_{ab} = a_0 + \sum_{h=1}^{\infty} a_h \cos(hwt) + \sum_{h=1}^{\infty} b_h \sin(hwt) \tag{3.14}$$

Where coefficients a_0, a_h, and b_h can be determined by considering one fundamental period of v_{ab}.

The average voltage is calculated as a_h = zero since the v_{ab} waveform is symmetrical. On the other hand, the coefficient b_h is determined as seen in (3.15) since it also has odd-wave symmetry [38].

Therefore,

$$b_h = \frac{2}{\pi}\int_{0}^{\pi} V_{dc}\sin(hwt)d(wt) \tag{3.15}$$

$$b_h = \frac{2}{\pi}\int_{\alpha}^{\pi-\alpha} V_{dc}\sin(hwt)d(wt) = \frac{4V_{dc}}{\pi h}\cos(h\alpha) \tag{3.16}$$

$$\therefore V_{ab} = \sum_{h=1,3,5..}^{\infty} \frac{4V_{dc}}{\pi h}\cos(h\alpha)\sin(hwt) \tag{3.17}$$

The triple harmonics in the line voltage will be zero when the switching angle is set to α = 30° as seen from (3.16). It is also seen that the harmonic contents of the converter occur in the (6n ± 1). f_o orders where f_o is the fundamental frequency of line voltage and n = 1, 2, 3... It is apparently seen that the harmonic orders of 6-pulse VSC are 5th, 7th, 11th, 13th… moreover, so on that makes the VSC impractical for power systems.

In a view to coping with this problem, increased pulse levels such as 12-pulse, 24-pulse, and 48-pulse are achieved by combining basic 6-pulse VSCs together [36].

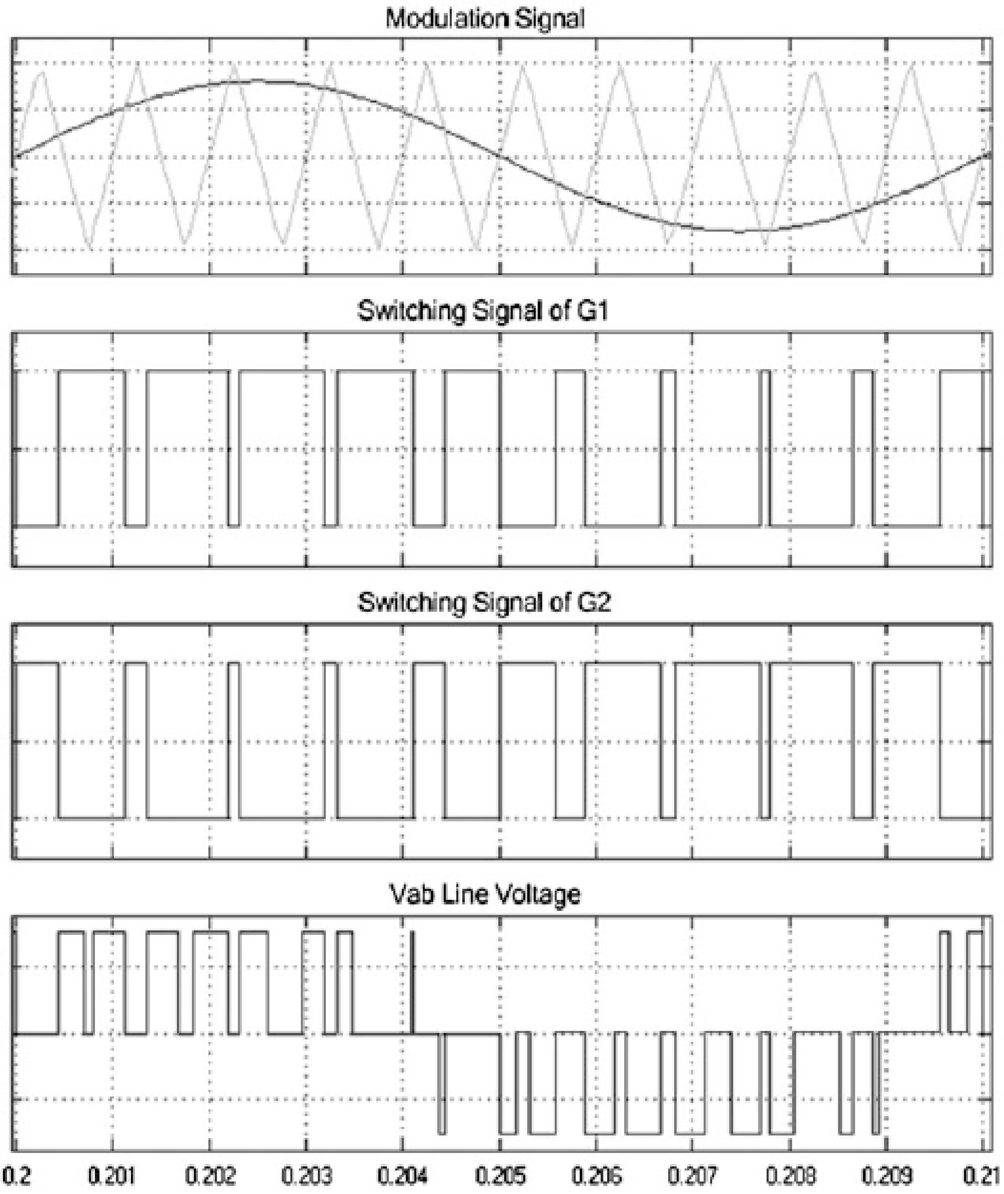


Figure 3.19: Output line voltage of a VSC operated at 120° conduction sequence [36].

3.7.2 Multi-pulse (Twelve-Pulse) Converter

The 12-pulse converter requires two 6-pulse converters connected in parallel over the single DC bus where they are serially connected to transformers on the output side as seen in Figure (3.20) [39]. Two different topologies can be used to generate a 12-pulse static compensation. The first one consists of two level VSCs (Zafari, Ali, and Mostafa Jazaeri. 2016) as shown in Figure (3.20) while the second one is based on three level VSCs (K. Girish Nayak et al.2016) that is depicted in Figure (3.21). The first approach requires a different transformer connection for each six pulse VSC, i.e. one is Δ-Y connected while the other is Y-Y connected to the AC grid [40]. The Δ connected secondary of the transformer has three times higher winding turns and provides 30° phase shift comparing to the Y connected one. Therefore, the lower order harmonics are eliminated efficiently [36].

The phase-*a* output voltage of DSTATCOM in any instant can be calculated by using (3.18) where n_1 and n_2 are the voltage ratios of the corresponding VSC transformers while v_{a-Y} and $v_{a-\Delta}$ are the output voltages of the Y-Y and Δ-Y connected converters, respectively [36].

$$v_a = n_1 v_{a,Y} + n_2 \frac{v_{a,\Delta}}{\sqrt{3}} \tag{3.18}$$

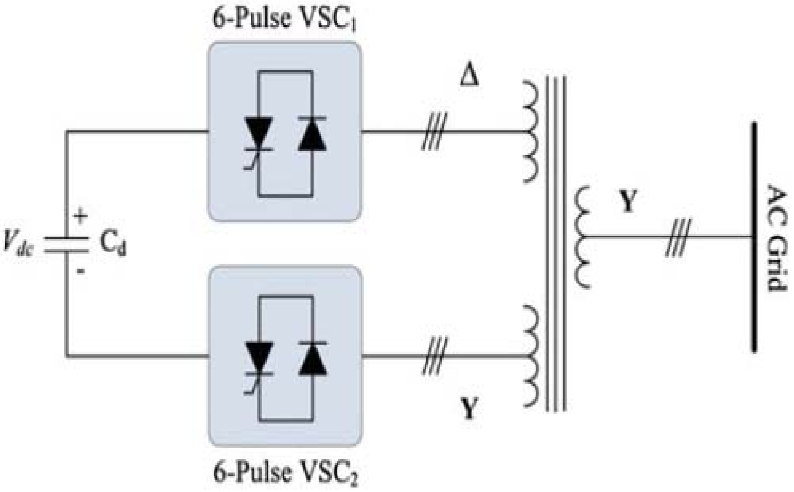


Figure 3.20: The 12-pulse converter [36].

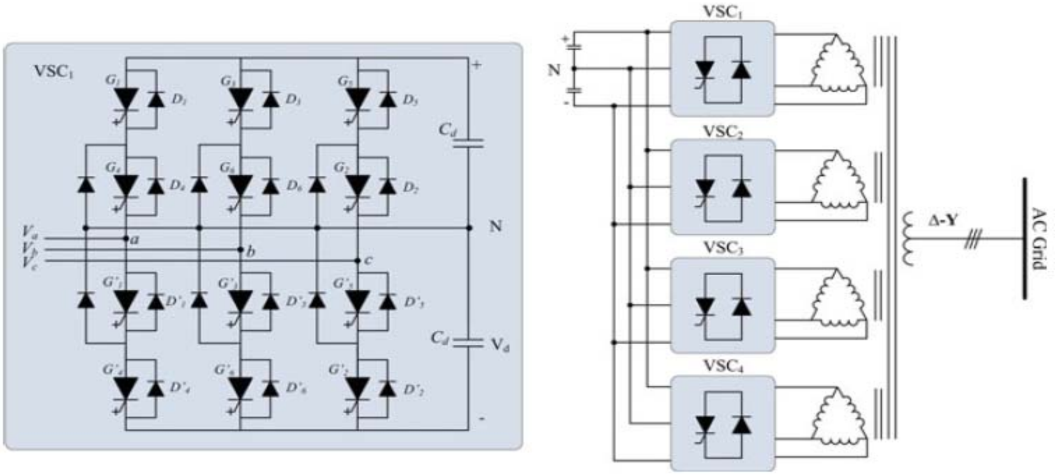


Figure 3.21: Three-level 12-pulse DSTATCOM [36].

The amplitude of VSC output voltage depends on the modulation index (m_i) of the controlling signal that allows obtaining the output voltage at $m_i V_{dc}$ where V_{dc} is the voltage across the capacitor [36].

3.7.3 Multilevel Converters

The multi-pulse DSTATCOM topologies have several drawbacks such as higher costs, large device structures, higher active power losses, and nonlinearities caused by multi-winding transformers when compared to the multilevel converter based topologies [36]. The multi-level VSC DSTATCOMs are widely used owing to its advantages against drawbacks above (Tejinder Singh Saggu et al..2016a). In addition, due to its modular structure, independent phase control ability, and decreased costs [41][42].

The Multilevel Converters (MLC) are one of the extensively studied research areas of power converters [36]. Nabae introduces the initial studies on MLCs where a two-level converter is improved by utilizing neutral point of the DC line voltage to constitute the third level [43]. This early device is presented as neutral point clamped (NPC) inverter [43]. In the following years, several topologies and arrangements are proposed by numerous researchers to increase the efficiency of MLCs while decreasing the switching losses. However, three topologies that are diode clamped, a flying capacitor (FC), and cascaded H-bridge (CHB) hold the superior rate of utilization [44]. The most significant contribution of MLCs are related to their benefits such as lower voltage stress on switching devices, lower dv/dt in voltage source, higher power outputs, decreased electromagnetic interference (EMI), and staircase output voltages depending on multilevel generation [43].

3.8 Output Filter

The conventional method to filter harmonics is connecting passive filters to the output of VSC. The output filter design requires more attention to operating the DSTATCOM in an efficient way [45]. The filtering methods are passive filters such as L filters, LC filters, and LCL filters [42]. All of these reactive components are connected to a small resistor to increase the stability in comparison to the pure reactive filters [46]. The simplest passive filter is an inductor, which is low cost and is expected to meet the ripple current requirements while the voltage drop across the inductor should be within an acceptable limit. The design criteria of L filter requires that the reactance of the inductor should be around 20 % of DSTATCOM while the ripple current should be lower than 25 %, and the voltage drop lower than 10 % [47].

The main drawback of the L filters is that they require higher inductance to decrease the total harmonic distortion (THD). On the other hand, in high power applications, the switching frequency is restricted to minimize the power losses. Other passive filter topologies are widely researched to cope with the drawbacks of simple L filter by increasing the reactive components. The LC filter is implemented to reduce the inductance of filter while obtaining the same filtering properties [48].

3.9 Applications and Benefits of DSTATCOM in The Distribution System

DSTATCOMs in the distribution system can be used by the utility, at customer sites, or in microgrids. At the distribution level (Figure 3.22), DSTATCOMs are realized with three phase IGBT based inverters with active and reactive current control. Further, the DSTATCOM functionality may be integrated into inverters used to connect energy storage and distributed generation sources like photovoltaic (PV), microturbines, and fuel cells to the grid. DSTATCOMs in distribution systems can be used for voltage regulation, power transfer capability, and enhancing stability [36]. DSTATCOM has played a major service in the appropriate operational of electric distribution power systems. In individual, some schemes have fixed the guide in the application of DSTATCOM; Table (3.1) illustrates the most significant schemes and their typical features.

Finally, several control objectives could be combined in a single DSTATCOM, e.g., energy storage, imbalance mitigation and reactive power dispatch by the utility. The main features of the DSTATCOM compensators are the following [2, 36, 50, 51, 52, 53, 54, and 55]:

1. Increases the maximum power transmission capability of the transmission line while improving the voltage instability limits.
2. Compensation of loads with poor power factor in order to obtain nearly unity power factor.
3. Voltage regulation for the loads that cause fluctuations in the supply voltage.

4. Load balancing by canceling the effect of unbalanced loads.

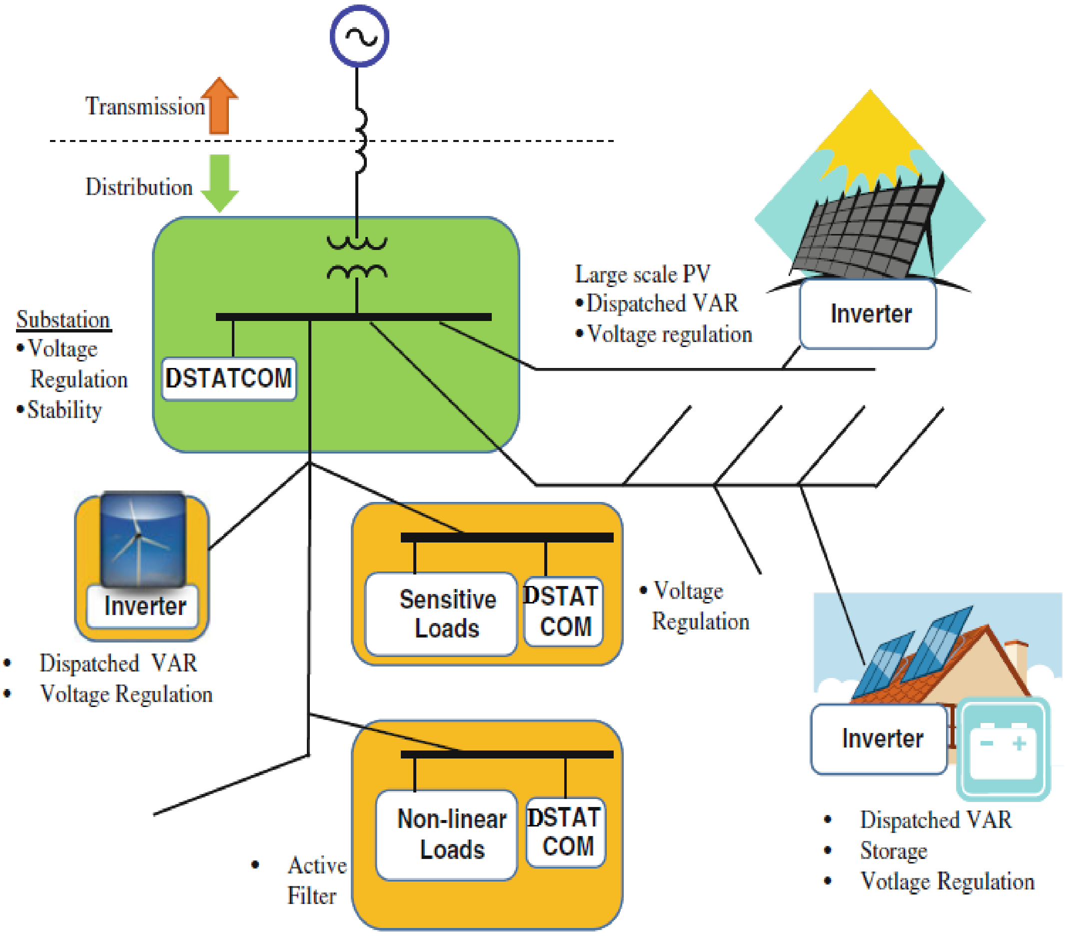


Figure 3.22: DSTATCOMs in distribution systems [36].

5. Avert the voltage swells produced by capacitor interchanging and decreases the voltage sags as a result of common feeder faults.
6. Decreases the frequency of mechanical exchanging procedures in load tap changing (LTC) transformers and mechanically switched capacitors for a drastic reduction in their maintenance.
7. Faster response.
8. Less space requirement and re-locatable.

Table 3.1: The most important DSTATCOMs installations and their representative characteristics.

DSTATCOM installed	Rating (MVAr)	Application	Country	Year
Kita Osaka[40]	±20	Voltage and dynamic stability	Japan	1980
Toshiba and Mitsubishi Transmission and Distribution[49]	±5MVA	Voltage Flicker Compensation	Japan	2000
ACECR Research Institute [20]	±0.250	Voltage regulation and reduction of unbalance issue.	Iran	2004
Kemerköy Thermal Power Plant [21]	±0.750	Reactive power compensation	TURKEY	2007

CHAPTER FOUR

LOCATION, SIZE AND PROPOSED DESIGN OF DSTATCOM

This chapter offers selection the proper location, size and proposed design of DSTATCOM to improve the power quality in a part from Iraqi distribution network (11kv) is selected DSTATCOM. The main sections of this chapter are:

1) The area under this study.
2) DSTATCOM's location.
3) DSTATCOM size determination.
4) Proposed design of DSTATCOM.

The power quality monitoring determines the optimal position of DSTATCOM. Iraqi distribution system does not have these devices. However, the proper location of installation the DSTATCOM can select by choosing the sensitive buses. In this thesis, the place of DSTATCOM was adjusted by selection an area for the system. This area consists of single transmission substation and three distribution substations, all of these substations have 11KV buses. The weakest 11KV bus was chosen to place and test the DSTATCOM.

DSTATCOM size was calculated by using the reactive power-voltage (VQ) curve. The size was optimized for the load voltage regulation by the requiring of the reactive power for management the load voltage under normal and transient conditions.

The rating components of the DSTATCOM have been designed for control the load voltage from the reactive power required to regulate the voltage at the selected bus. Then, the parts of the DSTATCOM has been computed such as the compensation current, the DC voltage of the converter, and the capacitor. A VSC was designed to operate with low THD and simple structure for cost issues. The control strategy was carried out for voltage regulation, mitigation voltage sag, swell, compensation of the load unbalance and the reactive power compensation. The synchronous reference frame-based control method is used for regulating voltage. Finally, all of these components are implemented on MATLAB/SIMULINK/Simscape Power System.

4.1 The Area Under This Study

The area is a part of Iraqi distribution network in South region / Thi-Qar/ Rifai city. This area consists of three distribution stations 33/11KV. These stations are Rifai2, Qala1, and Qala2. They deliver the power from sub-transmission station 132/33/11KV (Rifai.1) by the primary distribution system 33KV [57]. Distribution Operator distributes power by the secondary distribution network 11 and 0.4 KV.

The area was chosen for installation and testing the DSTATCOM because there are no compensation devices like capacitor bank in this area. In addition, only the tap changer in power transformers is used to regulate the voltage. Figures (4-1) shows the single line diagram of the area. While Table (4-1) presents the components, voltage level, capacity, and the number of buses in the area. In addition, the maximum power, P.F, distribution transmission lines length, and more details are shown in Appendix-B.

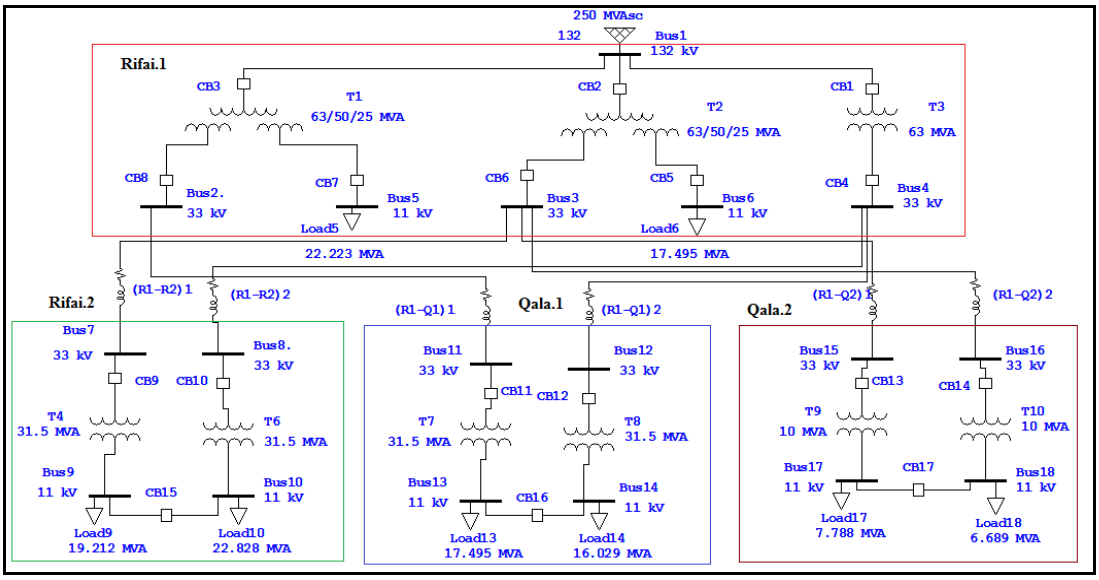


Figure 4.1: The single line diagram of the area [57].

Table 4.1: Substations' components of the area under study, voltage level, capacity, and number of buses [57].

Substation	*Voltage level KV*	*Capacity (No. Transformers ×MVA)*	*Number of buses and (Symbol)*		
			132 KV	*33KV*	*11KV*
Rifai.1	132/33/11	3×63	1 (Bus1)	3 (2,3 and 4)	2 (5 and 6)
Rifai.2	33/11	2×31.5	/	2 (7 and 8)	2 (9 and 10)
Qala.1	33/11	2×31.5	/	2 (11 and12)	2 (13 and14)
Qala.2	33/11	2×10	/	2 (15 and 16)	2 (17 and18)
TOTAL	/	/	1	9	8

4.2 Location of the DSTATCOM

Different methodologies have been developed to identify the optimum location of DSTATCOM placement in distribution systems. Determination the place of DSTATCOM depends on the type of the power quality problem that should be improved in the utility or a particular part of the network (Ganguly, 2014b).

The purpose of this work is to study the DSTATCOM performance in a distribution substation at 11KV side for improving power quality, which related with voltage quality such as under voltage, over voltage, sag, swell and unbalance. So that the proper location for DSTATCOM was achieved by selecting the bus that has the lowest voltage level in the area.

Power flow solution determines the weakest bus. The most common techniques are used to solve power flow problem Gauss-Seidel and Newton-Raphson [58]. These methods have been developed and built graphical user interface by MATLAB [59].

MATLAB/SIMULINK and Newton-Raphson method have been obtained to construct and simulate the network in this study. The stations were built in MATLAB/ SIMULINK model, and Figures (4-2) shows the SIMULINK model block diagrams of the stations.

The simulation has been accomplished at maximum load on the buses. These load collected in August last year (Appendix -B). The simulation results are presented in Table (4-2), it is clearly shown that Bus13 has the lowest voltage level. Finally, the position of installation and test performance of DSTATCOM has specified at Bus (13).

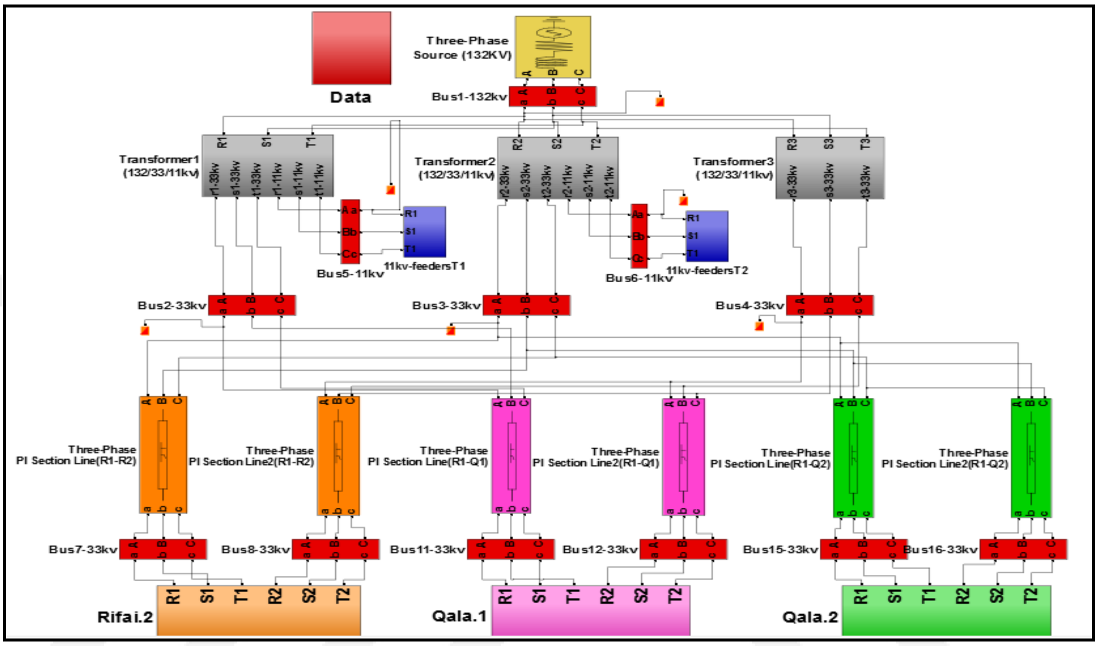


Figure 4.2: The SIMULINK model block diagram of the stations.

Table 4.2: Power flow solution of the system/

Bus. No	*Voltage (p.u)*	*Voltage angle*	*P (MW)*	*Q (Mvar)*
5	0.97	25.38	21.4	5.6
6	0.974	26.24	16.7	5.5
9	0.965	24.41	18.5	5.2
10	0.949	23.27	22.7	7.4
13	0.931	21.71	16.7	5.49
14	0.950	22.79	15.3	4.6
17	0.955	22.88	7.5	2
18	0.962	23.31	6.5	2.1

4.3 DSTATCOM Size Determination

DSTATCOM is used to boost the voltage profile of the distribution network within acceptable limit by providing reactive power. As the reactive loading of distribution system increases, voltage profile of the network decreases. The benefits of DSTATCOM placement is to increase the reactive loading capability of the distribution system in all loading conditions. Voltage profiles at each bus of distribution network can be enhanced and kept within tolerable limits. The system stability is improved to make the best use of the distribution network; reactive power flow is reduced so as to decrease line losses. Therefore, DSTATCOM size to enhance the voltage at the bus is related to the amount of reactive power demand to hold the voltage stability at different load demand including capacity growth.

Voltage stability is defined as the ability of a power system to keep the voltage on any bus in the system remain stable after a disturbance. Voltage instability appears due to the inability of the power system to supply substantial power to cover the increased demand of load [60].

Some methods have been suggested to determine voltage stability including the VQ curve method. It studies how variations in reactive power (Q) affects the voltage (V) in the system [61]. VQ curve is the relationship between the reactive power Q and receiving end voltage for different values of active power at a particular bus [62], and it is widely used for this purpose [63 and 64]. Therefore, the VQ curve for mesh-type power network has been adopted in this study to choose the DSTATCOM size.

Figures (4.3) shows the typical VQ characteristic curve. In this figure, the points P and P1 represent the operation points of a bus at fixed active power and different reactive power Q and Q1, V and V1 are the voltages of this bus at these various loads. QD1 is the reactive power required for compensating voltage of this bus and moving it from point P to the new operation point P2 with higher voltage level V2. While QD2 is the reactive power required for compensating voltage and running the operation from point P1 to point P2 at voltage V2.

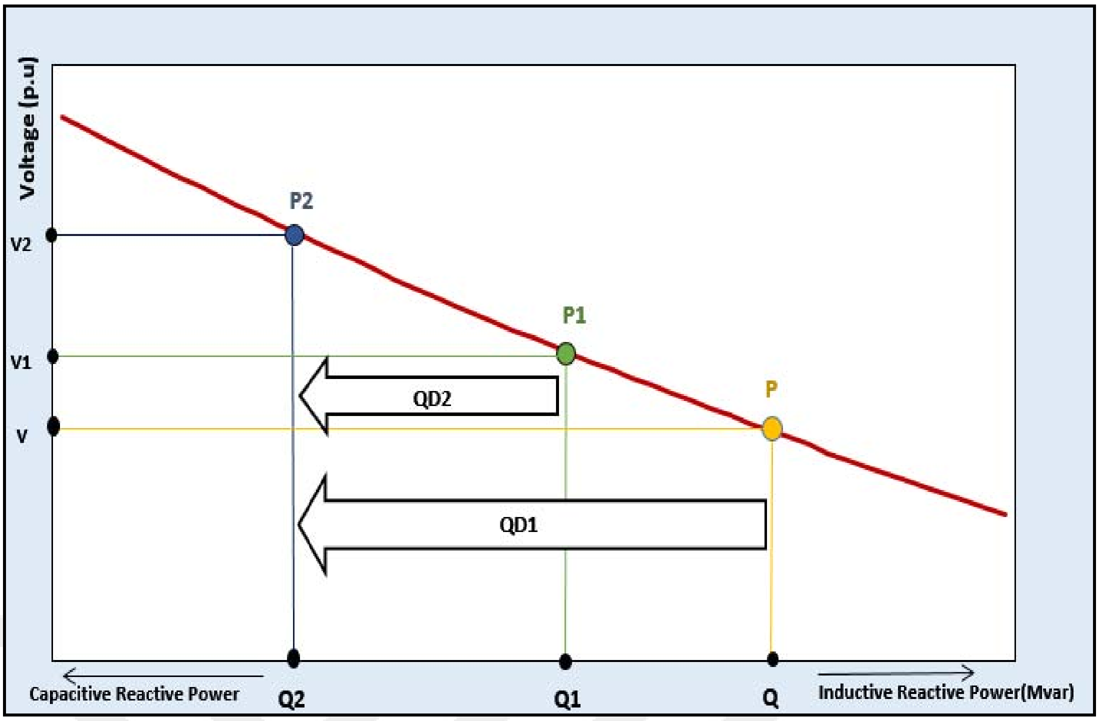


Figure 4.3: The standard VQ characteristic curve [63].

The methodological steps have been followed for plotting the VQ curve for the bus (at any active power P) are listed as following [63 and 65]:

1. Select a bus. The VQ curve is plotted at this selected bus. Bus 13 has been chosen for this case due to the low voltage level.
2. Fixed Q at the full capacitive load (MVA of the transformer that feeds bus 13 specifies the maximum Mvar)while maintaining adjusted P.
3. Run the power flow program by using MATLAB/SIMULINK.
4. Changing the value of Q by ±0.5 Mvar while maintaining fixed P. After that, execute the power flow program. A new voltage value on the bus 13 will be obtained. Record the values of Q and voltage.
5. Repeat Steps 3,4 until the full inductive reactive power at this value of P.
6. Finally, adopt all the recorded value of Q collected in 3 and 4 and plotted it against the voltage of the bus 13 with Microsoft Excel.

The VQ curve of bus13 has been drawn with two different cases; firstly, it has been planned at an active power equal to 16.7MW, which is the peak load recorded in last year. While the second instance, the VQ curve has been plotted with higher load condition and with consideration of the load growth. This load is 25MW, which is the maximum load can be supplied to the bus from sub-transmission station

132/33/11KV (Rifai.1). Figures (4.4) and (4.5) show the VQ curves at power 16.7 MW and 25MW respectively.

In figure (4.4), it can be seen that bus13 operates at point C with a voltage equal to 0.931 p.u and P.F 0.95 lag. While it works at C1 with a voltage equal to 0.98 p.u and unity P.F. QD1 is the DSTATCOM's size required to compensate bus voltage and move its operation for from 0.98 to 1 p.u voltage. Whereas, QD2 is the DSTATCOM size to recompense voltage from 0.931 to 1 p.u voltage. Similarly, in figure (4.5) QD1 is the DSTATCOM's size required to compensate the bus and move it for from 0.962 to 1 p.u voltage level. Whereas,QD2 is the DSTATCOM's size to offset bus voltage and move it for from 0.893 to 1 p.u.

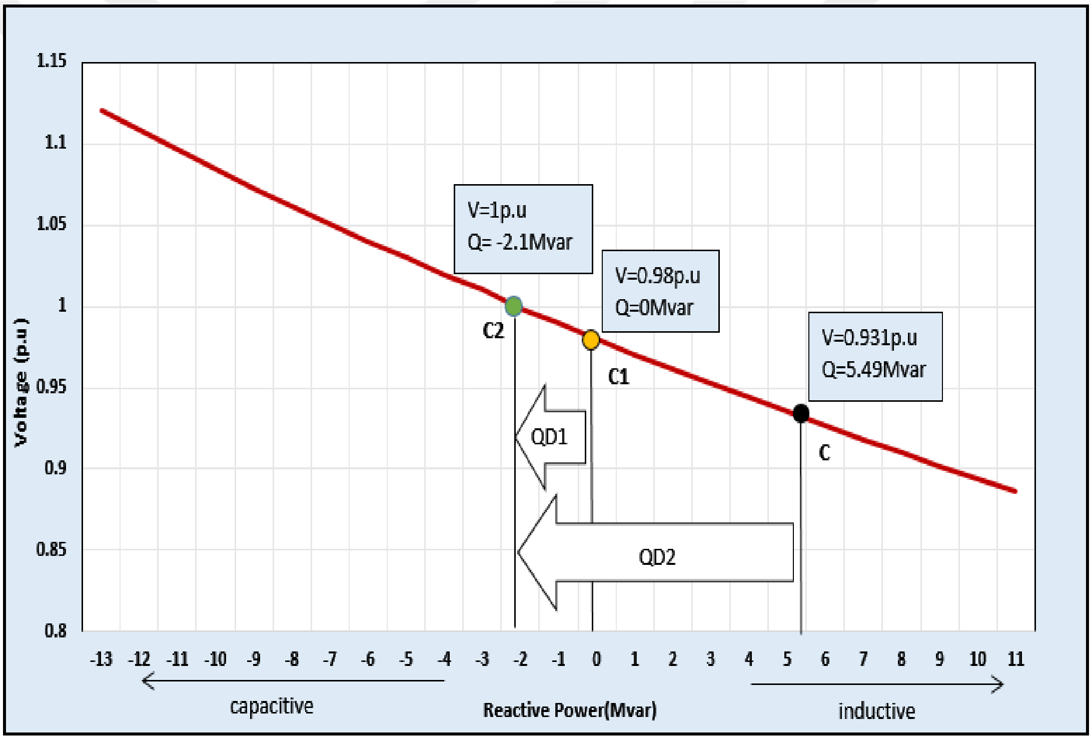


Figure 4.4: The VQ curve of Bus13 at (P=16.7MW).

It should be noted that the bus would operate with too low voltage level if it is loaded with 25MW. Power transformer cannot regulate this voltage level so that installation of a compensator device is very significant.

From these two figures, the reactive power required and DSTATCOM size for different loads at bus13 are presented in Table (4-3).

Finally, a ±10Mvar DSTATCOM is selected for load voltage regulation in this work. This size of DSTATCOM can regulate the load voltage as 1 p.u when the load is less than 17MW. Also From figure (4.5), 10Mvar is the reactive power that is required to keep the voltage at a minimum acceptable level which is equal or higher than 0.95 p.u ("EN 50160, Voltage Characteristics of Public Distribution Systems")[2] when consideration of load growth (25 MW).

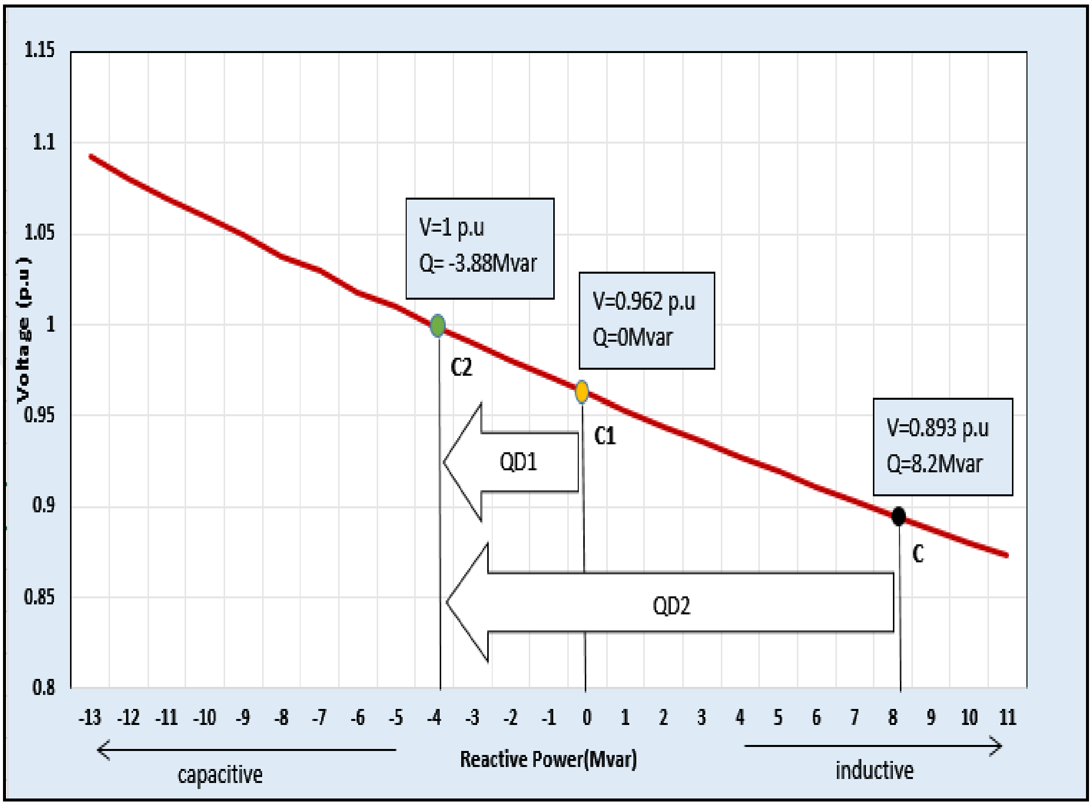


Figure 4.5: The VQ curve of Bus13 at (P=25MW).

Table 4.3: DSTATCOM size required for different loads.

Load active power (MW)	*DSTATCOM size (Mvar)*	*DSTATCOM size (Mvar)*
	(Load as PF= 1.0)	*(Load as PF= 0.95 lag)*
16.7	2.1	7.5
25	3.88	12

4.4 Proposed Design of DSTATCOM

The DSTATCOM design comprises by estimating and selecting of different components of the D-STATCOM like DC voltage, DC capacitor rate, AC inductor, and the filter [2]. The ripple in the currents and voltages is executed by the interfacing inductor and a ripple filter [2]. The energy storage capacity required during transient conditions determines the design of a DC bus capacitor. The required reactive power compensation determined the rating of the D-STATCOM. Therefore, the load power rating influences the current rating of the DSTATCOM [2]. But DSTATCOM voltage level be determined by on the DC bus voltage [2].

The design and selection of the components of the DSTATCOM are depended on the purposes and control strategy of using DSTATCOM and Figure (4.6) shows the main DSTATCOM's components. In this thesis, the DSTATCOM is designed and verified to improve power quality. These problems related to a voltage such as voltage regulation, mitigating the voltage sag, swell, enhancing the load voltage unbalance and compensation the reactive power.

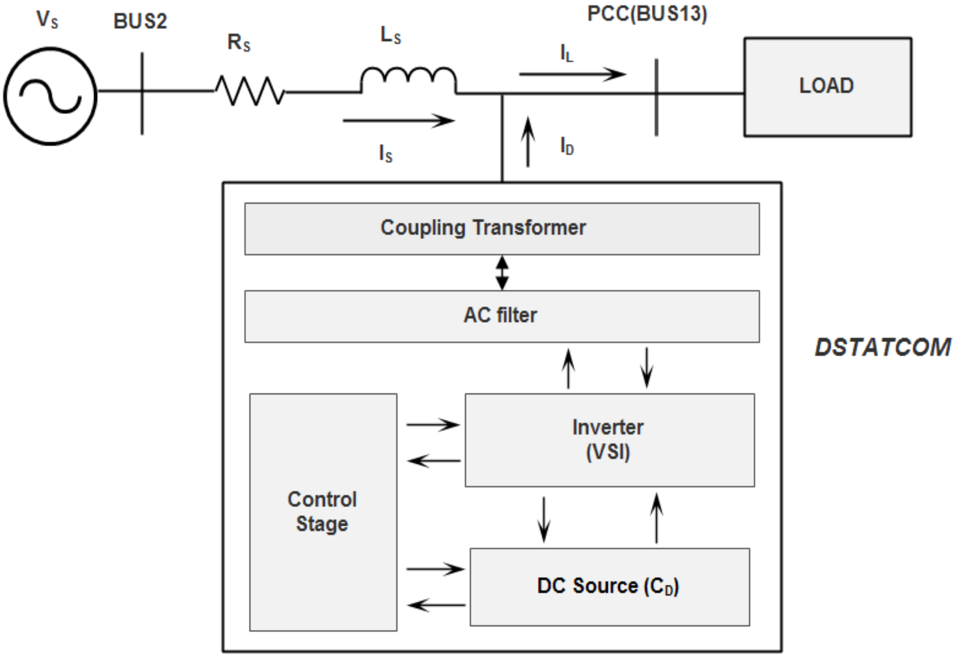


Figure 4.6: Diagram illustrating components of the DSTATCOM [2].

The Sim-Power Systems (SPS) software provides us with the required simplicity and relative analytical power to rapidly design of the DSTATCOM model example, which had been validated from Power Systems Testing and Simulation Laboratory of Hydro-Quebec, a utility lab situated in Canada [22]. The proposed design of DSTATCOM consists of following parts:

1- Proposed design of Power Circuit Components of DSTATCOM.
2- Proposed Control Circuit.

4.4.1 Proposed Design of Power Circuit Components of DSTATCOM

The power circuit of DSTATCOM contains the components on the AC side and DC side of DSTATCOM. The AC side parts are a coupling transformer, VSC inverter, a ripple filter and an interfacing AC inductor. DC side consists of a capacitor value, DC bus voltage. Since the inverter circuit revises DC power to AC power, three-phase IGBT with anti-paralleling diodes having turn-off fitness are used in the inverter circuits [2]. A voltage source inverter is energized by a capacitor at the input. Then the inverter is connected in parallel to the distribution line through interface filter (LC) and the coupling transformer as shown in Figure (4.6). The Power circuit of DSTATCOM consists of the following components:

1) Voltage Source Inverter and Transformer.
2) Interface Filter.
3) DC Link.

It is apparently seen in chapter 3 (section 7) that the harmonic orders of 6-pulse VSC are 5th, 7th, 11th, 13th… and so on, which makes the VSC impractical for power systems. A view to coping with this problem, increased pulse levels such as 12-pulse, 24-pulse, and 48-pulse are achieved by combining basic 6-pulse VSCs together.

The 12-pulse two-level converter with IGBT is used as a VSC in this work. It requires two 6-pulse converters connected in parallel over the single DC bus where they are serially attached to the transformer on the output side. In order to achieve an acceptable accuracy, the switching frequency used is 1.85 kHz (The IGBT modules switching frequencies in the range of 800 Hz-2 kHz [66 and 67]. The three single phases transformer (2.2/11KV) is used to connect the output of the converter to the PCC (bus13). The output voltage of the converter (V_{LL}) must be 2200V since it is connected to primary of the transformer. The output of the converter is achieved by [2]:

$$V_{LL} = \frac{\sqrt{3}V_{DC}}{\sqrt{2}} m \qquad (4.1)$$

m: modulation index and it is considered as 0.85

V_{DC}: the DC Bus Voltage

The lowest DC bus voltage of the VSC must be bigger than two times of the peak of the voltage on the grid (“Singh, B., Chandra, A. and Al-Haddad, K., 2014”), the DC bus voltage is calculated from (4.1) as:

$$V_{DC} = \frac{2\sqrt{2}V_{LL}}{\sqrt{3}m} \tag{4.2}$$

The modulation index is considered as 0.85 and V_{LL} the AC line output voltage of the DSTATCOM is 2200 V. The V_{DC} is obtained as 4226V.

The instantaneous energy accessible to the DSTATCOM during transients determines the amount of the DC capacitor (C_{DC}) of the voltage source convertor (Kumar, A. and Srivastava, S.K., 2015). The principle of energy supervision is applied as:

$$\frac{1}{2}C_{DC}(V_{DCmax}^2 - V_{DC\min}^2) = k_1 3V_{ph}aIt \tag{4.3}$$

Where V_{DCmax} is the DC voltage which is the same to the consultation DC voltage, and it is selected as 4500, and V_{DCmin} is the lowest voltage of the DC, *a* is the overloading factor (1.2), V_{ph} is the output voltage, I is the phase current,and diversity of energy during dynamics =10% (k_1= 0.1). The response time of DSTATCOM (*t*) is the time by which the DC voltage is to be recuperated. It is around 20 to 35 *ms* (Hingorani and Gyugyi, 2000). It is selected as *t*=20 *ms, which* is equal to one cycle.

Making the minimum voltage of the DC bus (V_{DCmin}) =4226V, V_{DCmax} = 4500 V, V_{ph} = 2200/√3 V.

If the converter losses are neglected, the current rating of the DSTATCOM corresponds to reactive power required for load voltage regulation is calculated from this equation:

$$Q_{DSTATCOM}(MVar) = \sqrt{3}V_t I_D \tag{4.4}$$

Where V_t is the desired load line voltage and I_D is the DSTATCOM line current. For the 10MVar, DSTATCOM in this work the V_t is 11kV in the HV side of the transformer while it is 2.2kV in LV side. From (4-4) the I_D is 2624 A.

Therefore, from (4.3) the C_{DC} is calculated as 20073 μF, and it is selected as 20 000 μF.

LC input filter is used to eliminate output switching harmonics of the converter and to enhance the voltage THD at PCC as it is mentioned in chapter 3(section 3.8). LC input filter has been designed with the 12-pulse two-level converter to eliminate harmonic (Giroux & Sybille, 2014). The value of C was selected as 100μF, and the inductance was calculated to equal 0.8 mH [68].

Finally, the proposed design of Power Circuit Components of DSTATCOM has been implemented on MATLAB/SIMULINK/Simscape, and Figure (4.7) shows these components.

4.4.2 Proposed Control Circuit

The proposed control algorithm in this study is the synchronous reference frame theory (Cristian A. Sepulveda et al...2013b) as mention in Chapter 3 (section 3.6). This control algorithm of the DSTATCOM control system for maintaining the desired PCC voltage is shown in Figure (4.8). From this figure, the proposed control circuit contains the following sub-circuits:

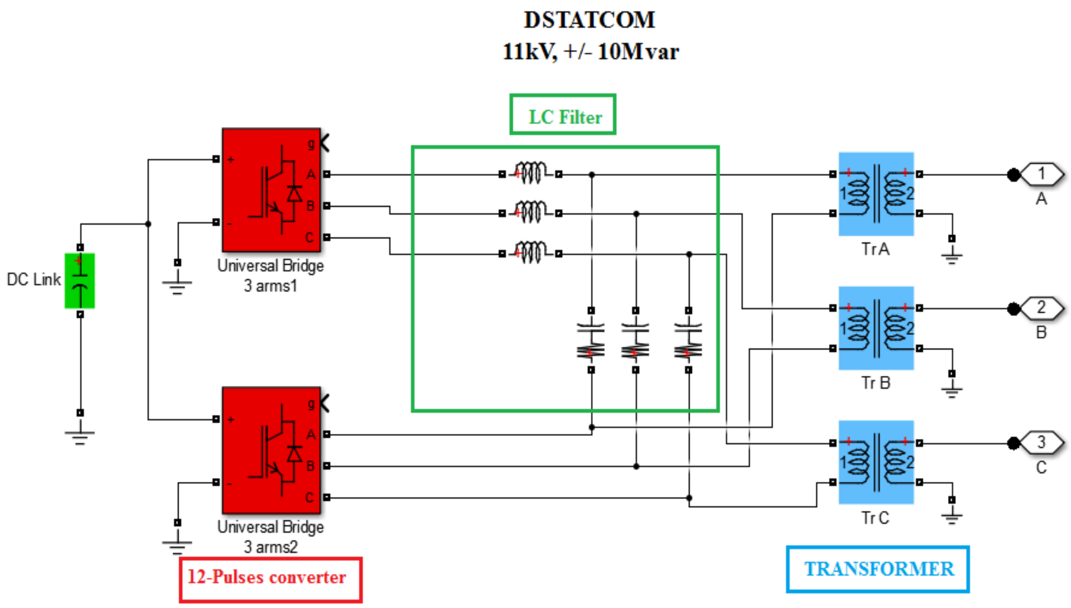


Figure 4.7: Power Circuit Components of (±10MVar) DSTATCOM on MATLAB/SIMULINK/ SIMSCAPE.

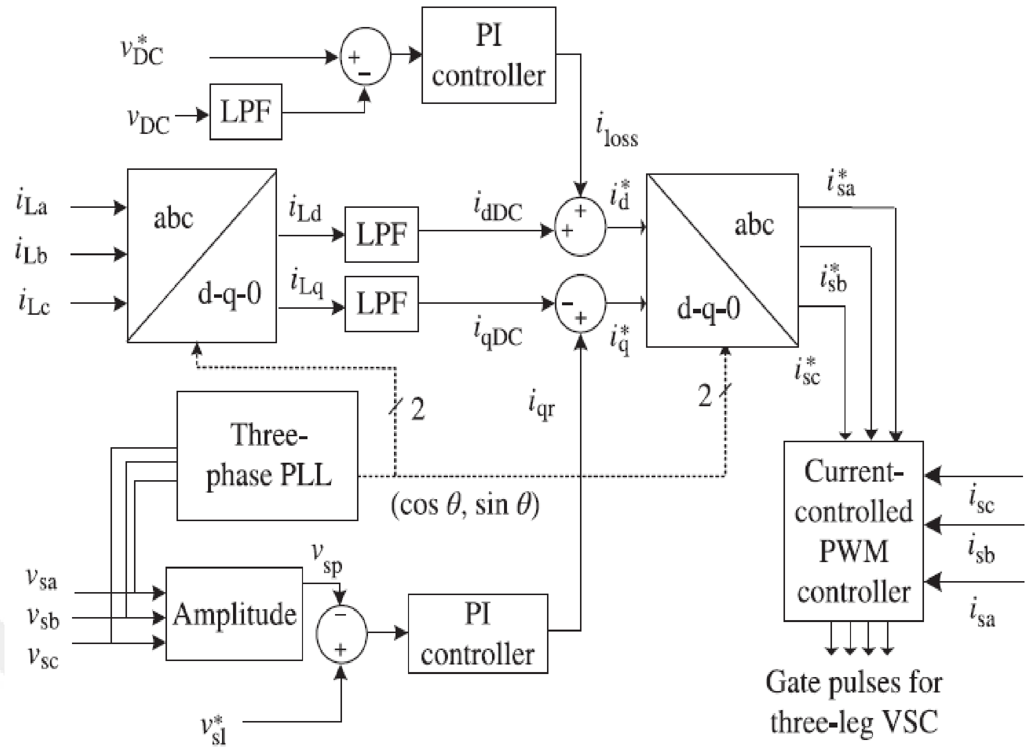


Figure 4.8: Block figure of SRF control system of D-STATCOMs [2].

1) Measurements Circuit.
2) Three-Phase PLL.
3) DC voltage Control Circuit.
4) AC Voltage Control Circuit.
5) Current Regulator.
6) PWM Generators.

The graph of the control algorithm shows that the load currents (i_{La}, i_{Lb}, i_{Lc}), PCC voltages (v_{sa}, v_{sb}, v_{sc}), and the DC voltage (V_{DC}) of the DSTATCOM are measured by measurements circuit and sensed as feedback signals.

A three-phase PLL (phase locked loop) is applied to synchronize these signals with the PCC voltages. With using the Park's transformation blocks, the load currents are modified to dq0 frame [2]. Then the d-q components are delivered to an LPF to remove the DC of i_{Ld} and i_{Lq}. These d-q components are also used in DC voltage and AC voltage control circuits [2].

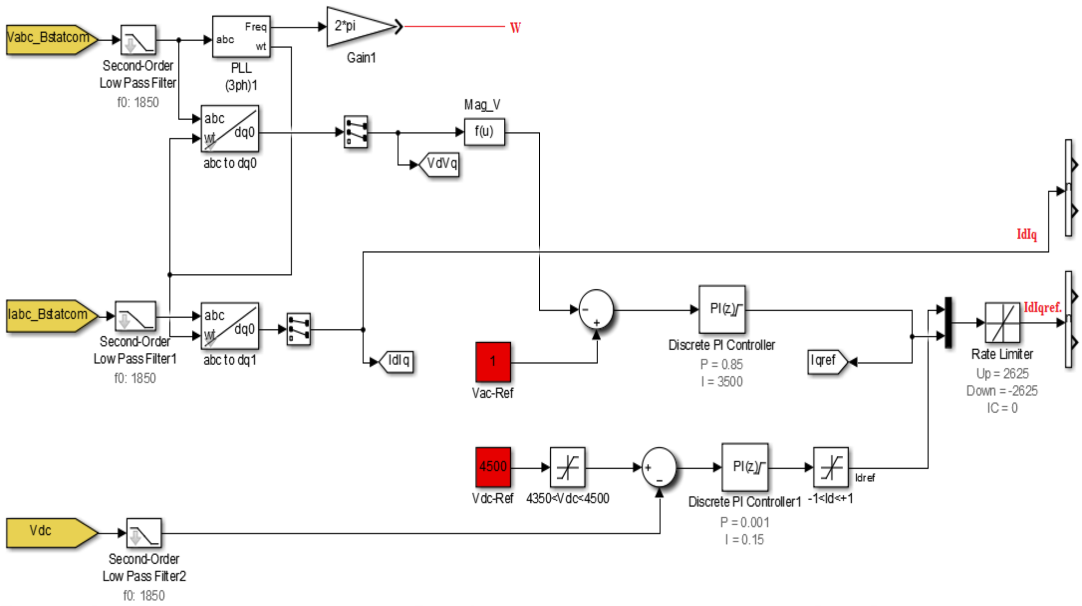


Figure 4.9: Block diagram of the measurements circuit, the three-phase PLL, DC voltage control circuit, and AC voltage control circuit.

The DC voltage control circuit is used to keep the DC voltage around its reference. This objective can be regulated indirectly by controlling i_{Ld}. This regulation is achieved by i_{d^*} signal. This signal is determined by comparing V_{DC} of the DC capacitor with V_{DC^*} reference. In proposed design, V^*_{DC} has been chosen as 4500V.

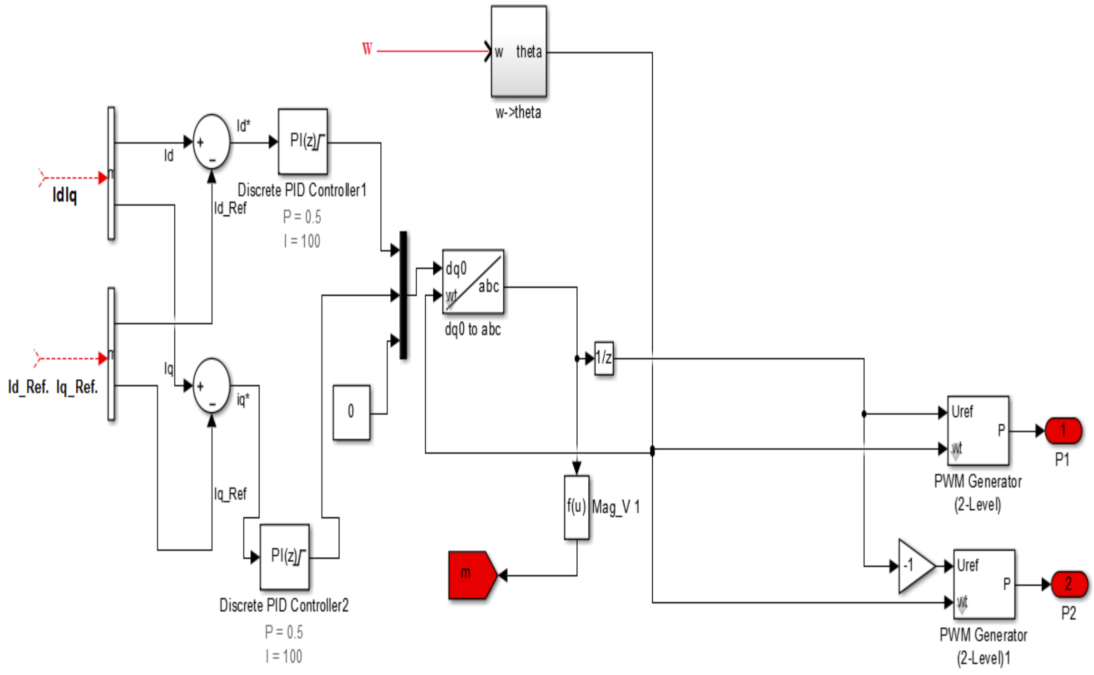


Figure 4.10: Block diagram of the current regulator and PWM generators.

The AC voltage control circuit is used to regulate the AC voltage at PCC. Regulation of AC voltage is achieved by controlling the reactive current. This objective can be accomplished by i_{q*} signal. This signal is generated by comparing the reactive current reference i_{qr} with the DC component i_{Lq}. The signal i_{qr} is determined by the difference between the voltage desired of the PCC and a reference voltage v^*_{s1}. The reference voltage has chosen as 1 p.u.

The two components i_{d*} and i_{q*} finally are used to control the PWM generators with the current regulator. Figure (4.9) shows the control blocks of the measurements circuit, the Three-Phase PLL, DC voltage control Circuit, and AC voltage control circuit. In addition, Figure (4.10) shows the blocks of the current regulator and PWM generators, which are implemented on MATLAB/SIMULINK.

Finally, the proposed parameters of the power circuit and control circuit for the DSTATCOM are presented in the Table (4-4).

Table 4.4: The proposed parameters of the DSTATCOM.

Parameters	*Value*
Converter	12-pulses two levels VSC
DC link voltage	4500V
DC capacitor	20000 μF
Switching frequency	1850 Hz
LC filter	0.8 mH and 100μF
Transformer	2.2/11 kV
AC Reference Voltage	11000 V (1 p.u)

CHAPTER FIVE

SIMULATION THE NETWORK WITH DSTATCOM AND RESULTS

5.1 Introduction

This chapter presents the application of the DSTATCOM with the proposed design control technique for power quality improvement in Iraqi distribution network. The 11 kV, ±10 Mvar, two-level, 12-pulses DSTATCOM designed in Chapter 4 has been tested in the grid at the location, which has been selected in the previous chapter at bus 13. The simulation and results are shown in this chapter.

For testing the system without and with the DSTATCOM and for investigating the DSTATCOM performance with different power quality problems, this chapter is organized as follows:

1. DSTATCOM for regulating the load voltage.
2. DSTATCOM for mitigating the voltage sag and swell.
3. DSTATCOM for mitigating the voltage unbalance.
4. DSTATCOM for compensating reactive power.

The single-line diagram of the system after installation DSTATCOM on bus13 is shown in Figure (5.1). Bus 2 is the distribution source (33KV) at sub-transmission station. This bus is represented by using an ideal voltage source and impedance. R_S and L_S represent the total resistance and inductance of the transmission line and the power transformer. The DSTATCOM is connected with bus13 as PCC. This system has been built on MATLAB/SIMULINK/Simscape, and Figure (5.2) presents the block diagrams of the system.

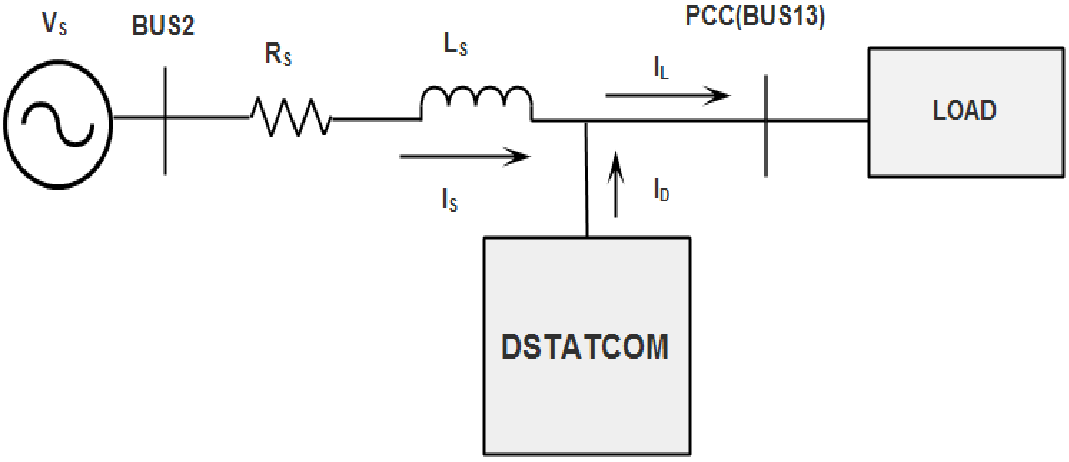


Figure 5.1: The single line diagram of the DSTATCOM with bus13.

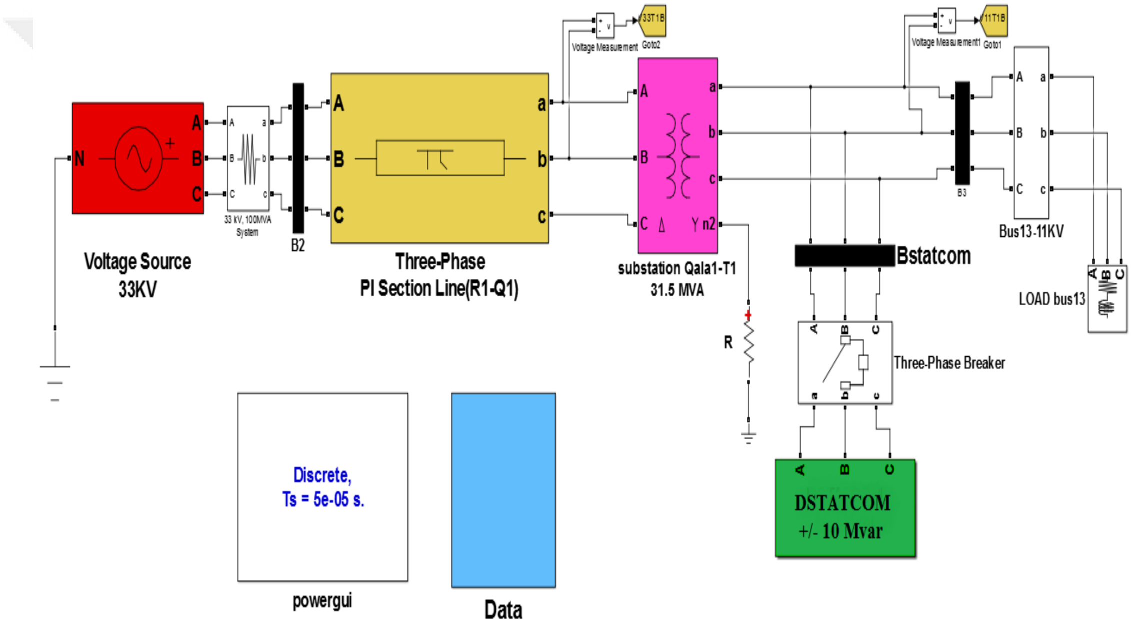


Figure 5.2: MATLAB/SIMULINK model of the distribution network with the DSTATCOM.

5.2 DSTATCOM for Regulating Voltage

This section is presented the simulation results for the DSTATCOM with the proposed controller design to regulate the load voltage at bus13 (11 kV). The simulation and effects are studied with different load power. The required reactive power for various load power also is shown in this section. In addition, the performance of the DSTATCOM is presented in detail.

The simulation results of the DSTATCOM with the proposed controller design are separated into three parts in this section:

1. Voltage regulation with unity power factor.
2. Voltage regulation with lagging and leading power factor load.
3. DSTATCOM's performance with voltage regulation mode.

5.2.1 Voltage Regulation With Unity Power Factor

This case explains the simulation of the system with time varying load conditions. The load is changed between two resistant loads at bus13, which represent the load in last summer, and the maximum load can be supplied by this bus. Figure (5.3) shows the source and load voltages of the system without DSTATCOM when the load is varied. As may be seen, the voltages characterize with two different load conditions. The load is 16.7 MW from t = 0.15 to 0.3 second and the load is 25 MW from t = 0.3 to 0.5 second. Meanwhile, figure (5.4) shows the voltages of the system with DSTATCOM when the load is varied. Furthermore, in this figure, the active and the reactive power generated or absorbed by DSTATCOM (P_D, Q_D) are presented.

Figure (5.3) shows the voltage of the bus 13 without DSTATCOM when the load is varied. As may be seen, the load voltage corresponds to two different voltage conditions 0.984 p.u and 0.963 p.u when the load is varied between 16.7 and 25 MW, respectively.

Compared without using DSTATCOM, it can be observed from (5.4), the DSTATCOM with proposed control design can be regulated the bus13 voltage at the 1 p.u when the load is 16.7MW. DSTATCOM also keeps the voltage at 1 p.u when the load is varying to 25MW. It can be noted that the load voltage waveform reaches the desired value within 0.03 second when the load is varied. In addition, this figure presents the active and the reactive power of the D-STATCOM for the system when the load is varied between 16.7 and 25 MW.

As may be seen, the active power absorbed is insignificant when the DSTATCOM compensates the load voltage. This means that the DSTATCOM consumes active power to regulate the DC voltage at the constant value. Whereas, the reactive powers absorbed are +2.1 and +4 Mvar to compensate the load voltage when the loads are 16.7 and 25 MW, respectively.

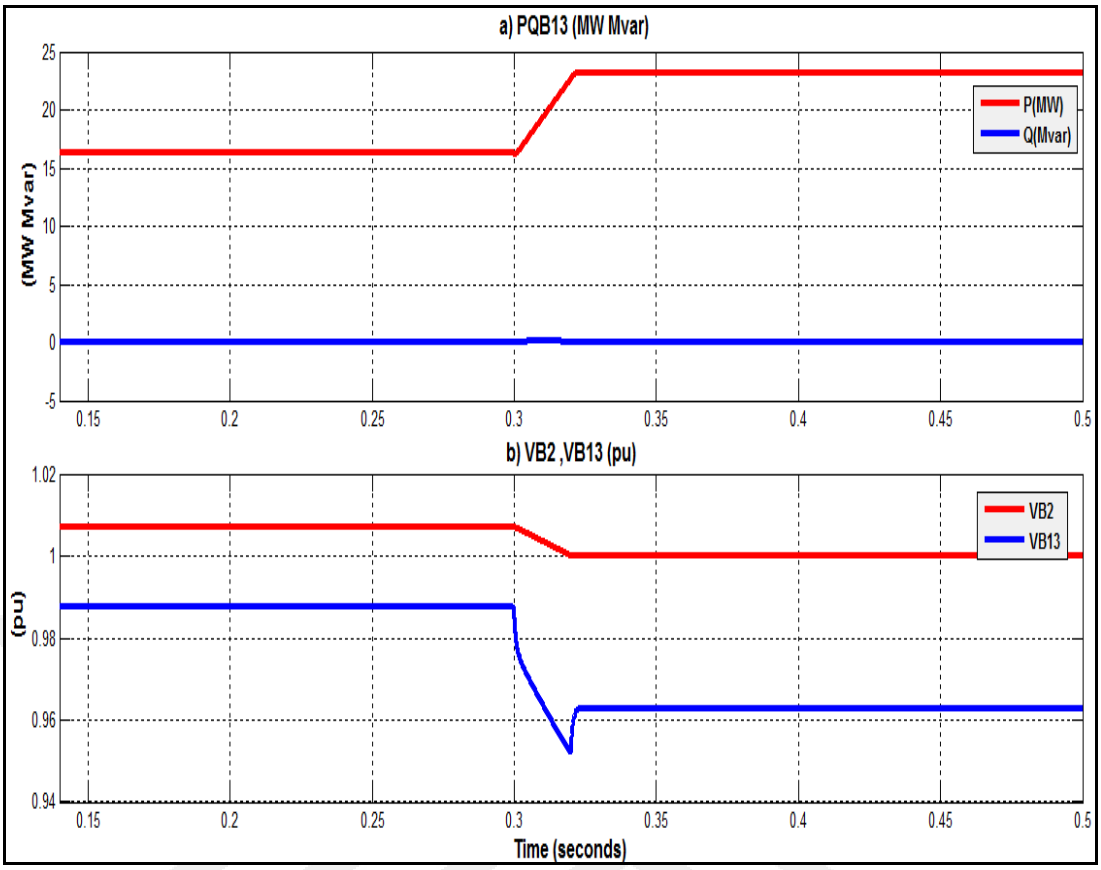


Figure 5.3: The voltages of bus2 and bus13 with varying between two resistant loads and without connecting DSTATCOM.

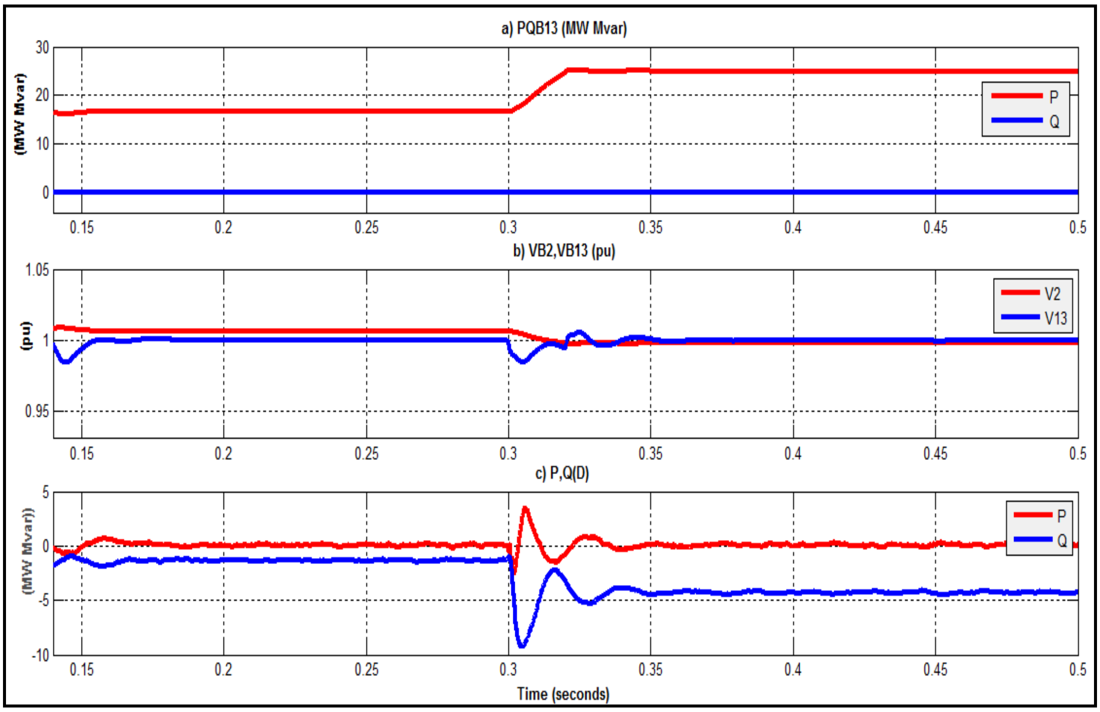


Figure 5.4: The voltages of Bus2 and Bus13, $P_{DSTATCOM}$, and $Q_{DSTATCOM}$ with varying between two resistant loads and with DSTATCOM.

5.2.2 Voltage Regulation With Lagging and Leading P.F Load

This case presents the simulation of the system with the load varying between an inductive and capacitive load. Figure (5.5) shows the source and load voltages of the system without DSTATCOM when the load is varied. The first load is 16.7 MW with 0.95 leading power factor from t = 0.1 to 0.3 seconds; then the load is changed from t = 0.3 to 0.6 seconds to the 16.7MW with 0.95 lagging power factor load. Finally, the load is changed to 25MW with 0.95 lagging power factor from 0.6 to 1 seconds. Meanwhile, figure (5.6) shows the voltages of the system with DSTATCOM when the load is varied with the same time ranges. Moreover, this figure shows the active and the reactive power generated or absorbed by DSTATCOM (P_D, Q_D).

In Figure (5.5), the voltage of the bus 13 without DSTATCOM when the load is varied. As may be seen, the load voltage corresponds to the three different voltage conditions 1.04, 0.94 and 0.8964 p.u when the load is varied between 16.7 MW with 0.95 leading P.F, 16.7MW with 0.95 lagging P.F, and 25MW with 0.95 lagging power factor, respectively.

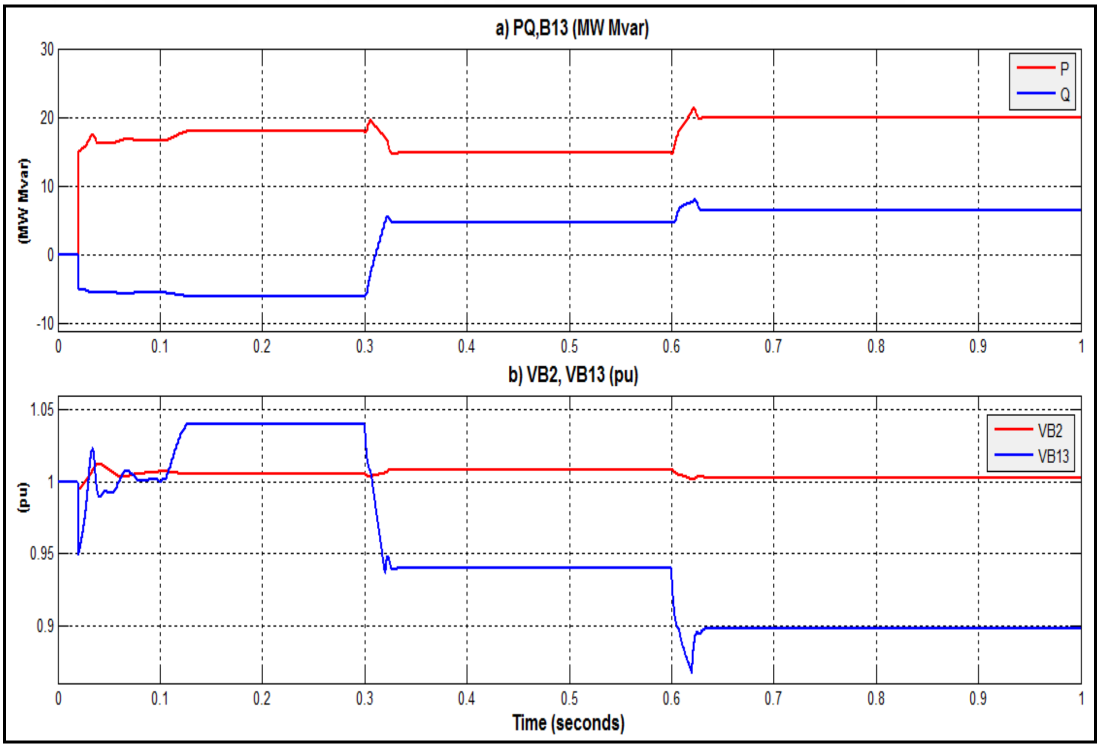


Figure 5.5: The load voltage (V_B13) with varying between an inductive and capacitive load and without DSTATCOM.

Compared without using DSTATCOM, it can be observed from (5.6), the DSTATCOM can be regulated the bus13 voltage at the 1 p.u and in the first two cases of the load. In addition, DSTATCOM keeps the voltage equal to 0.98 p.u when the load changed to 25MW with 0.95 power factor.

It can be noted that the load voltage waveform reaches the desired value within 0.03 seconds when the load is varied. Moreover, this figure presents the P and Q power of the DSTATCOM when the load is changed. As may be seen, the active power (P_D) absorbed in each case of the load is very low when the DSTATCOM compensates the voltage. This means that the DSTATCOM consumes active power to regulate the DC voltage at the constant value.

While a +10 Mvar reactive power is absorbed to offset the load voltage when the load is 25 MW with 0.95 lagging P.F. Whereas, the reactive power absorbed to make up the load voltage is - 4 Mvar when the load is 16.7 MW with 0.95 leading P.F and the reactive power absorbed is +7.5Mvar when the load equal to 16.7 MW with 0.95 lagging P.F whereas the reactive power is 10Mvar when the load is 25MW with 0.95 lag P.F.

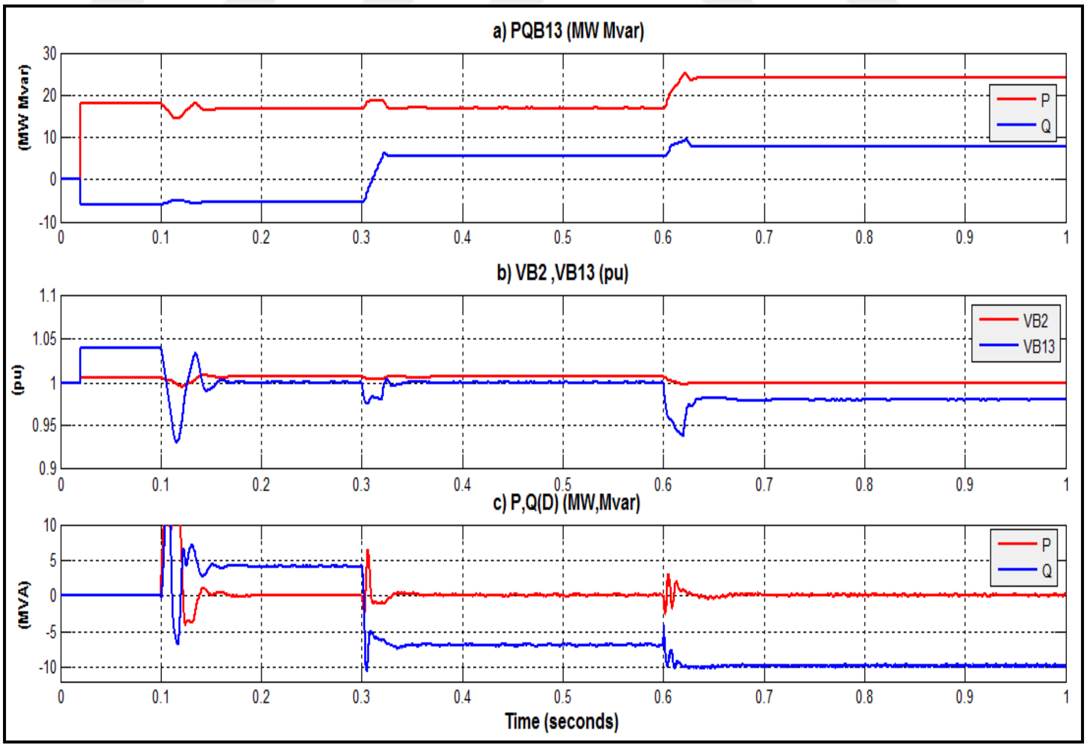


Figure 5.6: The load voltage (V-B13) with varying between an inductive and capacitive load and with DSTATCOM.

5.2.3 DSTATCOM’s Performance At Voltage Regulation Mode

The dynamic effectiveness of the DSTATCOM for regulating voltage mode is studied in this section. Performance indices are as the inverter voltage (Va), inverter current (Ia), modulation index, and the THD of the output voltage of the inverter before and after the filter. The simulation and test are presented with two types of linear loads. The indices are shown under no load, an inductive and a capacitive load mode. The system starts with no load from t=0 s then a 16.7MW, the 5.49Mvar inductive load is switched at t=0.1 s. Finally, the load is varying from the inductive to a capacitive at t = 0.3 s.

Figure (5.7) shows the waveforms of the inverter voltage (Va) and the inverter current (Ia). After a short period of 0.15 sec, the steady state is reached. In the beginning, there is on load so that the DSTATCOM is not active and it does not produce or absorb any reactive power from the network. Therefore, the voltage of the inverter is set as 1 p.u, and the current is zero. When time t= 0.1s, the inductive load with Q=+5.49Mvar is connected to the bus13. The DSTATCOM absorbs reactive power for maintaining 1 p.u voltage by injecting leading reactive current to the PCC (bus13) so that the inverter current (Ia) increases. At t=0.3 s, the load is changed to the capacitive load with Q= -5.49 Mvar. The DSTATCOM decompensates by producing an inductive reactive power Q to the network. Therefore, the inverter current is reversed very fast from the leading to the lagging current, approximately in 0.03 s.

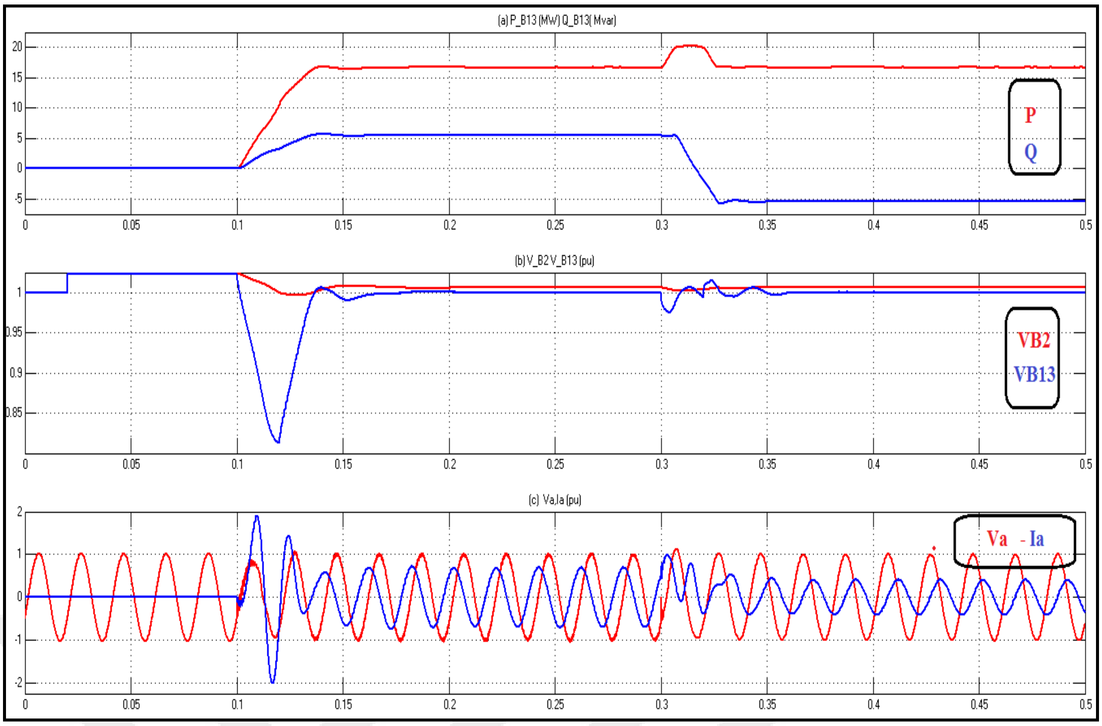


Figure 5.7: The inverter voltage (Va) and the inverter current (Ia) with inductive and capacitive modes of operation.

In Figure (5.8), we can also see the modulation index of the PWM inverter. It is changing with two the different methods of operation to a proportionate increase or decrease in the voltage of the inverter. PWM inverter's modulation index is 0.55 when the DSTATCOM in the capacitive mode. While in the inductive mode, the modulation index decreases to 0.3 to reduce the output voltage of the DSTATCOM and maintain the PCC voltage.

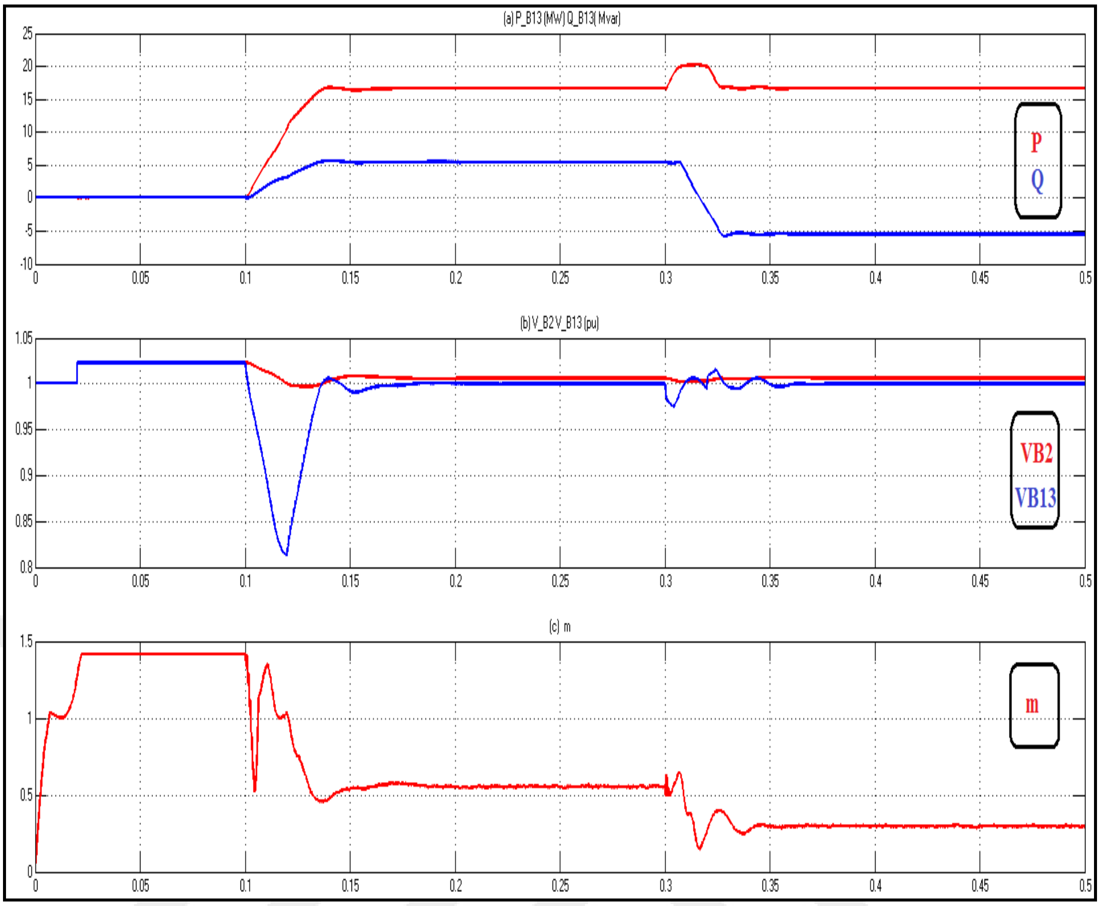


Figure 5.8: PWM inverter's modulation index with inductive and capacitive modes of operation.

Figure (5.9) and (5.10) show the THD of the output voltage and current of the inverter after the filter. THD is calculated by using FFT Analysis Tool box in MATLAB to perform Fourier analysis of simulation data signals and the THD at PCC for the voltage and current are equal to 3.68 % and 1.58 % respectively. The IEEE 519-1992 limits the THD at a 2kV level lower than 5 %. It is clearly that the proposed filter has kept the THD at PCC less than 5 %. Finally, it is clearly to see the satisfactory performance of DSTATCOM for regulating the voltage of bus13 with the capacitive and inductive modes. In addition, DSTATCOM keeps bus13 to operate with different loads and avoids it the operation with over-voltage and under-voltage. Moreover, it is very fast changes from the capacitive to inductive mode, approximately in 0.03 s. In summary, Table (5-1) reviews the operation of bus13 without and with connecting the DSTATCOM and with different loads.

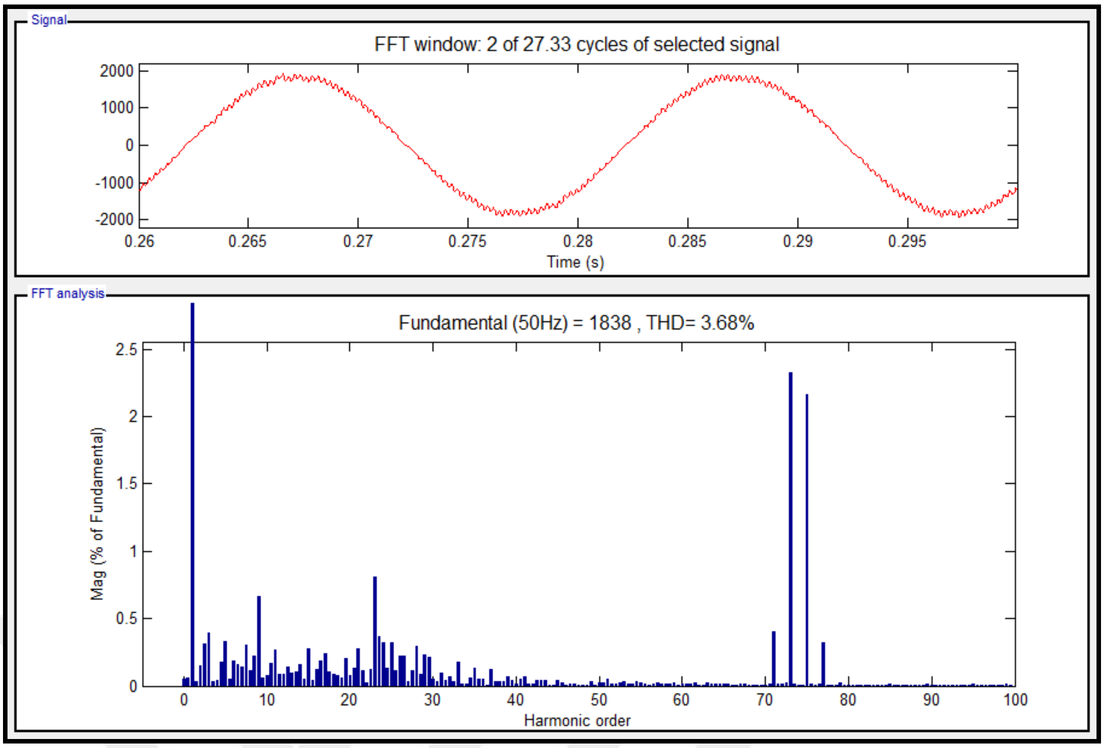


Figure 5.9: The THD of the output voltage.

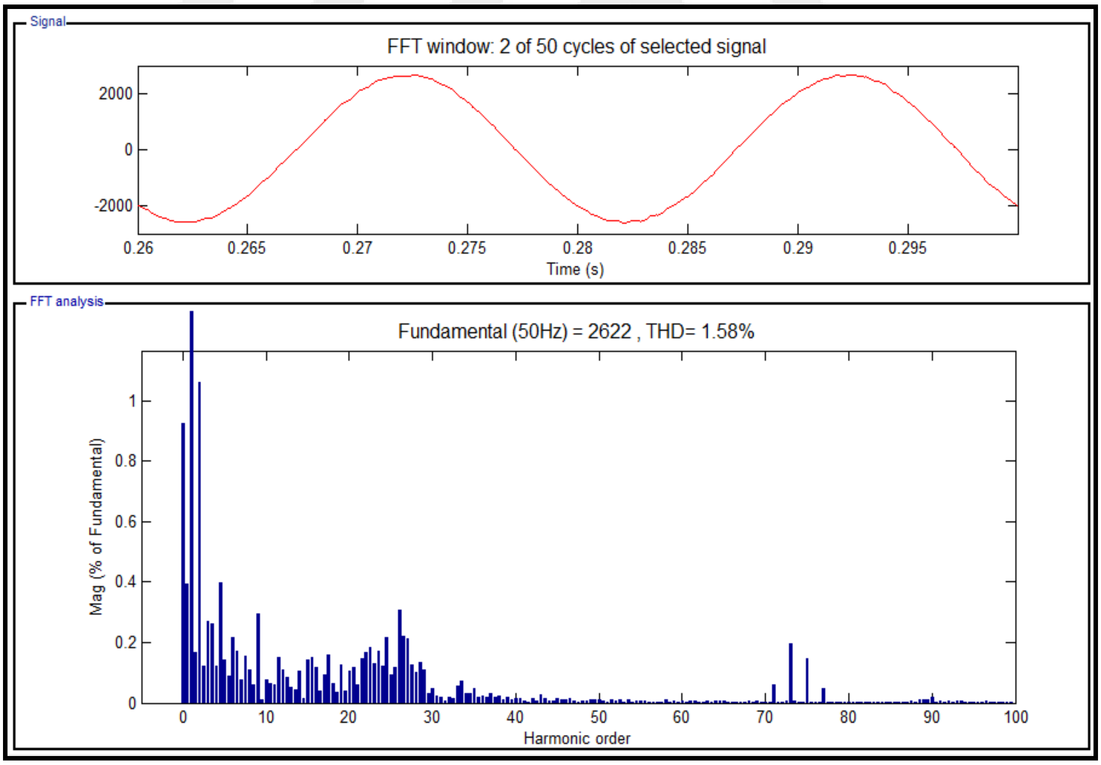


Figure 5.10: The THD of the output current.

Table 5.1: The amplitude voltages of bus13 without and with attaching the DSTATCOM.

Bus's Load		*Bus's Voltage (p.u)*	
MW	*Mvar*	*Without DSTATCOM*	*With DSTATCOM*
16.7	0	0.98	1
16.7	-5.49	1.04	1
16.7	+5.49	0.94	1
25	0	0.96	1
25	+8.2	0.89	0.98

5.3 DSTATCOM For Mitigating The Voltage Sag and Swell

In this section, the simulation has been completed to study the voltage sag and swell in the network. Depending on definitions of the sag and swell, the voltage sag is a reduction of r.m.s voltage for short duration to an extent stuck between 0.1 and 0.9 p.u. While the voltage swell, is a short period phenomenon of rise in r.m.s voltage and the voltage level is between 1.1 and 1.8 p.u and period of the event varieties from half cycles to 3 minute. The simulation is presented in the two cases.

The first case is the voltage sag; in this case, the system is simulated with decreasing in the amplitudes of the voltage source 33KV (bus2 in Figure 5.1) lower than 0.9 p.u and with duration 0.1 s. At 0.2s of the simulation the amplitude of the voltage source decreases to 0.7 p.u for 0.1s, then the second sag with 0.8 p.u amplitude accusers at 0.4 and with time duration 0.1s. Figures (5.11) and (5.12) demonstrate the voltage waveform of bus13 without and with DSTATCOM and Table (5-2) presents the voltage sag values of bus 13 with and without the installation DSTATCOM.

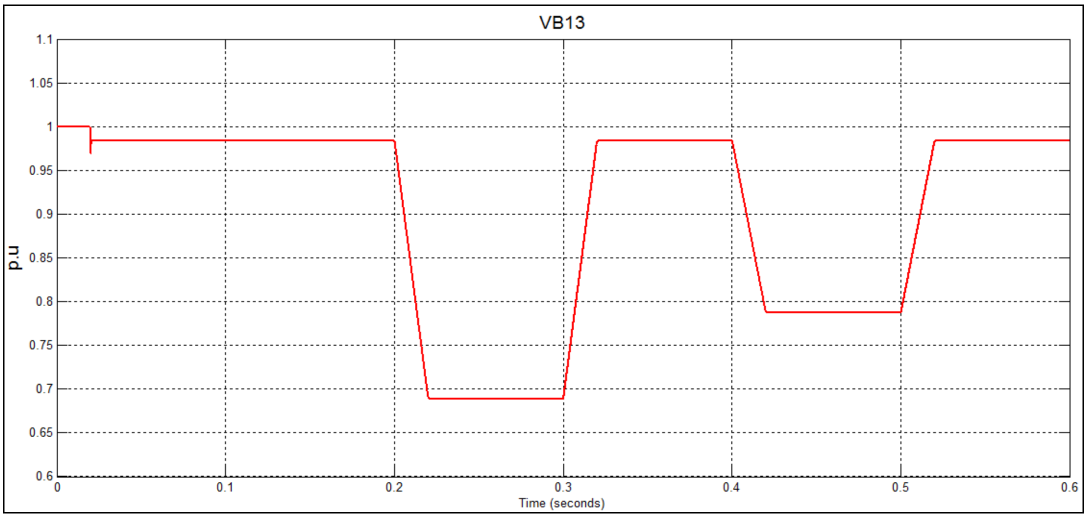


Figure 5.11: Voltage (r.m.s) waveform of bus13 through sag and without installation DSTATCOM.

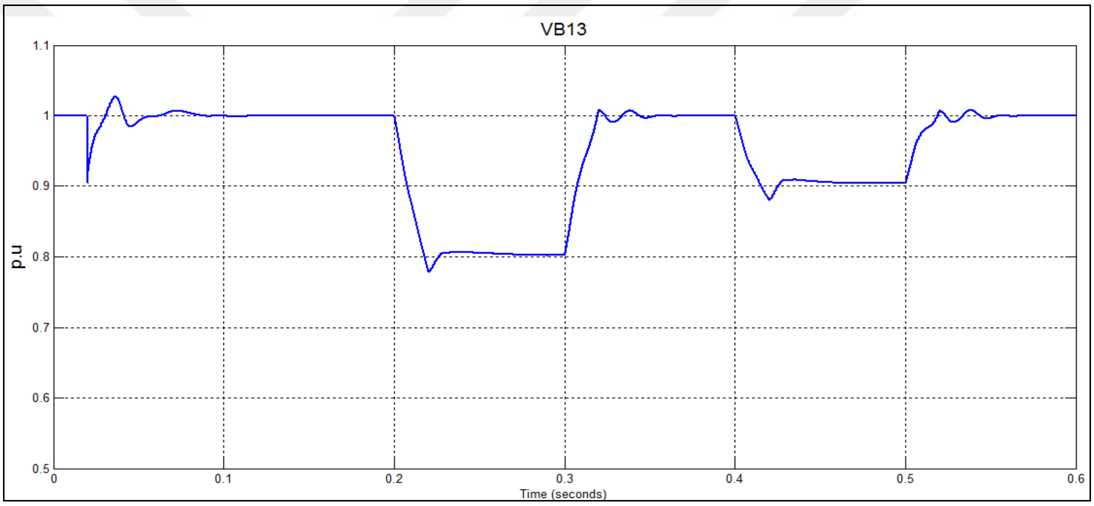


Figure 5.12: Voltage (r.m.s) waveform of bus13 through sag and with installation DSTATCOM.

Table 5.2: Voltage at bus 13 for voltage sag without and With DSTATCOM.

Voltage source (p.u)	*Bus13 voltage Without DSTATCOM (p.u)*	*Bus13 voltage With DSTATCOM (p.u)*
0.7	0.68	0.81
0.8	0.78	0.92

Secondly, in the voltage swell case, the system is simulated with increasing in the amplitudes of the voltage source 33KV (bus2) more than 1.1 p.u and with duration 0.1 s. At 0.2s of the simulation the amplitude of the voltage source increases to 1.3 p.u for 0.1s, then the second swell with 1.2 p.u amplitude accusers at 0.4 and with time duration 0.1s. Figures (5.13) and (5.14) clarify the voltage waveform of bus13 without and with DSTATCOM. Table (5-3) presents the voltage swell values of bus 13 with and without the installation DSTATCOM.

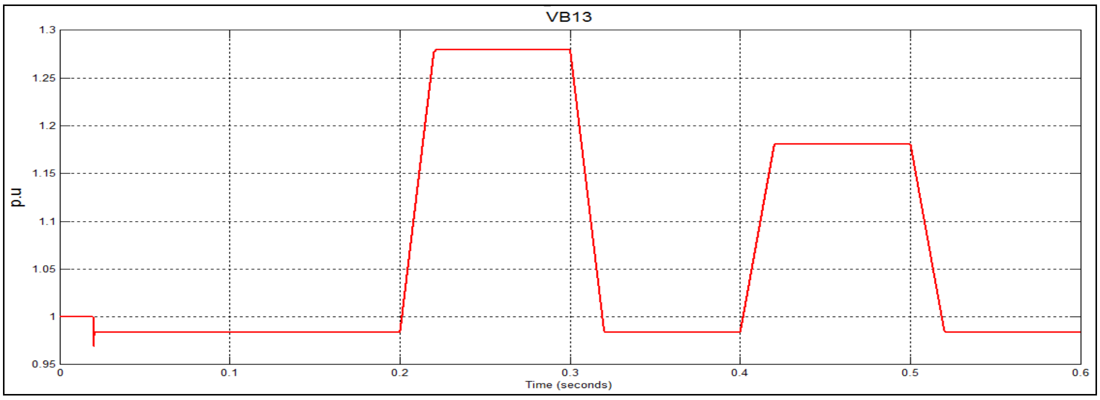


Figure 5.13: Voltage (r.m.s) of bus13 with swell and without installation DSTATCOM.

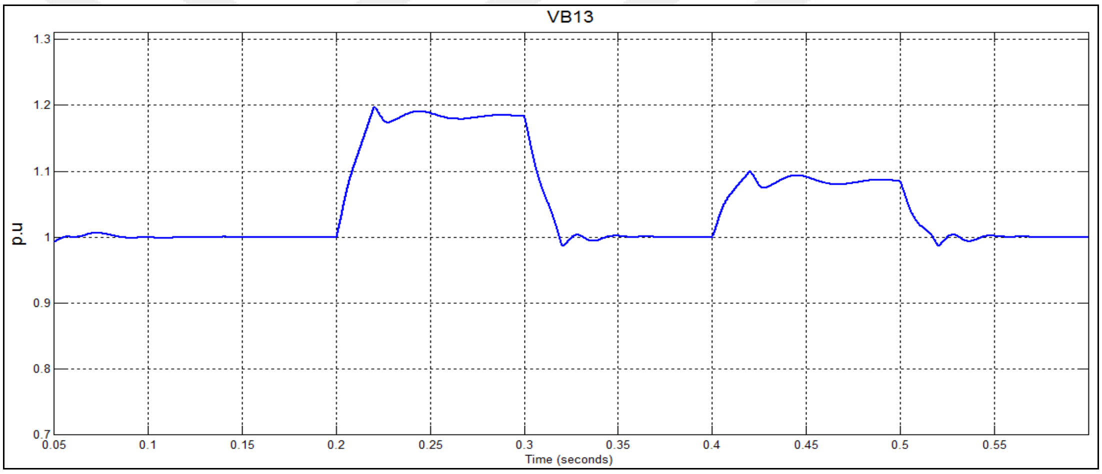


Figure 5.14: Voltage (r.m.s) waveform of bus13 through swell and with installation DSTATCOM.

Table 5.3: Voltage at bus 13 for voltage swell without and With DSTATCOM.

Voltage source (p.u)	*Bus13 voltage Without DSTATCOM (p.u)*	*Bus13 voltage With DSTATCOM (p.u)*
1.3	1.28	1.17
1.2	1.18	1.07

Finally, from the results above, the Figure (5.12), and Table (5-2), it is noticeable that the proposed design of DSTATCOM can mitigate the terminal voltage of bus13 when the voltage dip is equal or less than 0.8 p.u. Whilst, the

DSTATCOM can improve the voltage approval, but it is not in the acceptable region (IEEE Std. 1159-1995). In addition, from the Figure (5.14) and Table (5-3), the DSTATCOM mitigates the voltage at bus13 when the voltage swell is equal or less than 1.2 p.u and it can enhance the voltage when the swell is equal or less than that, but it is not in the acceptable region (IEEE Std. 1159-1995). This illustrates the DSTACTCOM's size should be bigger than the selected size if it is installed to improve the voltage with extremely sagging and swell for injecting or generating more reactive power.

5.4 DSTATCOM for Mitigating the Voltage Unbalance

This section presents the simulation and results of the DSTATCOM with the proposed controller design to mitigate the voltage unbalance at bus13. Since the unbalance refers to the variation in amount of voltage or current of any 1 or 2 of the three phases, the simulation and effects are studied with two worst cases of unbalance in load at bus 13.

Case1, an unbalance load has one-phase unbalance load is connected to the bus 13. The 10 MW loads on phases A and B are attached while there is not load connected to phase C. The system is tested without and with connected DSTATCOM. Figure (5-15) shows the waveforms of the three-phase voltages of bus13 without connected DSTATCOM and with DSTATCOM. While, Figure (5.16) presents the sequence components of Vbus13 in the two conditions.

Case2, an unbalance load has three-phase unbalance load is connected to the bus 13. The 10 MW loads on phase A, 5 MW loads on phase B and 2.5 MW load on phases C are attached. The system is experienced without and with coupled DSTATCOM. Figure (5-17) shows the waveforms of the three-phase voltages of bus13 in the two conditions. While, Figure (5.18) presents the sequence components of Vbus13 without and with coupled DSTATCOM.

For presenting, how DSTATCOM improves the voltage unbalance in the system, Table (5.4) shows the peak amplitude of the three-phase voltages (p.u) without and with coupled the DSTATCOM, and Table (5.5) presents the amplitude of the sequence components of bus13 voltage without and with coupled the DSTATCOM. In addition, Table (5.5) contents UF, which is calculated by using equation (2.2) in chapter two (section 2.4.1). It can be seen from Table (5.4); the

DSTATCOM improves the voltage unbalance in the two cases of the simulation and keeps them between the maximum and minimum range. In addition, it can be noted from Table (5.5), the DSTATCOM improves the sequence components in the two cases of the simulation and the unbalance factor is reduced to less or equal 2%.

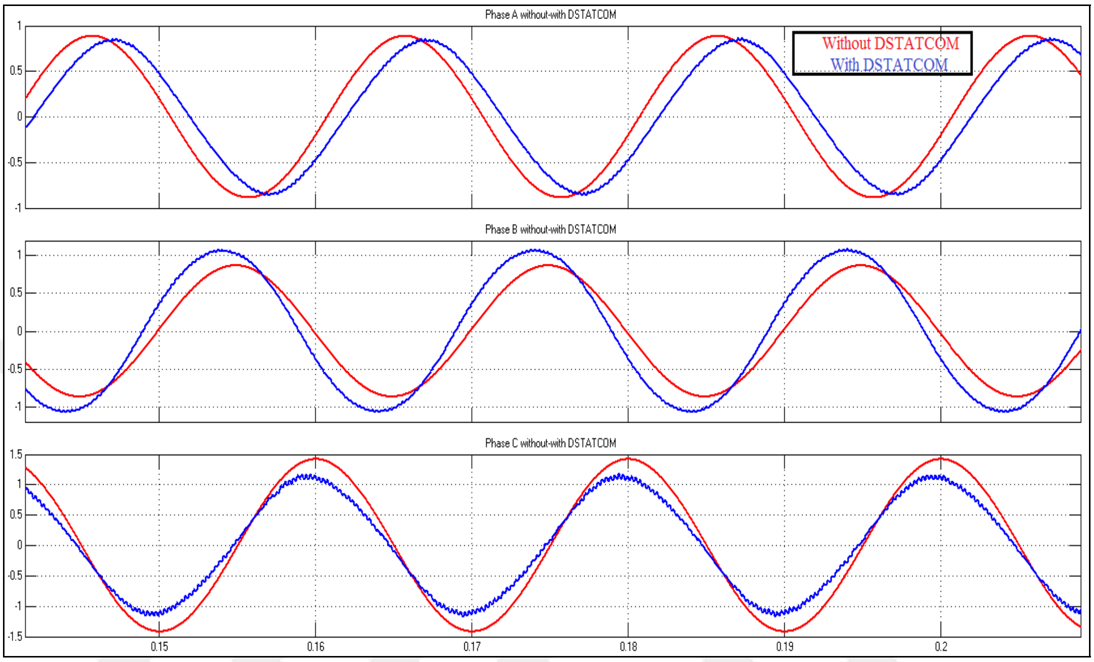


Figure 5.15: Phase voltage (p.u) waveforms of bus13 at two-phase unbalance load, without, and with installation DSTATCOM.

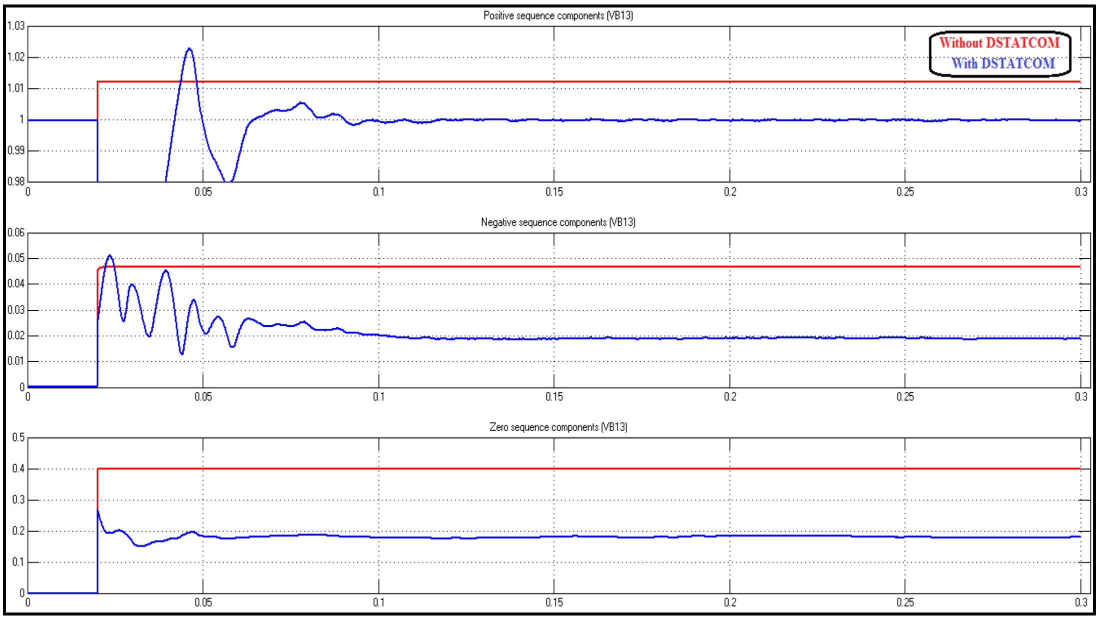


Figure 5.16: The sequence components of bus13 (p.u) at two -phase unbalance load, without, and with installation DSTATCOM.

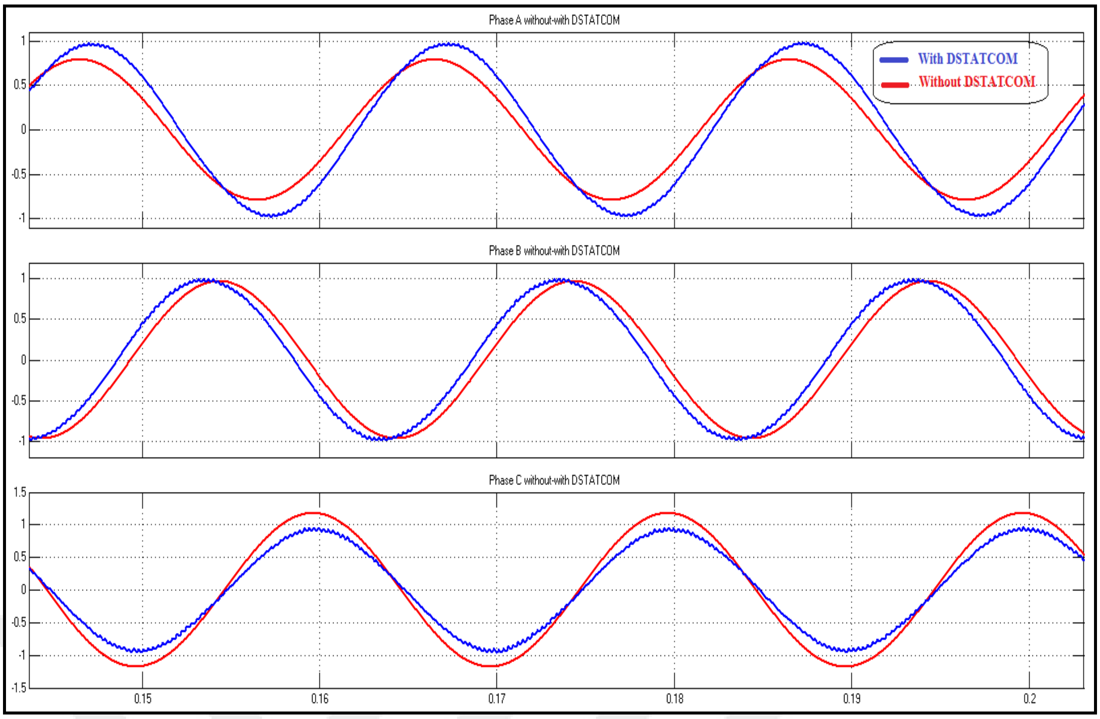


Figure 5.17: Phase voltage (p.u) waveforms of bus13 at three phase unbalance loads, without, and with installation DSTATCOM.

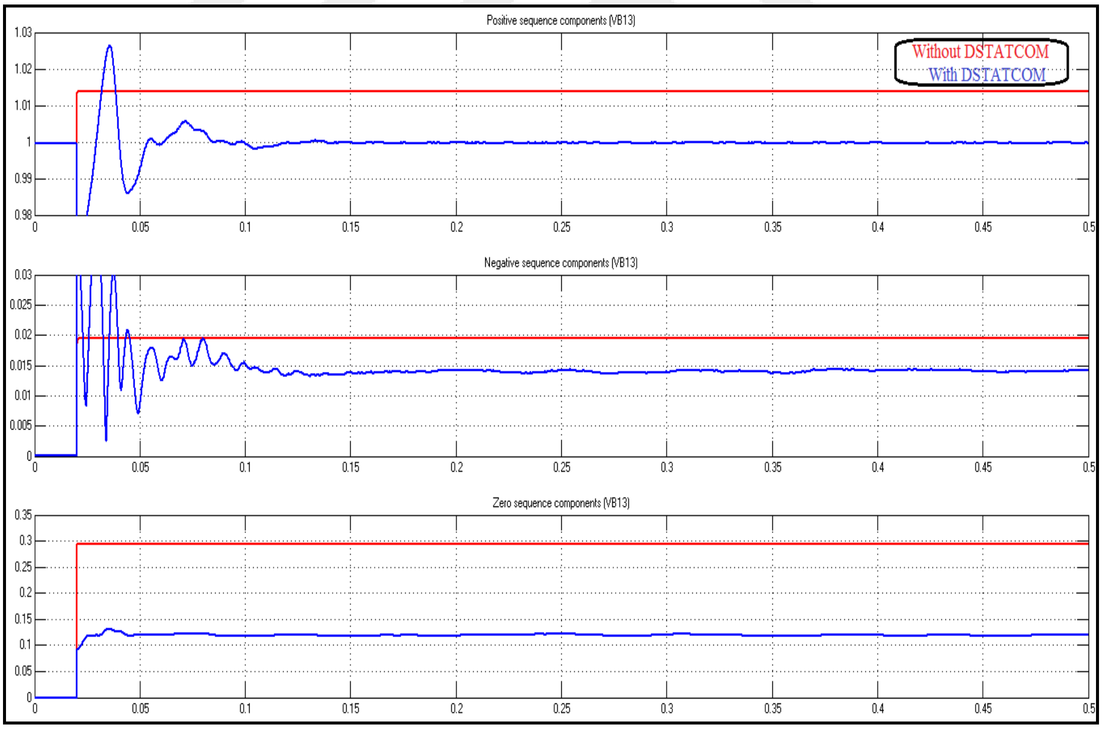


Figure 5.18: The sequence components of bus13 (p.u) at three-phase unbalance loads, without, and with installation DSTATCOM.

Table 5.4: The amplitude voltages of unbalance loads without and with connected the DSTATCOM.

Phases' Load (MW)			*Voltages (p.u)*			
A	B	C		A	B	C
10	10	0	Without DSTATCOM	0.9	0.87	1.42
			With DSTATCOM	0.92	1.05	1.1
10	5	2.5	Without DSTATCOM	0.75	1.08	1.26
			With DSTATCOM	0.93	1.07	1

Table 5.5: The Sequence components (VB13) of unbalance loads and UF without and with connected the DSTATCOM.

Phases' Load (MW)			*Voltage Sequence components (p.u)*				
A	B	C		Positive sequence	Negative sequence	Zero sequence	UF (%)
10	10	0	Without DSTATCOM	1.015	0.046	0.4	4.5
			With DSTATCOM	1	0.019	0.18	1.9
10	5	2.5	Without DSTATCOM	1.014	0.02	0.3	2
			With DSTATCOM	1	0.014	0.12	1.4

5.4 DSTATCOM For Compensating The Reactive Power

This section presents the operation of the proposed DSTATCOM for reactive power compensation and improving the power factor of the power consumption. The power factor of the source is studied with DSTATCOM and without DSTATCOM in the section. From Figure (5.1) DSTATCOM compensates reactive power at Bus13 as PCC, and the power consumption is delivered from Bus2 (33KV) so that the power factor on Bus2 should be explained without and with installation DSTATCOM. The system is simulated for a total time of 0.6 seconds, and the results are complemented with various load conditions.

Inductive and capacitive loads with different power factor are used to test the system. Figure (5.19) displays the operation of the DSTATCOM for the reactive power compensation and power factor correction of Bus2. In this Figure, the load on Bus13, power factor of Bus2 and the reactive power of DSTATCOM are presented respectively.

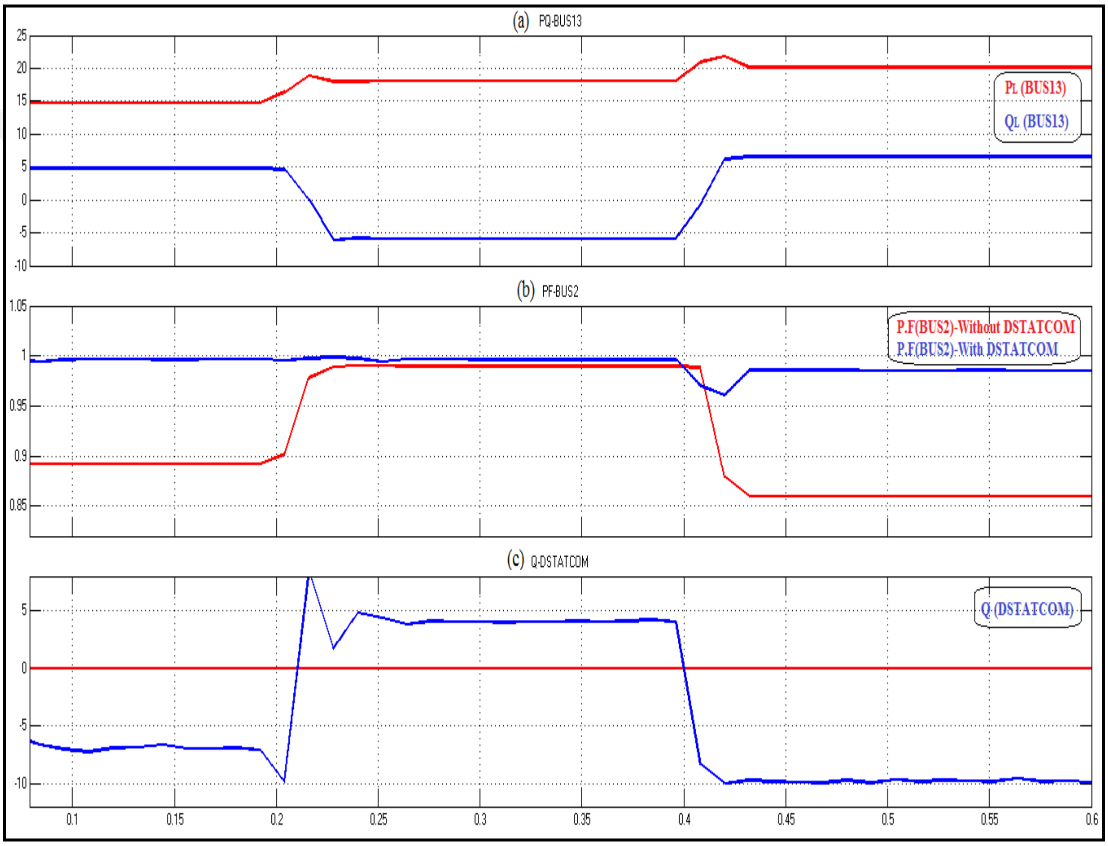


Figure 5.19: (a) The load on bus13, (b) power factor of Bus2, and (c) the reactive power of DSTATCOM with different loads.

In the beginning, the load demands active power (16.7MW) and reactive power (+5.49 Mvar) are switched from 0.1 to 0.2 seconds. From Figure (5.19b), the power factor of the Bus2 without connecting DSTATCOM is 0.892 at the time of 0.1 to 0.2 seconds while it is 0.996 with DSTATCOM. In addition, from the Figure (5.19c) the DSTATCOM operated in capacitive mode and absorbed (-7.4Mvar) reactive power. Secondly, the load of Bus13 is varied to 16.7MW and -5.49Mvar during the time interval of 0.2 to 0.4 seconds (Figure 5.19a). From Figure (5.19b), the power factor of the Bus2 without connecting DSTATCOM is 0.99 whereas it is 0.996 with DSTATCOM and from the Figure (5.19c) the DSTATCOM operates in inductive mode and generates (+4Mvar) reactive power.

In the final period from 0.4 to 0.6 seconds, the load is changed to the maximum load can be supplied by Bus13 which is 25MW and +8.2Mvar. In this time, the power factor is 0.85 before connecting DSTATCOM, whilst it is 0.98 after connecting DSTATCOM, and it can be seen clearly in Figure (5.19b). From Figure (5.19c), it is evident that DSTATCOM operated in full inductive mode and absorbed (-10Mvar) reactive power.

Table (5-6) summarizes the DSTATCOM's performance for correcting the power factor of the system. From this table and the results above, it can be concluded that the DSTATCOM improve the power factor of Bus2 with different load demands and keep it almost near unity power factor. Moreover, it means DSTATCOM decreases the power losses in the transmission line and increases the capacity power transport by compensating the reactive power supplied from the source.

Table 5.6: The power factor of the system without and with connected the DSTATCOM.

Load at Bus13		Power Factor of Source (Bus2)	
MW	*Mvar*	*Without DSTATCOM*	*With DSTATCOM*
16.7	+5.49	0.89	0.996
16.7	-5.49	0.99	0.996
25	+8.2	0.85	0.98

CHAPTER SIX

CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

This thesis has investigated and simulated one of the modern power electronics devices Distributed Static Compensator for improvement power quality. The performance of proposed DSTATCOM has been tested in a part from the Iraqi distribution power system. The appropriate location for testing DSTATCOM has been chosen in one of the distribution substations (33/11KV). The size of DSTATCOM is calculated by using the voltage - reactive power curve, and the synchronous reference frame theory is used as a control algorithm of the D-STATCOM, which can use for maintaining the desired PCC voltage and correcting power factor. A ±10 Mvar/11KV DSTATCOM is implemented and simulated in MATLAB/ SIMULINK using SIMPOWER SYSTEM TOOLBOX program.

The results indicate that using DSTATCOM with the synchronous reference frame theory as a control algorithm improves power quality such as voltage regulation, voltage unbalances, voltage sag, voltage swell, and power factor correction. Moreover, the results demonstrate how the installation of DSTATCOM in the system can increase the capability of power transmit and decrease the transmission losses.

Below is a summary of the most important conclusions for improving different power quality problems, which have studied in this work by using DSTATCOM:

6.1.1 Voltage Regulation

It is clearly to see the satisfactory performance of DSTATCOM for regulating the voltage with the capacitive and inductive modes. Also, DSTATCOM keeps the system to operate with different loads and avoids it the operation with over-voltage and under-voltage. Moreover, it is very fast changes from the capacitive to inductive mode, approximately in 0.03 s and Table (5-1) reviews the operation of the system without and with connecting the DSTATCOM and with different loads.

6.1.2 Mitigation of Voltage Sag and Swell

From the results, the Figure (5.13), and Table (5-2), it is noticeable that the proposed design of DSTATCOM can mitigate the terminal voltage of bus13 when the voltage dip is equal or greater than 0.8 (p.u). Whilst, the DSTATCOM can improve the voltage approval, but it is not in the acceptable region (IEEE Std. 1159-1995). In addition, from the Figure (5.14) and Table (5-3), the DSTATCOM mitigates the voltage at bus13 when the voltage swell is equal or less than 1.2 p.u and it can enhance the voltage when the swell is greater than that, but it is not in the acceptable region (IEEE Std. 1159-1995). This illustrates the DSTACTCOM's size should be clearly optimized if it is installed to improve the voltage with extremely sagging and swell for injecting or generating more reactive power.

6.1.3 Voltage Unbalances

For presenting, how DSTATCOM improves the voltage unbalance in the system. Figures (5.15), (5.17) and Table (5.4) present the three-phase voltages without and with coupled the DSTATCOM. It can be seen; the DSTATCOM improves the voltage unbalance in the three worst cases of the unbalance could be happened in the distribution network and the simulation shows that the DSTATCOM keeps them between the maximum and minimum ranges of overvoltage and under voltage. Also, Figures (5.16), (5.18) and Table (5.5) show that the DSTATCOM improves the sequence components in the two cases of the simulation and the unbalance factor is reduced to less or equal 2%.

6.1.4 Reactive Power Compensation

Table (5-6) summarizes the DSTATCOM's performance for correcting the power factor of the system. From this table and the results above, it can be concluded that the DSTATCOM improves the power factor of Bus2 with different load demands and keeps it almost near unity power factor. Moreover, it means DSTATCOM decreases the power losses in the transmission line and increases the capacity power transport by compensating the reactive power supplied from the source.

6.2 Future Works

The research presented in this thesis has investigated in detail analysis, choosing the suitable design and simulation one of the power electronics modern devices (DSTATCOM) for improvement power quality in Iraqi power system especially in the distribution network. Distributed Static Compensators are well established in the literature and market. However, some topics still need further investigation and analysis. The recommendations for the future works can be summarized as follows:

1. Designing a Transformer-less DSTATCOM by using a multi-level converter, which is cascaded, by designing a control system, which reduces harmonic elimination with multilevel inverters.
2. The cost estimation of reactive power compensation by using the DSTATCOM in distribution power system could be demonstrated. In addition, the cost estimation for voltage sag and swell mitigation, unbalance, power factor correction and energy loss reduction could be undertaken, and the results will show the benefit of implementing of the DSTATCOM depends on the size of the DSTATCOM.
3. Comparison using SRF theory with another advanced control methods like Current synchronous detection (CSD) method. CSD is used for the estimation of reference supply currents and implemented this controller with DSTATCOM can mitigate unbalance factor and decrease natural current, especially in four wire distribution system.

REFERENCES

1. Çetin and D. of E. and E. E. Ph.D., "Design and Implementation Of a Voltage Source Converter Based STATCOM for Reactive Power Compensation and Harmonic Filtering," Middle East Technical University, 2007, pp. 2-72.

2. Anadol MA, Aydin M, Yalcinoz T (2013). "A real-time extraction of active and reactive current using microcontrollers for a multiples STATCOM". Turk J Electr Eng Comput Sci 21 (4):1044–1060.

3. Angelo Baggini, "Handbook of power quality". Italy, University of Bergamo, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester. pp. 36-51, 1992.

4. Angelo Baggini, "Handbook of power quality". Italy, University of Bergamo, John Wiley & Sons Ltd, The Atrium, Southern Gate, Chichester. pp. 36-51, 2008.

5. Aydin, B., "Voltage security assessment using P-V and Q-V curves", Master's thesis, Department of Electrical and Electronic Eng., Bahcesehir University, Istanbul, Turkey, 2008.

6. Singh, A. Chandra, and K. Al-Haddad, "Power Quality: Problems and Mitigation Techniques". École de Technologies Supérieure, Canada: 2015 John Wiley and Sons Ltd, pp. 1-120.

7. Badru H. Chowdhury and Carson W.Taylor, "Voltage Stability Analysis - V-Q Power Flow Simulation versus Dynamic Simulation," IEEE Trans. On Power Systems, Vol.15, No.4, Nov. 2000, pp. 1354-1359.

8. Bartak G. "Evaluation of Responses to the 2nd Questionnaire / Power Quality-Service Level Report". Nº 2004-030-0703, Nov. 2004, pp. 2-10.

9. Beres, R.N., Wang, X., Blaabjerg, F., Liserre, M. and Bak, C.L. "Optimal design of high-order passive-damped filters for grid-connected applications". IEEE Transactions on Power Electronics, 31(3), 2016, pp.2083-2098.

10. Bhaladhare, Snehal B., A. S. Telang, and Prashant P. Bedekar. "PV QV Curve-A Novel Approach for Voltage Stability Analysis." NCIPET (2013).

11. Chattopadhyay, Surajit, Madhuchhanda Mitra, and Samarjit Sengupta. "Electric power quality." Springer Dordrecht Heidelberg London, 2011, pp. 12-39.

12. Chattopadhyay, Surajit, Madhuchhanda Mitra, and Samarjit Sengupta. "Electric power quality." Springer Dordrecht Heidelberg London, 2011, pp. 12-39.

13. Colak Ilhami, Kabalci Ersan, Bayindir Ramazan (2011) "Review of multilevel voltage source inverter topologies and control schemes". Energy Convers Manage 52(2): pp.1114–1128.

14. M. N. Rehan Abidi, "ANALYSIS OF A D-STATCOM IN A 25 KV," International Journal of Electrical and Electronics Research, Vol. 2, Issue2, pp.: (26-34), Month: April - June 2014.

15. EN 61000-4-30. EMC, Part 4. "Testing and measurement techniques: Power Quality measurement methods".2003.

16. European standard EN-50160, "Voltage characteristics of electricity supplied by public distribution systems", CENELEC, Brussels, Belgium, 2007.

17. Flores-Arias, J.M., Domingo-Perez, F., Moreno-Munoz, A., De, J.J.G., Rosa, L. and Pallares, V., 2013. "Voltage Dips Test System According to IEC 61000-4-11". International Journal of Computer and Electrical Engineering, Vol. 5, No. 1, p.115.

18. G.F.Reed, et.al, "Application of a 5MVA, 4.16kV D-STATCOM System for Voltage Flicker Compensation at Seattle Iron & Metals", IEEE Pow. Eng. Soc. Summer Meet. vol. 3, pp. 1605-1611, July 2000.

19. G.F.Reed, et.al, “Application of a 5MVA, 4.16kV D-STATCOM System for Voltage Flicker Compensation at Seattle Iron & Metals”, IEEE Pow. Eng. Soc. Summer Meet. vol. 3, pp. 1605-1611, July 2000.

20. General Directorate of Electricity Distribution of the South of Iraq, “Annual Statistical Report” 2015 Operation and Control. Iraq/ Basra.

21. Gultekin B, Gerçek CO, Atalik T, Deniz M, Biçer N, Ermis M, Kose KN, Ermis C, Koç E,Çadirci I, Açik A, Akkaya Y, Toygar H, Bideci S (2012) “Design and implementation of a 154-kV ± 50-Mvar transmission STATCOM based on 21-level cascaded multilevel converter”. IEEE Trans Ind Appl 48(3): pp. 1030–1045.

22. Gupta, A.R., and Kumar, A. “Impact of D-STATCOM Placement on Improving the Reactive Loading Capability of Unbalanced Radial Distribution System”. Procedia Technology, 25, 2016, pp.759-766.

23. H. Enrique, A. Soley, H. E. Rojas-cubides, A. S. Cruz-bernal, and H. D. Rojas-cubides, “Analysis of voltage sag compensation in distribution systems using a multilevel DSTATCOM in ATP / EMTP". Vol. 82, no 192, pp. 26–36. 2015.

24. H. H. Kajihara, “Quality power for electronics”, Electro- Technology, vol. 82, no. 5, November 1968, p. 46.

25. HE Abdel Aleem, S., T Elmathana, M. and F Zobaa, A. “Different design approaches of shunt passive harmonic filters based on IEEE Std. 519-1992 and IEEE Std. 18-2002”. Recent Patents on Electrical & Electronic Engineering (Formerly Recent Patents on Electrical Engineering), 2013, 6(1), pp.68-75.

26. Engineering, “Improvement of Power-Quality by using a Voltage-Controlled DSTATCOM,” Int. J. Adv. Res. Elect. Electron. Instrum. Eng., vol. 4, no. 10, pp. 8091–8096, 2015.

27. IEC Std. 61000-4-15, “Flicker meter-functional and design characteristics”, IEC, Geneva, Switzerland, 1997, pp. 2-15.

28. IEEE/CIGRE Joint Task Force on Stability Terms and Definitions, “Definition and Classification of Power System Stability”, IEEE Trans. on Power Syst., Vol. 19, No. 2, pp. 1387-1400, May 2004.

29. K. Fujii, K. Kunomura, K. Yoshida, A. Suzuki, S. Konishi, M. Daiguji, K.Baba, “STATCOM Applying Flat-Packaged IGBTs Connected In Series”,IEEE Transactions on Power Electronics, vol.20, No.5. pp. 1125-1132, 2005.

30. K. Zare, M. T. Hagh, and E. Naderi, “Determination of the performance of the distribution static compensator (D-STATCOM) in distribution network,” 22nd Int. Conf. Exhibit. Electr. Distrib. (CIRED 2013), no. January, pp. 1147–1147, 2013.

31. L. Pattathurani, R. K. Dwibedi, and P. Sivachidambaranathan, “A Voltage Controlled Dstatcom for Power Quality Improvement”. IOSR J. Elect. Electron. Eng. Ver. I, vol. 10, Issue 6 Ver. I (Nov – Dec. 2015), PP 27-34.

32. Lauttamus P, Tuusa H (2011) “Model-based cascade control of three-level STATCOM with a tuned LCL-filter”. In: Twenty-sixth annual IEEE applied power electronics conference and exposition (APEC), 6–11 Mar 2011, pp. 1569–1575.

33. Luo FL, Ye H, Rashid M (2005). “Digital power electronics and applications”. Elsevier, USA, ISBN: 0-1208-8757-6.

34. M. H. J. Bollen, “UNDERSTANDING POWER QUALITY PROBLEMS”, New York: A JOHNWILEY & SONS, INC., PUBLICATION, 2000, pp. 2-25.

35. M. Kullan, R. Muthu, and J. B. Mervin, “Design of DSTATCOM Controller for Compensating Unbalances,” Scientific Research Publishing. July, pp. 2262–2272, 2016.

36. M. M. De Oliveira, “Power Electronics for Mitigation of Voltage Sags and Improved Control of AC Power Systems,” Royal Institute of Technology, 2000, pp.13-74.

37. M. Singh and J. Kaur, “Role of DSTATCOM in Distribution Network,” Int. J. Adv. Res. Elect. Instrumentation Engineering, vol. 4, no. 7, pp. 6307–6315, 2015.

38. M. T. Bina, M. D. Eskandari, and M. Panahlou, “Design and installation of a 250 Kvar D-STATCOM for a distribution substation,” Electric Power Systems Research 73, vol. 73, no. 3, pp. 383–391, 2005.

39. Mathur RM, Varma RK (2002). “Thyristor-based facts controllers for electrical transmission systems”. Wiley-IEEE Press, Hoboken, ISBN: 978-0-471-20643-9.

40. Ministry of Electricity /IRAQ, “The Third Qualitative Fair of Electricity,” in Investment towards Energy Integration in Iraq, 2016, p. 35.

41. Ministry of Electricity/Operation and Control. Iraq, “Annual Statistical Report,” Iraq/Baghdad, 2012.

42. Ministry of Electricity/Operation and Control. IRAQ, “Annual Statistical Report,” Baghdad, 2015.

43. MUREŞAN, Călin, et al. "Application for Implementing the p-q Theory in a Three Phase System." vectors 18.20 (2015): 23-27.

44. Nayak, N., Wadhwani, A.K. and WADHWANI, D.S., 2014. “Software Implementation in Load Flow Analysis by Newton-Raphson Technique using MATLAB”.

45. Okou FA, Dupuis D, Akhrif O, Tarbouchi M (2009) “A robust nonlinear controller for a Statcom based on a 3-phase neutral point clamped converter”. In: 35th Annual conference of IEEE industrial electronics, pp. 3623–3630.

46. P. Antonio Moreno-Muñoz, Á. de Electrónica, U. de Córdoba, and C. de Rabanales, “Power Quality Mitigation Technologies in a Distributed Environment”. Córdoba Spain, pp. 6-14, 2015.

47. Padiyar KR. “Analysis of subsynchronous resonance in power system”. Kluwer Academic Publisher, USA.1999.

48. Ping T, Xianggen Y, Zhe Z.“Topology analysis of the output filter in D-STATCOM and its parameters multi-objective optimal design”. In: International conference on advanced power system automation and protection, 16–20 Oct 2011, vol 2, pp. 998–1002.

49. R. Grünbaum, T. Johansson, U. Olsson ‘‘Energy and Environmental Savings in Steel Making By Means Of SVC Light ’, www.abb.com.

50. Raimondo, Giuliano. “Power quality improvements in 25 kV 50 Hz railways substation based on chopper controlled impedances”. Diss. Institut National Polytechnique de Toulouse-INPT; Seconda Universita degli Studi di Napoli, 2012.

51. Republic Of Iraq/ Ministry Of Electricity/ “Iraq Electricity Master Plan- Final Report”. Hague, Volume 1. Iraq, Baghdad, 2010, pp. 46.

52. S&C ELECTRIC COMPANY, 2007. [Online]. Available: https://www.sandc.com/en/products--services/products/purewave-dstatcom-distributed-static-compensator/.

53. S. By and T. Vishnoi, ‘Managing Reactive Power Using Cascaded Multilevel D -STATCOM in Sub- Transmission / 11kV Distribution System’ M.SC.Department of Electrical Engineering Delhi Technological University,” Delhi Technological University, 2011, pp.4.

54. S. G. S, “Multilevel Inverter Based Dstatcom for Compensation of Reactive Power and Harmonics,” pp. 11–15, 2015.

55. S. Nithin and A. Kulshrestha, “Enhanced Designing of Five-Level Inverter based DSTATCOM using Fuzzy Logic,” vol. 3, no. 5, pp. 48–51, 2016.

56. S. R. S, N. Shobana, and K. R. Vairamani, “Mitigation of Power Quality Problems Using Custom Power Device (DSTATCOM),” vol. 6, no. 6, pp. 7650–7653, 2016.

57. Saadat, H., 2015. “Power System Analysis”. Tata McGraw Hill Publishing Company, New Delhi, 2002, pp. 195-212.

58. Sabin, D.D. and Bollen, M.H., 2015, May. “Overview of IEEE std. 1564-2014 guide for voltage sag indices”. 2015 IEEE 23th International Conference on Electricity Distribution (Paper 0253).

59. Saif Rashid. “Electricity Problem in Iraq”, HCU- Hamburg: Economics and Planning of Technical Urban Infrastructure Systems. https://www.academia.edu/1952306/Electricity, 2012, pp. 6-12.

60. Shahnia, F., Rajakaruna, S. and Ghosh, A. eds., 2015. “Static Compensators (STATCOMs) in Power Systems”. Springer, PP 5-18.

61. Singh B, Srinivas KV (2009). "Three-level 12-pulse STATCOM with constant DC link voltage". In: Annual IEEE India conference (INDICON), 18–20 Dec 2009, pp. 1–4.

62. Somsai, K.; Kulworawanichpong, T.; Voraphonpiput, N. "Effects of Maximum Loading Ability and Minimum Voltage Source on Voltage Regulation by Using D-STATCOM", Accepted to be published by The International Review on Modelling and Simulations. 2011, Vol 4, No. 5. pp. 2410-2416.

63. Sulaiman, M. and Nor, A.F.M. "PV and QV Curves Approach for Voltage Instability Analysis on Mesh-Type Electrical Power Networks Using DIgSILENT" 2015, (Vol. 3, No. 6, pp. 36-42). MAGNT Research Report.

64. Wang C, Yin X, Wen M, Jian L, Xiong Q, Zhang B. "Structure and parameters design of output LC filter in D-STATCOM". In: International conference on power system technology (POWERCON). 2010, pp. 1–6.

65. Wang, Y., Xiao, X.Y. and Bollen, M.H., 2016, October. "Challenges in the calculation methods of point-on-wave characteristics for voltage dips". In Harmonics and Quality of Power (ICHQP), 2016 17th International Conference on (pp. 513-517). IEEE.

66. Ward, DJ. "Power quality and the security of electricity supply". Proceedings of the IEEE 2001; 89(12): pp. 1830–1836.

67. Xia Zhenglong, Shi Liping, Yang Xiaodong "Parameters design and control strategy of cascade STATCOM based on LCL filter". Int. J Control Autom 7(1): 2014, pp.307–320.

68. Y. Xu, Z. Y. Dong, and K. P. Wong, "Static Compensators (STATCOMs) in Power Systems", Springer S. Perth Australia, 2015, pp. 5-324.

APPENDICES

Appendix-A: Clarke and Park Transformations

A-1 Introduction.

Clarke and Park's transformations are used in high-performance architectures in three phase power system analysis. Current and voltage are represented in terms of space vector which is represented in a stationary reference frame.A general rotating reference frame has then been introduced. This frame is described by d and q axes Clarke. Through the use of the Clarke transformation, the real and imaginary currents can be identified.

A-2 Clarke and Park transformation Matrices.

The voltage and current in a power system can be converted to a stationary reference frame and to a rotating reference frame using Clarke transformation and Park transformation respectively. Inverse Clarke and inverse Park transforms can restore Original signals. A block diagram in Figure (A.1) shows the transformation between R-Y-B, Clarke plane and Park plane.

The transformations can be summarized in general form as:

$$\begin{bmatrix}\alpha\\ \beta\end{bmatrix} = \left[Clarke.Matrix\right]\times\begin{bmatrix}R\\ Y\\ B\end{bmatrix} \tag{A-1}$$

$$\begin{bmatrix}d\\ q\end{bmatrix} = \left[Park.Matrix\right]\times\begin{bmatrix}\alpha\\ \beta\end{bmatrix} \tag{A-2}$$

$$\begin{bmatrix}d\\ q\end{bmatrix} = \left[Park.Matrix\right]\times\left[Clarke.Matrix\right]\times\begin{bmatrix}R\\ Y\\ B\end{bmatrix} \tag{A-3}$$

Where,

$$\left[Clarke.Matrix\right] = \frac{2}{3}\times\begin{bmatrix}1 & -\frac{1}{2} & -\frac{1}{2}\\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2}\end{bmatrix} \tag{A-4}$$

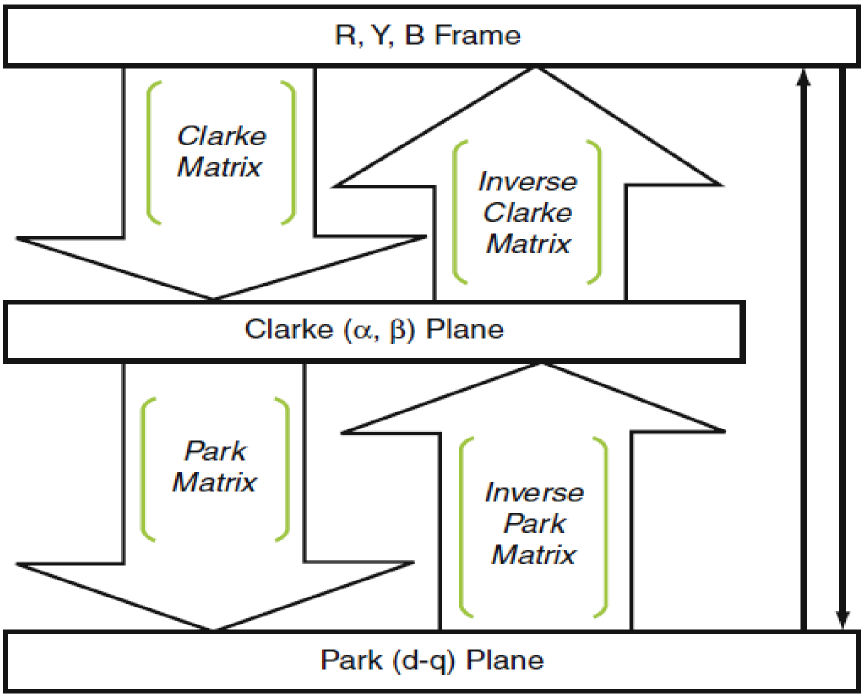


Figure A.1: Transformation of reference frame.

$$\left[Park.Matrix\right]=\begin{bmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{bmatrix} \tag{A-5}$$

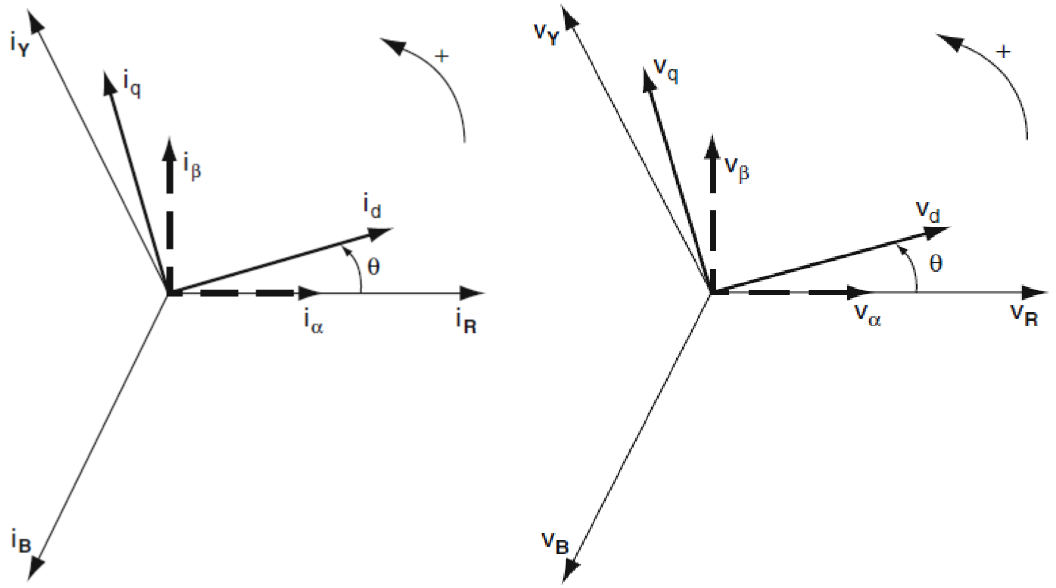
These transformations can be applied both for phase currents and for phase voltages. First, consider phase currents with respect to all frames of reference as shown in Figure (A.2). Currents in Clarke plane can be obtained from phase currents as follows:

$$\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix}=\left[Clarke.Matrix\right]\times\begin{bmatrix}i_R\\ i_Y\\ i_B\end{bmatrix} \tag{A-6}$$

Currents in Park plane can be obtained from Clarke plane currents as follows:

$$\begin{bmatrix}i_d\\ i_q\end{bmatrix}=\left[Park.Matrix\right]\times\begin{bmatrix}i_\alpha\\ i_\beta\end{bmatrix} \tag{A-7}$$

Voltages in Clarke plane can be obtained from phase voltages as follows:



(a) (b)

Figure A.2: R-Y-B, (α, β) and (d, q); (a) current reference frames and (b) voltage reference frames.

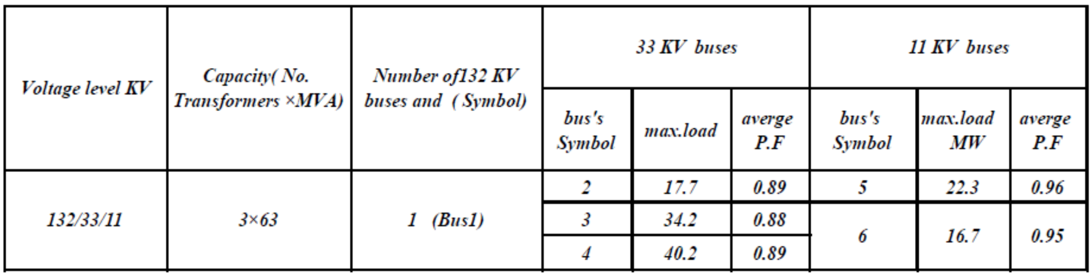
$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = \left[Clarke.Matrix \right] \times \begin{bmatrix} v_R \\ v_Y \\ v_B \end{bmatrix} \tag{A-8}$$

Voltages in Park plane can be obtained from Clarke plane voltages as follows:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \left[Park.Matrix \right] \times \begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} \tag{A-9}$$

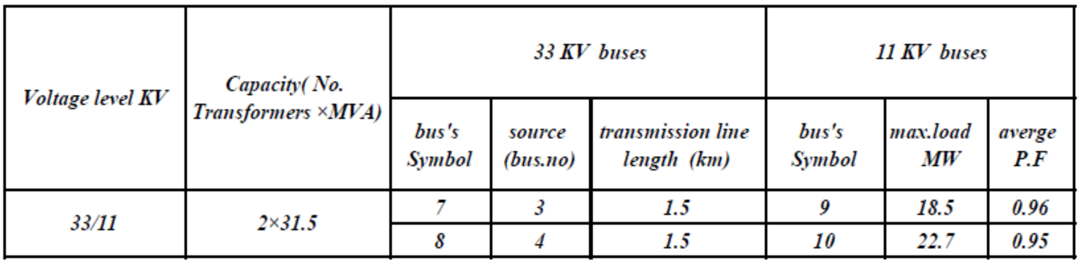
Appendix-B: Substations' Parameters In The Area Of The Study

Table B.1: Rifai.1 substation.



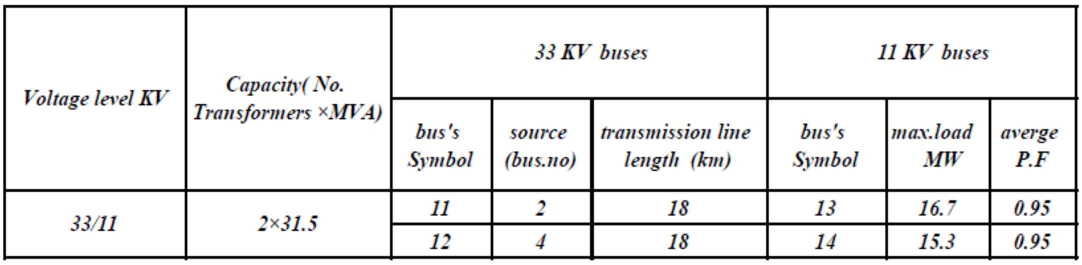
Voltage level KV	Capacity(No. Transformers ×MVA)	Number of132 KV buses and (Symbol)	33 KV buses			11 KV buses		
			bus's Symbol	max.load	averge P.F	bus's Symbol	max.load MW	averge P.F
132/33/11	3×63	1 (Bus1)	2	17.7	0.89	5	22.3	0.96
			3	34.2	0.88	6	16.7	0.95
			4	40.2	0.89			

Table B.1: Rifai.2 substation.



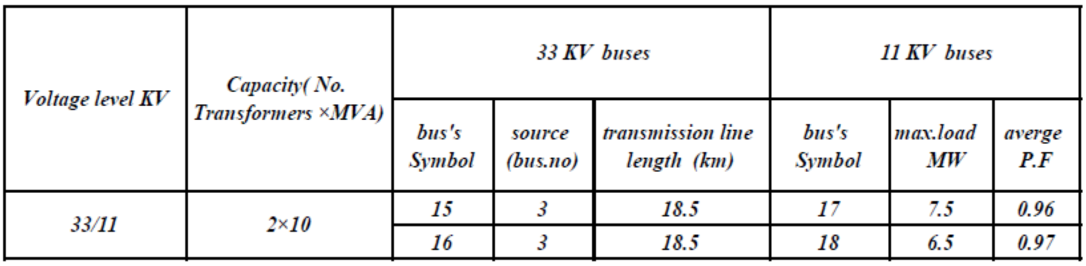
Voltage level KV	Capacity(No. Transformers ×MVA)	33 KV buses			11 KV buses		
		bus's Symbol	source (bus.no)	transmission line length (km)	bus's Symbol	max.load MW	averge P.F
33/11	2×31.5	7	3	1.5	9	18.5	0.96
		8	4	1.5	10	22.7	0.95

Table B.1: Qala.1 substation.



Voltage level KV	Capacity(No. Transformers ×MVA)	33 KV buses			11 KV buses		
		bus's Symbol	source (bus.no)	transmission line length (km)	bus's Symbol	max.load MW	averge P.F
33/11	2×31.5	11	2	18	13	16.7	0.95
		12	4	18	14	15.3	0.95

Table B.1: Qala.1 substation.



Voltage level KV	Capacity(No. Transformers ×MVA)	33 KV buses			11 KV buses		
		bus's Symbol	source (bus.no)	transmission line length (km)	bus's Symbol	max.load MW	averge P.F
33/11	2×10	15	3	18.5	17	7.5	0.96
		16	3	18.5	18	6.5	0.97

CURRICULUM VITAE

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