Design and Simulation of Power Factor Correction Using D-STATCOM
(case study on Almeda Textile Factory)

Name of Candidate: Gebrehiwot Miruts Kebedew

A Thesis Submitted to Adama Science and Technology University

Department of Electrical and Computer Engineering

School of Electrical and computing

Presented in Partial Fulfillment of the Requirement for the Degree of Master of Science in **Electrical Power System Engineering**

Office of Graduate Studies

Adama Science and Technology University

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Approval of Board of Examiners

We, the undersigned, members of the Board of Examiners of the final open defense By Gebrehiwot Miruts have read and evaluated his thesis entitled *"**Design and Simulation of Power Factor Correction Using D-STATCOM (case study on Almeda Textile Factory)**"* and examined the candidate. This is, therefore, to certify that the thesis has been accepted in partial fulfillment of the requirement of the Degree of **Master of Science in Electrical Power Engineering**

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External Examiner	Signature	Date

DECLARATION

I hereby declare that this MSc Thesis is my original work and has not been presented for a degree in any other university, and all sources of material used for this thesis have been duly acknowledged.

Name: Gebrehiwot Miruts Kebedew

Signature:_______________________

This MSc Thesis has been submitted for examination with my approval as thesis advisor.

Name: Dr.Kemal Ibrahim

Signature:__________________

Date of submission may 25/2018 G.C

Supervisor's/Advisor's approval sheet

To: **Electrical and Computer Engineering Department**

Subject: Thesis Submission

This is to certify that, the thesis entitled "***Design and Simulation of Power Factor Correction Using D-STATCOM (case study on Almeda Textile Factory)***" submitted in partial fulfillment of the requirements for the degree of Master's in **Electrical Power System Engineering** the Graduate program of the department of **Electrical and Computer Engineering**, and has been carried out by **Gebrehiwot Miruts Kebedew** **Id.No** ***GSR/1377/08***, under my supervision. Therefore, I recommend that the student has fulfilled the requirements and hence hereby he can submit the thesis to the department.

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Name of major Advisor	Signature	Date

ACKNOWLEDGEMENTS

First, I would like to thanks to the Almighty God and the Virgin Mary for the willingness without which this thesis work is impossible. In addition, I would like to thank ASTU (Adama Science& Technology University) for facilitating the thesis work.

Next, I would like to express my deepest gratitude to my advisor Dr. Kemal Ibrahim not only for his guidance, criticism, encouragements and insight throughout this research but also for his continuous confidence in me, and his unforgettable and valuable contributions to my career.

I am also grateful to show my gratitude to Dr. Taffese Assrat , Dr. Getachew Biru and Dr. Sathish Shikuran for their guidance & encouragements in proposal selection and throughout this research.

Besides, I would like to acknowledge Almeda Textile factory workers for their all kind of support, especially the electrical Department workers who helped me in collecting the necessary data for my thesis work.

At last, I would like to express my gratitude to my mother & my family as whole for their sacrifice, encouragement and continuous morale support.

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NOMENCLATURE

AC	Alternative Current
ALTEX	Almeda Textile
APFC	Automated Power Factor Correction
CSI	Current Source Inverter
CSC	Current Source Converter
DC	Direct Current
D-STATCOM	Distribution Static Synchronous Compensator
DVR	Dynamic Voltage Restorer
EEU	Ethiopian Electric Utility
ETAP	Electrical Transient and Analysis Program
FACTS	Flexible Alternating Current Transmission System
FFM	Fundamental Frequency Modulation
FLC	Fuzzy Logic Controller
f_h	Harmonic Frequency
FPGA	Field Programmable Array
GTO	Gate Turn Off Thyristor
HV	High Voltage
IRP	Instantaneous Reactive Power Theory
IGCT	Insulated Gate Commutated Thyristor
IGBT	Insulated Gate Bipolar Transistor
Kp	Proportional Gain
Ki	Integral Gain

KWH	Kilo Watt Hour
KVAR	Reactive Power
IEEE	International Electrical Electronics Engineering
LCL	inductor, capacitor& inductor Passive Filter
LC	(Inductor & Capacitor) Filter
Lf	Interfacing Inductors
LPF	Low Pass Filters
MATLAB	Matrix Laboratory
MPFC	Modulated Power Filter Capacitor Compensator
MVA	Mega Volt Ampere
PAM	Pulse Amplitude Modulation
PLL	Phase Locked Loop
PCC	Point of Common Coupling
PI	Proportional Integral
PWM	Pulse Width Modulation
RMS	Peak To Peak Voltage
RLC	Resistive Inductive and Capacitive
STATCON	Static Synchronous Condenser
SMES	Superconducting Magnetic Energy Storage
SRF	Synchronously Rotating Reference Frame
SSG	Static Synchronous Generator
SVC	Static VAR Compensator
VA	Apparent Power

V_{AN}	Line-to-Neutral Voltage
V	Voltage
VLL	line-to-line voltage
VSI	Voltage Source Inverter
SVPWM	Space Vector Pulse Width Modulation
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
UPQC	Unified Power Quality Conditioner
VSC	Voltage Source Converter
P	Active Power

ABSTRACT

Textile Industry is one of the most important industries in Ethiopia. Those industry suffers from power factor problem's. As the other textile industries, Almeda textile factory has a problem of low power factor in which this low power factor should be corrected. Power factor correction is the main consideration for utilities and large power consumers as low power factor increases the ratings of distribution and generation equipment resulting in large expense for both the supplier and consumer. The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system. In order to ensure most favorable conditions for a supply system, it is important to have power factor as close to unity as possible. This condition is attained by shunt a preferable power factor corrector equipment near to the load area. The low power factor of the factory is assessed or checked by direct measurement of load power factor using power stability recorder, from recorded data and from the samples of power factor charged bills of Almeda textile factory, which is charged by Ethiopian electric utility. To solve the low power factor of the factory, this thesis have designed and simulated a fact controller three-leg voltage source converter (VSC) D-STATCOM (distribution Static Synchronous Compensator) that, is connected in shunt at the three-phase power entrance of the factory in parallel to the load. A VSC based D-STATCOM is used for the compensation of reactive power for power factor correction, voltage regulation, to eliminate unbalancing load current, and elimination of harmonic currents at the point of common coupling. For this system, this thesis objective is to improve the power factor of the factory from presently operating 0.66 lagging to between 0.85 and 0.95 lagging. The system simulated a D-STATCOM employing a Synchronously Rotating Reference Frame (SRF) theory, which is modeled and simulated in MATLAB Simulink software. This design enabled to maintain power factor of the factory between 0.85 to 0.95 all times whilst keeping the load bus voltage at one per unit. These goals were, fully accomplished in MATLAB simulation and MATLAB coding software's. Now, depend on the different MATlab simulation results, the Almeda textile factory load power factor has been improved from 0.66 to 0.92 lagging which is within the designed range of the thesis objective. The active and reactive power components of the system act as completely independently during changes in the system.

Key words*: Distribution Static Synchronous Compensator, power factor correction, MATLAB, Synchronously Rotating Reference Frame (SRF) theory*

CHAPTER ONE

INTRODUCTION

The electrical energy is almost exclusively generated, transmitted and distributed in the form of alternating current. Most of the customer loads are induction motors, arc lamps, transformers are inductive in nature and they produce a magnetizing current that causes to lower the power factor of the system. The low power factor is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system from power station generator down to the utilization devices. In order to ensure most favorable conditions for a supply system from engineering and economic standpoint, it is important to have power factor as close to unity as possible. This thesis work designed a D-STATCOM to improve the low power factor of Almeda textile factory.

1.1 Background of the Study

Maintaining power quality in a power system is very essential in today's scenario, because of the increase in a wide variety of loads that pollute the power system. Inductive loads like induction generators, induction motors, power transformers and arc furnaces, require reactive power for their magnetization and if the reactive power is consumed from the grid, a poor power quality occurs.

The active and reactive power between sending end and receiving end in an electrical power system should be balanced. If it is not so, the system frequency and voltage unbalance may occur hence power system will become unstable. For stable power system operation, active and reactive power control are needed. Static synchronous compensator (STATCOM) technology is one of the advanced power electronics device which provides fast and continuous capacitive and inductive reactor power compensation. The majority of loads in electrical power system are inductive in nature which draw's lagging power factor currents. This excessive reactive power demand increases losses in feeders and reduces the active power flow.

Power factor correction at distribution level is an important consideration for large consumers and utilities. By definition, power factor is the ratio of active power (W) to apparent power (VA). A low power factor causes indecencies in the electrical supply network by forcing utilities to increase the VA rating of their switchgear and distribution transformers in order to supply more reactive power. In the past, utilities used capacitor banks for power factor correction, but they have proven bulky and inflexible. The advent of Flexible Alternating Current Transmission System (FACTS) controllers such as the D-STATCOM (Distribution Static Compensator) has paved the way for more efficient and flexible methods of reactive power compensation.

The Problem of power quality in industrial plants are growing due to the increasing number of rectifier-controlled motors and the overall increase of harmonics and inter-harmonics. These loads cause poor power factor in those industrial plants and a poor power factor indicates ineffective utilization of electricity there by affects the total energy of the plant as well as cost of bills. These problems are happened in Almeda textile factory results a high amount of electrical energy is loosed always. This low power factor operating of the factory is due to the imbalance of machine size and driving loads, which results a numerous amount of reactive power consumptions, is takes place. This improper utilization of reactive power led to lower the power factor of the factory which affects the total electric consumption of the country and these problems are aggravated by the proper selection, sizing and installation of selective corrective equipment. To improve the low power factor of the factory this thesis work have designed and simulated a three-leg voltage source-converter (VSC) based D-STATCOM is used for compensation of reactive power for power factor correction, voltage regulation or for along with load balancing and elimination of harmonic currents at the point of common coupling.

1.1.1 Power Factor Correction

The amount of reactive power KVAR required to correct a system to a desired power factor level is the difference between the amount of KVAR in the uncorrected system and the amount of desired KVAR in the corrected system.

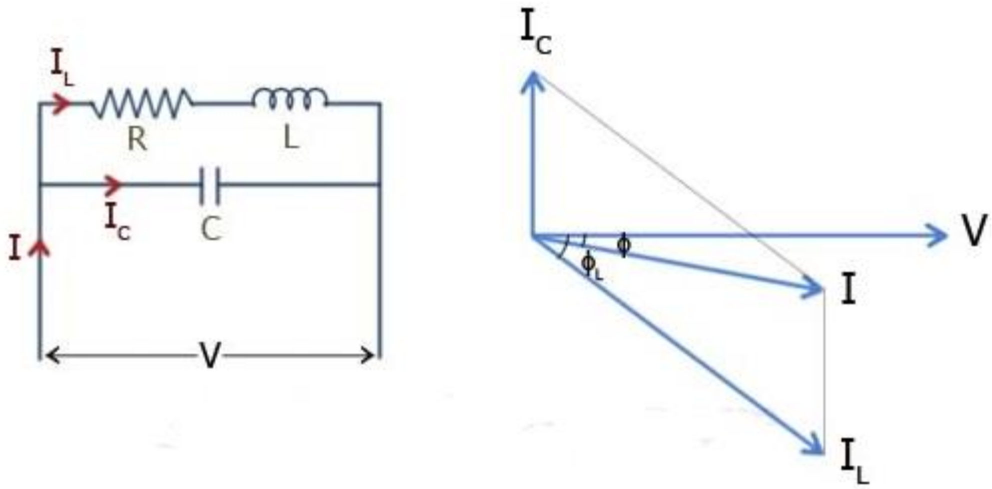


Figure 1.1 RLC Circuit and its Voltage and Current Phasor Diagram

Figure 1.1 shows an electrical common circuit of R and L which are present in all inductive equipment's and the C is used for power factor improvement.

Here, I_L = current drawn by the circuit capacitor C is not used,

ϕ_L = phase angle between voltage V and load current IL,

I_C = capacitive current drawn by C,

I = resultant current when C is used,

ϕ = phase angle between voltage V and net current I.

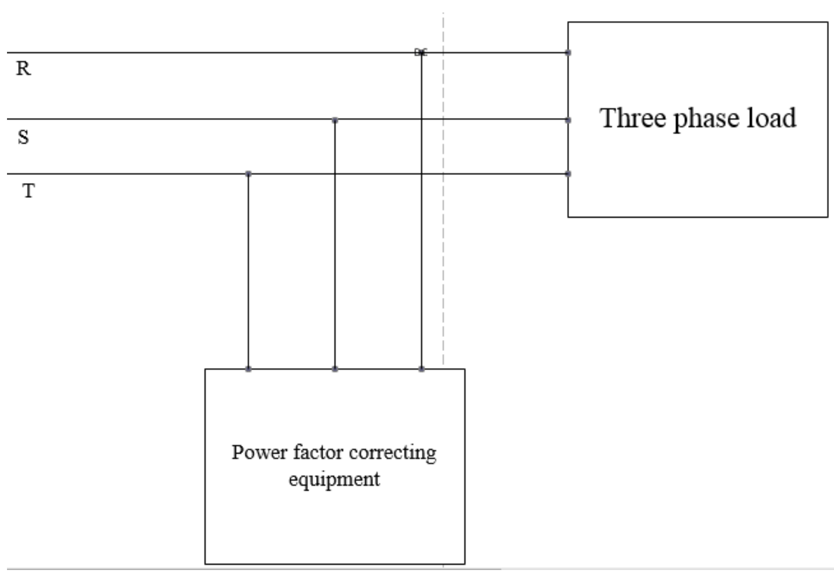


Figure 1.2 Representation of Three-Phase Load with Power Factor Correcting Device

1.1.2 Motivation of the thesis work

Power factor correction at distribution level is an important consideration for large consumers and utilities. A low power factor causes inefficiencies in the electrical supply network by forcing utilities to increase the VA rating of their switchgear and distribution transformers in order to supply more reactive power. In the past, utilities used capacitor banks for power factor correction, but they have proven bulky and inflexible. From this, this thesis work motivated to solve a power factor problem that happen on Almeda textile factory. Using Flexible Alternating Current Transmission System (FACTS) controllers which is D-STATCOM (Distribution Static Compensator) has paved the way for more efficient and flexible methods of reactive power compensation and to improve the low power factor of Almeda textile.

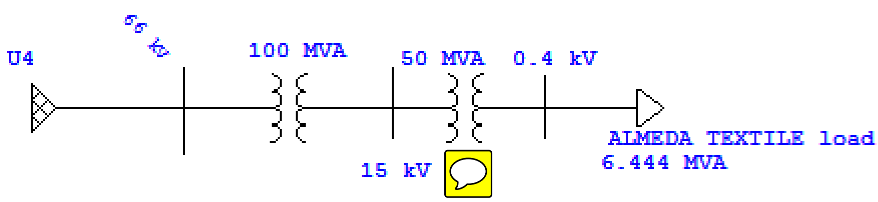


Figure 1.3Almeda Textile Load Single Line Diagram

1.2 Statement of the Problem

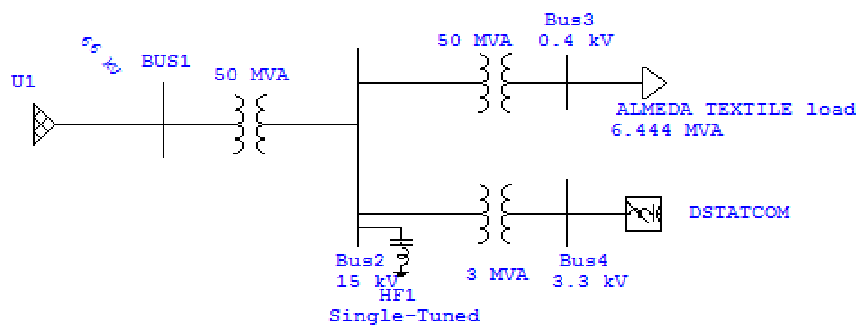
Power quality is the main issue to reduce the amount of energy required to provide products and services. Improvements in power quality are, generally achieved by adopting a more efficient technology or production process or by application of commonly accepted methods to reduce power losses.

Almeda textile (ALTEX) factory uses electricity, as a common power source for machinery, cooling and temperature control systems, steam generators, lighting, office equipment, etc. The main problem of the factory is, operating power factor is out of the prescribed limit of EEU and unbalanced current as seen from the three sample of transformers data as indicated in the appendixes D, is the big problem of the factory. The factory receives 15KV from EEU at 50-Hertz frequency and operates at a power factor of 0.66 lagging. Due to this the factory as well as EEU loses a high amount of energy every seconds. As this thesis work compare's the power factor of ALTEX with EEU standard of minimum 0.8 lagging, and IEEE minimum standard power factor of 0.85 lagging, thus ALTEX power factor is below 0.8 lagging, due to this the Ethiopian electric utility (EEU) charges the factory around 69000birr per month as indicated the power factor charged bill in the appendix A.

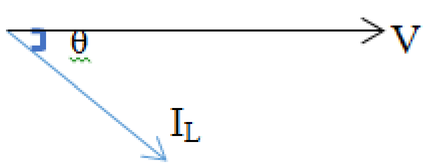
Now, this thesis work has done to solve the energy loss due to the operating of low power factor and to eliminate the unbalanced current from the load system.

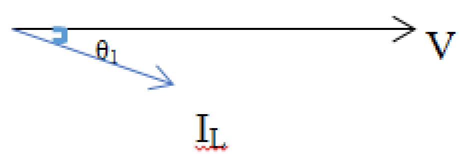
Some of the reasons for the low power factor operating of the factory are:

- ✓ Absence of power factor corrective equipment to compensate the consumed reactive power
- ✓ Absence of harmonic filters to filter harmonic currents
- ✓ Due to the operating of large Induction motors with lightly loaded system
- ✓ Due to the unbalanced current of the load.



a)





b) c)

Figure 1.4 a) Representation of ALTEX load b) Phasor diagram of load current and angle θ before correction c. Phasor diagram of load current and angle θ1 after the D-STATCOM is connected

1.3 Objective of the Study

1.3.1 General Objective

The main objective of this thesis is Design and simulation of D-STATCOM for Power Factor correction in Almeda textile factory.

1.3.2 Specific objectives

To achieve the main, the following specific objectives will be accomplished

- To compensate the reactive power of the load
- In order to improve the existing low power factor using D-STATCOM from 0.66 to between 0.85 and 0.95 lagging
- Improving of voltage stability and saving of energy

1.4 Research Questions

This topic deals with the problem of power factor at Almeda textile factory, causes of the problem and how a power factor of the factory can be solved. Generally, the following thesis questions will be raised:

1. What are the causes of lower the load Power Factor at Almeda textile factory?
2. Why Should Improve the load Power Factor of the factory?
3. How do you improve the load low Power Factor?
4. How long will it take this Investment in Power Factor Correction to Pay for itself?

This thesis work will solve the Almeda textile factory problems with respect to the addressed research questions. Using a proper design and methods of the factory problem of low power factor will solve.

1.5 Scope and Limitations of the Study

The study involves reading relevant literature, collecting and analyzing data from the factory to improve the low power factor of the factory. Within the scope of this thesis, three leg voltage source converter (VSC) based D-STATCOM employing reactive power compensation, power factor correction, and eliminating of current unbalance with simplest converter topology of medium voltage IGBT module is investigated. Synchronously rotating reference frame theory used as the reactive power control technique and PI controller PWM technique are investigated to approximate the input voltage and current waveforms to pure sine wave.

Thus, this thesis work has made the following contributions to the factory:

- ✓ The Low power factor, Reactive power compensation and unbalanced current problems of the factory are solved by VSC based D-STATCOM.
- ✓ Investigation of the effect of input filter size on the action of VSC based D-STATCOM for reactive power compensation and power factor correction.

1.6 Description of the Study Area

Almeda textile factory is found at Adwa town 1006 K.ms apart from Addis Ababa and 233 K.ms from Mekelle the capital of Tigray region of Ethiopia, at an altitude of 1985 m above sea level.

The factory was designed to produce polyester; cotton blended woven fabrics, yarns, garmenting and different types of closes. Equipped with spinning technology, open end spinning, the pre-spinning stages of 2nd passage drawing and roving, the post-spinning stage of winding can all be accomplished as just one point. The factory is also equipped with high speed shuttle less rap air loom; each of which fitted with a microprocessor facility to enable the operatives to adjust and configure the required production and machine parameters. Air conditioning system, well-equipped physical testing laboratory, water treatment plant, a complete fire-fighting and protection system as well as organized mechanical, electrical and automotive workshops are its additional features.

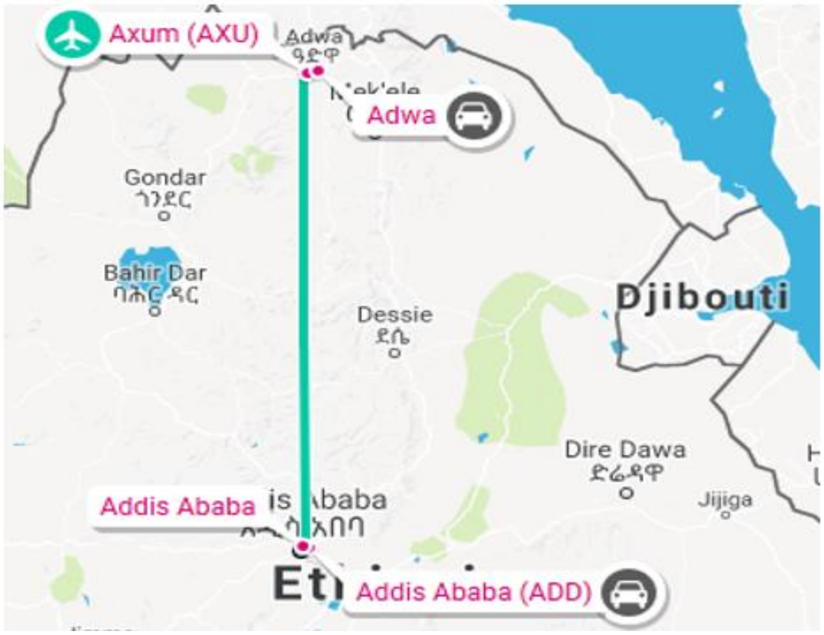


Figure 1.5 Distance From Addis Abeba to Adwa

The factory power distribution system consists of fourteen (14) distribution transformers as indicated in appendixes C with different capacity. The factory possess total designed connected load of about 6.4MVA as obtained from the designed energy consumption of the factory.

Figure 1.6 Part of Almeda Textile Factory

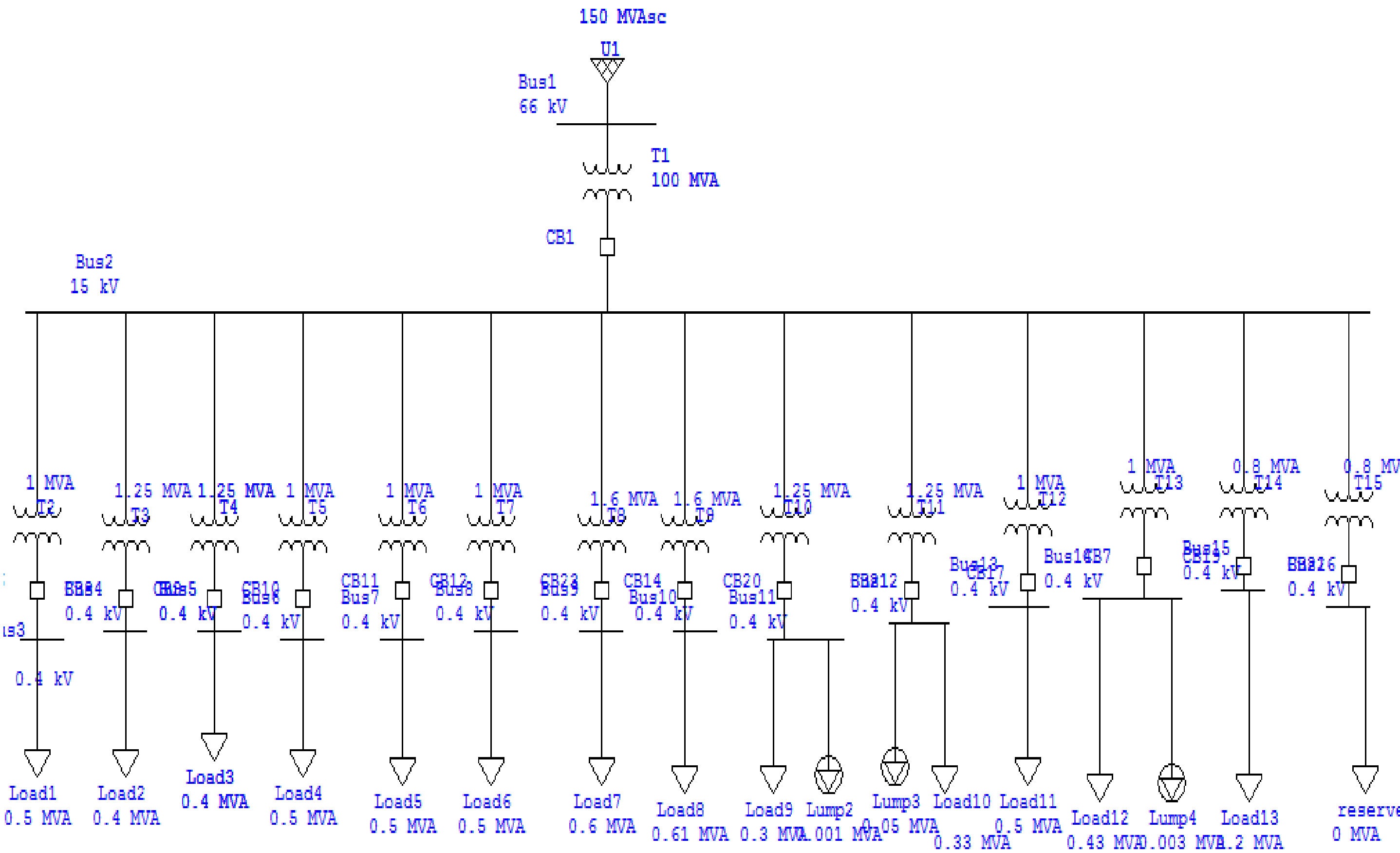


Figure 1.7 ETAP Designed Single Line Diagram of Almeda Textile Load Distribution

CHAPTER TWO

2. LITERATURE REVIEW

This thesis presents the enhancement of low power factor and reactive power compensation using Distribution Static Compensator (D-STATCOM) in Almeda textile factory. The model is based on the Voltage Source Converter (VSC) D-STATCOM principle. The D-STATCOM injects a current into the system to improve harmonic distortion and low power factor. Different related literatures review about methods of power factor correction are discussed and from the different power factor correction methods for this thesis work, it is selected three leg voltage source converter D-STATCOM to improve the low power factor of Almeda textile factory.

Moe Kay Thikhaing, [1] presents Power Factor Correction with Synchronous Condenser for Power Quality Improvement in Industrial Load. The researcher compare's power factor correcting methods such as capacitor banks, reactors, synchronous condenser in their role of load power factor correction. The researcher uses MATlab program for overall plant power factor calculations and from this, the researcher concludes that, the use of synchronous condenser to improve the load power factor is somewhat better than the capacitor banks.

Amol P. Patil, P.V. Baviskar, [2] presents "Implementation of Static VAR Compensator (SVC) For Power Factor Improvement on industrial loads". Those researchers describes that since most of the industrial loads are inductive in nature and hence have low lagging power factors which is highly undesirable as it causes an increase in current, resulting in additional losses of active power in all the elements of power system. They used a static VAR compensator consisting of capacitor bank in four binary sequential steps with a thyristor (SCR) controlled reactor of smallest step size is employed in the investigative work. From this the researchers conclude that, power factor of inductive loads without compensation is less than 0.9 lagging and With the help of static VAR compensator power factor can improves near to unity for inductive load.

Mr.Anant Kumar et al, [3] presents automatic power factor Correction Using Capacitor Bank. The researcher describes as power factor of electrical load is a common problem to all industrial companies. They Proposed that, automated power factor corrector (APFC) using capacitive load bank is helpful in providing the power factor correction. From this point, the researchers conclude that, By installing suitably sized power capacitors into the circuit the Power Factor is improved and the value becomes nearer to unity, thus minimizing line losses and improving the efficiency of the plant.

A. Noramin Ismail, [4] Wan Norainin Wan Abdullah " presents Enhancement of Power Quality in Distribution System Using D-STATCOM" their objective is the enhancement of voltage sags, harmonic distortion and low power factor using Distribution Static Compensator (D-STATCOM) with LCL Passive Filter in distribution system. It's model is based on the Voltage Source Converter (VSC) principle.

The researcher describes D-STATCOM is a custom power devices which locate shunt in the network and applied to mitigate voltage sag and voltage swell. From this the researcher concluded that D-STATCOM is emerged as a promising device to provide not only for voltage sag mitigation but also for a host of other power quality solutions such as voltage stabilization, flicker suppression, power factor correction, and harmonic control.

B. S.T.Nagarajan, Narendra kumar . [5]" fuzzy logic based control of STATCOM for Mitigation of SSR'"" IEEE STATCOM a FACTS device is a second generation Static VAR Compensator (SVC) based on voltage sourced inverter and has better reactive power support even at low voltages. From this, the researcher conclude that the Fuzzy logic controller does not depend on the system model. This eliminates the need to linearize the power system model to tune the parameters of controller. The researcher also conclude that, STATCOM is shunt device and is widely used FACTS device for reactive power generation, voltage support and improving steady state stability of power system.

Bhim Singh, et al. [6] has introduced new control approach for capacitor supported D-STATCOM in three phase four wire distribution systems under non-ideal supply voltage conditions based on SRF theory. From this research, the researcher has been concluded that SRF theory employed in D-STATCOM improves the performance of the system and it fulfils the objective of load balancing, harmonic current compensation, indirect current control and neutral current compensation.

Prafull A. desale, et al. [7] presents a review paper on custom power device for the improvement of power quality. This paper presents a comprehensive survey of device in distribution system.

The researcher conclude that, To illiminate various power quality disterbaces like voltage sag/swell, dip,flliker,low power factor etc. according to this paper shunt connected D-STATCOM provides better power quality in both transmission and distribution system, UPQC can compenstate both voltage and current related problems at the same time.

D.Masand, et al. [8] compairs the linear and nonlinear methods of current regulation refering to D-STATCOM performance using synchronous reference frame through this paper. In this paper merits and demerits of each regulation methods are stated. The researcher concluded that when the PWM with carrier teqnique in reference frame is implemented,fixing switching of VSC results in overshoot of about 2.5 times more as compaired to hysteresis current controller. in case of nonlinear load the THD in fixed switching frame is far hiegher than that in variable switching frame. He also concluded that hysteresis based D-STATCOM in SRF frame is feasible for load compensation at distribution level.

P.Bapaiah, et al. [9] this paper presents the compensation provided by D-STATCOM for power factor improvement and different control schemes are available for the D-STATCOM. The researcher concluded that, control method used for it must provide complete reactive power compensation, correction of power factor and voltage regulation and the harmonics are also checked for achieving improved power quality levels at distribution end. In addition to this the researcher conclude that power factor correction using D-STATCOM is the most efficient than the other power factor correction methods.

Wei Neng chang, et al. [10] presents a distribution level static synchronous compensator (D-STATCOM) for dynamic load compensation of unbalanced loads in distribution system. for dynamic response a new feed forward compensation method was derived and engaged. Compensation scheme of the D-STATCOM is derived with the symmetrical component method. MATlab simulation software is used to confirm the effectiveness of the proposed D-STATCOM.

This paper conclude that, D-STATCOM was a shunt device that generates a balanced three-phase voltage or current with ability to control the magnitude and the phase angle. The VSC converts the dc voltage across the storage device into a set of three-phase ac output voltages. These voltages are in phase and coupled with the ac system of network through the reactance of the coupling transformer.

Matthew Borody, et al. [11] presents Design and Implementation of a D-STATCOM for Power Factor Correction with in ECE4600 Group Design Project. This system uses IGBT-based power electronics in a 6-pulse inverter configuration, controlled through the use of a decoupled instantaneous current controller. From this the researcher concluded that, a solid-state device enabling full power factor correction with a completely independent control of both active and reactive power.

Adeesh Sharma1, Himmat Singh2 [12] presents Reactive Power Compensation using D-STATCOM for improving the power factor, power quality and to control power flow control in the distribution line. From this the researcher conclude that, by injecting suitable reactive power in the power distribution line, the load power factor and the overall electrical system performance improves. It was also conclude that, the system provides continuous support of the source voltage and current in phase with each other after compensation. From this the power factor of the utility supply is always remaining at unity.

2.1 FACTS Controllers

The IEEE Power Engineering Society (PES) task force of the FACTS working group has defined FACTS and FACTS Controller as given below [3].

Flexible AC Transmission System (FACTS): Alternating current transmission systems incorporating power electronic- based and other static controllers to enhance controllability and increase power transfer capability.

FACT Controllers are a power electronic-based system and other static equipment that provide control of one or more AC transmission system parameters

2.2 Power Factor

Power factor is the cosine of the angle between voltage and current in an a.c load system. When the power factor of the consumer lowered, the current of the system increases there by increasing the loss as it is not easy to increase the size of the conductor and raise the capacity of the system of an already established network. It will also make voltage regulation difficult and reduce handling capacity of the overall system.

In the interest of reducing the losses in the distribution system, power factor correction is added to neutralize a portion of the magnetizing current of the load. Typically, the corrected power factor will be 0.92 - 0.95, some power retailers offer incentives for operating with a power factor of better than 0.9, while others penalize consumers with a poor power factor. There are many ways that this is metered, but the net result is that in order to reduce wasted energy in the distribution system, thus the consumer will be encouraged to apply power factor correction.

To avoid the problem of reactive power, the utility advises and encourages medium and large-scale industries to install proper power factor correction equipment to maintain their power factor as close as unity. Otherwise, enforces proportional penalty created by artificial demand reactive power consumption up to a certain level.

2.3 Causes of Low Power Factor

Low power factor is undesirable from economic point of view in all electrical applications. Some of the causes of low power factor are:

A. Most of the AC motors of single phase or three-phase induction type which have low lagging power factor. These motors work at a power factor, which is extremely small on light loads (0.2 to 0.3) and rises to 0.8 or 0.9 at full load and since most of the Almeda textile factory machines are induction type and used these machines without any reactive power-compensating device that is why they suffer by low power factor operating problems.
B. Electric discharge lamps, arc lamps and industrial heating furnaces operate at low lagging power factor. Almeda textile factory needs industrial heating furnace and the above-described lamps without any compensating devises, thus decrease the factory average operating power factor.
C. The load on the power system is varying, that is high during morning and evening and low at other times. During low load period, supply voltage is increased which increases the magnetization current. This results in the decreased power factor.

The above low power factor problems can be solved by properly designed reactive power compensating devices.

Thus, Almeda textile factory suffers from that problem and to solve the factory low power factor operating system this thesis work have been designed a fact controller, which is VSC D-STATCOM to compensate the reactive power of the factory, by properly designing the inductive and capacitive value of the D-STATCOM with proper switching control of the switching devices of the D-STATCOM.

2.4 Disadvantages of low power factor

The power factor plays an important role in AC circuits since power consumed depends on the power factor.

$$P = V_L I_L \cos\theta \quad (2.1)$$

$$P = \sqrt{3} V_L I_L \cos\theta \quad (2.2)$$

From (2.2) for a fixed power and voltage, the load current is inversly proportional to the power factor. the lower the power factor the hiegher is the load current and vice versa.

A low power factor have the folowing disadvantages

A. Large KVA rating of equipments**:** all electrical equipments in power systems are rated in KVA.

The smaller the power factor, the larger the KVA rating. so at low power factor, the KVA rating of the equipment has to be made more,this is making the equipmet larger in size and expensive.

B. Greater conductor size:to distribuit a fixed amount of power at constant voltage, the conductor will have to carry more currents at low power factor, this needs larger conductor size.

C. Larger copper losses: the larger current at low power factor causes more I^2R losses in all the elements of the supply system. This results in poor efficiency of the system.

D. Poor voltage regulation: the larger current at low lagging power factor causes greater voltage drops in generators, transformers, transmission lines and distributers. This causes a low voltage available at the receiving end, this leads to use extra equipment's (i.e. voltage regulators) to keep the receiving end voltage with in permissible limits.

2.5 Methods of Power Factor Correction

Low power factor is mainly due to lagging currents drawn by inductive loads. In other words capacitors draw leading current, which cancel the effects of lagging inductive current and hence improve the load power factor.Based upon this principle, the following methods are used for power factor correction (PFC).

2.5.1 Capacitor bank

2.5.2 Synchronous Condenser

2.5.3 Modulated power filter capacitor compensator

2.5.4 Static VAR Compensator (SVC)

2.5.5 Static Synchronous Compensator (STATCOM)

2.5.1 Capacitor bank

Static capacitors are used which produce capacitive reactance that cancels out the inductive reactance of the lagging current. These banks can be star connected or delta connected. A control system is usually provided which monitors the power factor and switches the capacitors on or off.

Advantages

- low losses
- low maintenance
- light weight
- easy to install
- no foundation required

Disadvantages

- short life (8-10 years)
- capacitors can get easily damaged due to over voltage
- once damaged, the repair is costly and uneconomic

- due to constant switching, switching surges and harmonics may be produced

2.5.2 Synchronous condenser

Synchronous condenser is a salient pole synchronous generator without prime mover. Synchronous condenser stabilizes power system voltage by supplying reactive power to the power system and use for power factor correction. a synchronous motor takes a leading current when over excited and therefore behaves as a capacitor. An over excited synchronous motor running on no load is known as synchronous condenser. When such a machine is connected in parallel with the supply, it takes a leading current which partly neutralizes the lagging reactive component of the load. Thus, the power factor is improved.

Power factor correction using Synchronous condenser over capacitor bank gives the following advantages

- longer lifespan (almost 25 years)
- flexible and step less control of power factor
- reliable than capacitor banks
- does not get affected by harmonics
- No switching is required hence harmonics are not produced

Disadvantages

- higher losses
- expensive
- higher maintenance costs
- produces noise
- Synchronous motor is not self-starting, so auxiliary device is needed with extra cost.
- uneconomical for equipment below 500 kVA

2.5.3 Modulated power filter capacitor compensator

Modulated power filter capacitor compensator is a member of novel FACTS based devices and compensators developed by the First Author. The MPFC is composed of a capacitor, an inductor, a resistor, two PWM wave controlled IGBT switches and a three-phase diode bridge. The low cost modulated dynamic series-shunt power filter and compensator is a switched type filter, used to provide measured filtering in addition to reactive compensation. The modulated power filter and compensator is controlled by the on-off timing sequence of the PWM switching pulses.

2.5.4 Static VAR Compensator (SVC)

A static VAR compensator is a set of electrical devices for providing fast-acting reactive power on high-voltage electricity transmission networks. SVCs are part of the Flexible AC transmission system device family, regulating voltage, power factor, harmonics and stabilizing the system. Unlike a synchronous condenser which is a rotating electrical machine, a static VAR compensator has no significant moving parts (other than internal switchgear). Prior to the invention of the SVC, power factor compensation was the preserve of large rotating machines such as synchronous condensers or switched capacitor banks. The SVC is an automated impedance matching device, designed to bring the system closer to unity power factor.

Advantage of Static VAR Compensator

- It increased the power transmission capability of the transmission lines.
- It improved the transient stability of the system.
- It controlled the steady state and temporary over voltages.
- It improved the load power factor, and therefore, reduced line losses and improved system capability.

2.5.5 Static Synchronous Compensator (STATCOM)

According to definition of IEEE PES Task Force of FACTS Working Group: Static Synchronous Compensator (STATCOM): A Static synchronous generator operates as a shunt-connected static var compensator whose capacitive or inductive output current can be controlled independent of the ac system voltage.

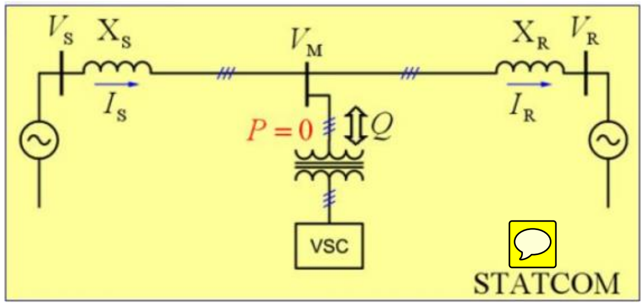
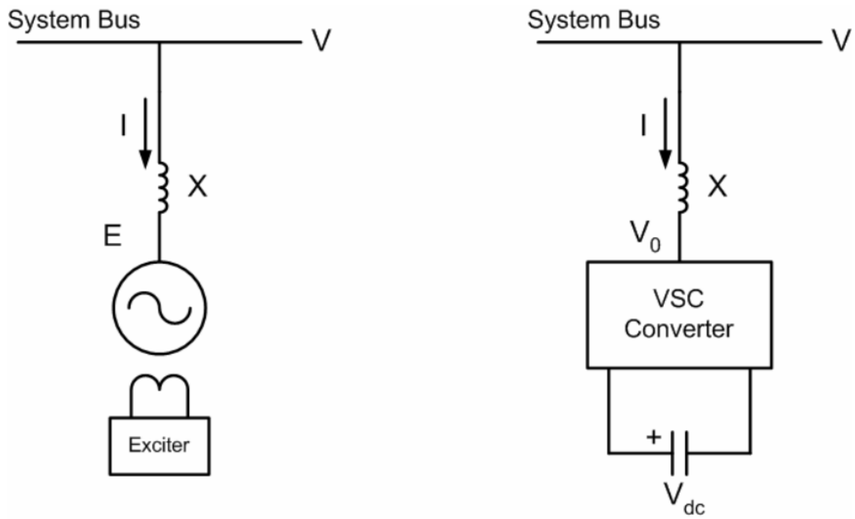


Figure 2.1 Reactive Power Control Using STATCOM

Gyugi disclosed the possibility of generating controllable reactive power directly, without the use of ac capacitors or reactors by various switching power converters in 1976 [3]. Functionality, from the standpoint of reactive power generation, their operation is similar to that of an ideal synchronous machine whose reactive power output is varied by excitation control. As if the mechanically powered machine these converters can also exchange real power with the ac system if supplied from an appropriate, usually dc energy source (Figure 2.2b). Because of these similarities with a rotating synchronous generator, they are termed Static Synchronous Generator (SSG). When SSG is operated without an energy source and with appropriate controls to function as shunt-connected reactive compensator, it is termed, analogously to the rotating synchronous compensator (condenser) a Static Synchronous Compensator (STATCOM) or Static Synchronous Condenser (STATCON).

Rotating synchronous condensers (Figure 2.2 a) have been used in both distribution and transmission systems for 50 years. However, they rarely used today because of the following drawbacks as compare to STATCOM.

i. Require substantial foundations and a significant amount of starting and protective equipment.
ii. Contribute to short circuit current.
iii. Cannot be controlled fast enough to compensate for rapid load changes due to the large time constant of their field circuit.
iv. Have much higher losses as compared with D-STATCOM.



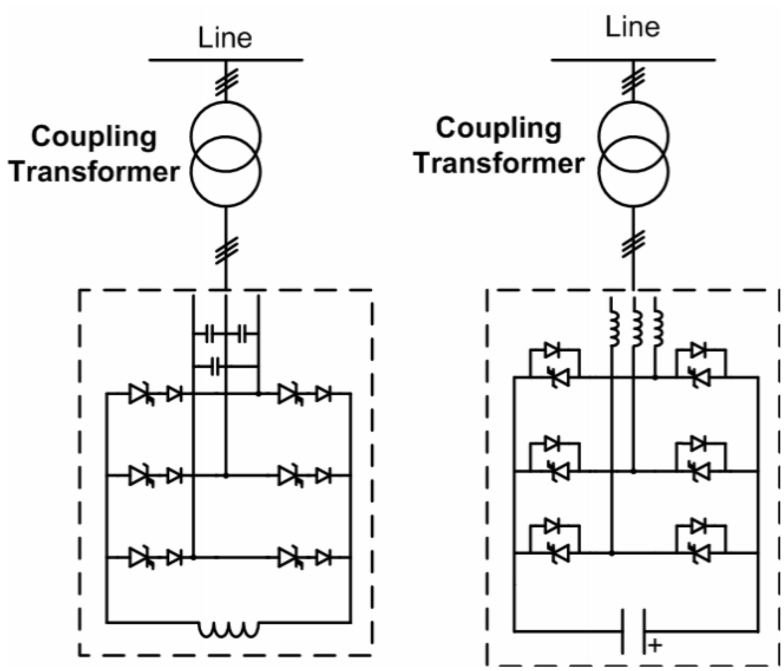
a) b)

Figure 2.2 Reactive Power Generation by a) Rotating Synchronous Compensator, b) Voltage Source Converter Based Static Synchronous Compensator (STATCOM)

For the generation of controllable reactive power by the converter can be a voltage source type (VSC) (Figure 2.3 a.) or a current source type (CSC) Figure 2.3 b.). However, converters presently employed in FACTS Controllers are based on voltage source converter (VSC).

The major reasons for this preference are as follows:

i. Current source converters require power semiconductors with bi-directional voltage blocking capability.
ii. Dc-link reactor of CSC has practically more loss than complementary dc-link capacitor of VSC.
iii. The CSC requires capacitors at its ac terminals while VSC requires reactors, which may be naturally provided by the leakage inductance of the coupling transformer.



(a) (b)

Figure 2.3 VSC & CSC STATCOM Based on (a) Current Source Converter (CSC) and (b) Voltage Source Converter (VSC)

A STATCOM is a static power-electronic version of the synchronous condenser. It is a shunt-connected reactive power compensation equipment and it provides operating characteristics similar to a rotating synchronous condenser.

Although they have the same structure, STATCOM systems are classified as Transmission STATCOM and Distribution STATCOM (D-STATCOM). While Transmission STATCOM having a larger MVAR rating is intended to inject a set of three balanced quasi-sinusoidal voltages for controlling reactive power flow in transmission system.

2.6 Power Factor Correction Using Distribution STATCOM

When the STATCOM is applied in distribution system it is called D-STACOM (Distribution-STATCOM) and its configuration is the same as transmission STATCOM. Since the study area is in the industry, it used the VSC based distribution-STATCOM to solve the problem of low power factor and unbalanced load current of Almeda textile factory.

A D-STATCOM is a shunt compensation device that provides an effective solution for reactive power compensation, voltage regulation, power factor correction, harmonic filtering, and load balancing in the distribution system. Therefore, D-STATCOM can be able to inject unbalanced and harmonically distorted current to eliminate unbalance or distortions in the load current or the supply voltage. It consists of a Voltage Source Converter (VSC), a DC capacitor, a coupling inductor or coupling transformer and a controller. The D-STATCOM is connected to the grid through a coupling inductor at the Point of Common Coupling (PCC), is controlled in such a way that it exchanges only reactive power with the grid. This is achieved by injecting the current in quadrature with the grid voltage.

A D-STATCOM consists of GTO/IGBT based VSI connected to the power system through coupling transformer. Generally, GTOs are used for the high power application like the STATCOM for transmission level. IGBTs are used for medium to small voltage, power application and are used in D-STATCOM. it employs either a voltage source inverter (VSI) or current source inverter (CSI) with reactive power storage as capacitor or inductor respectively. Generally, voltage source inverters are widely used because of their lower sizes, less dissipation of heat and less costly capacitor compared to the inductor used in the CSI for the same power rating.

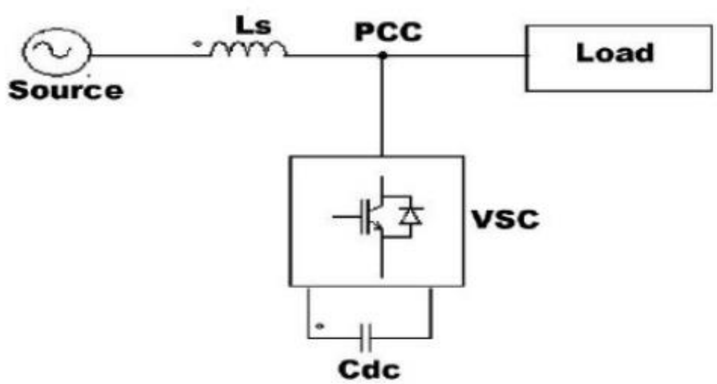


Figure 2.4 Short Hand Representation of VSC D-STATCOM

Advantages of power factor correction using D-STATCOM over the other methods of power factor correction

- It operates with a very fast transient response, thus appearing to be almost without any inertia, unlike the synchronous condenser.

- It provides virtually step-less compensation for reactive VARs and maintains the desired power factor set as control reference automatically, even in the event of load fluctuations. It can be controlled to provide leading or lagging VARs and adjusts itself automatically as per the load VAR requirement.
- In event of increase in plant load, putting additional units in parallel can increase compensation capacity.
- Better dynamics, no inertia, lower investment cost and maintenance cost than synchronous condenser.
- Continuous and dynamic voltage control.
- Allows full grid control.
- Better power factor correction than other power factor correction methods
- High dynamic and fast step response of 8 ms to 30 ms.
- Helps in system stability control, as active power control is possible with a D-STATCOM.
- Maximum reactive current over extended voltage range.
- High efficiency.
- Single-phase control for unbalanced loads.
- No potential for making a resonance point. This is because no capacitor banks or reactors are essential to produce the reactive power for a D-STATCOM.

From the different power factor correction methods of discussed (A to D) above the D-STATCOM method of power factor correction is the better for power factor correction at distribution level and large consumers. That is why the D-STATCOM is, selected for power factor correction in my thesis work in Almeda textile factory.

2.7 Operating principles of distribution static compensator (D-STATCOM)

A Distribution STATCOM (D-STATCOM) is a shunt compensation device used for reactive power compensation. It can be used either in the power factor correction mode or in the voltage regulation mode.

D-STATCOM is a three-phase shunt connected power electronics based device, which is connected near the load. The controller of the D-STATCOM is used to operate the inverter in such a way that the phase angle between the inverter voltage and the line voltage is dynamically adjusted so that, the D-STATCOM generates or absorbs the desired reactive power at the Point of common coupling (PCC). If output voltage of the inverter is equal to system voltage Vs, the reactive power is zero and the D-STATCOM does not generate or absorb reactive power. When inverter voltage is greater than system voltage, the collector current Ic, flows through the coupling inductor from the D-STATCOM to the ac system, which means D-STATCOM injects the current to the system and the device generates capacitive reactive power. If the inverter voltage is less than system voltage, the current flows from the ac system to the D-STATCOM, resulting in the device absorbing inductive reactive power. A three-phase voltage source converter (VSC) is realized using six IGBTs switches with anti-parallel diodes. Three phase loads may be a lagging power factor load or an unbalance load or a nonlinear load. A filter connected to the system in parallel with the load and the compensator to reduce switching ripples at the point of common coupling (PCC) voltage injected by switching of D-STATCOM.

A D-STATCOM schematic diagram as in Figure 2.5 is connected to a three phase AC mains feeding three phase loads, such as lagging power factor loads, unbalanced loads, non-linear loads and mixed of these loads of Almeda textile loads at PCC. Interfacing inductors (Lf) are used at AC side of the voltage source converter (VSC) for reducing ripple in compensating currents. The D-STATCOM injects harmonics/reactive currents to cancel the harmonics /reactive power component of the load currents. Hence, the source currents are harmonic free and load reactive power is also compensated. The voltage and current rating of the required compensation decides the rating of the switches.

When the two AC sources of the same frequency are connected through a series inductance, active power flows from leading source to lagging source and reactive power flows from higher voltage magnitude AC source to lower voltage magnitude AC source. Active power flow is determined by the phase angle difference between the sources and the reactive power flow is determined by the voltage magnitude difference between the sources.

Power stage selection of Voltage Source Converter depends on the reactive power compensation, harmonic reduction technique, load characteristics and control method preferred in the design. Each power semiconductor of the D-STATCOM is switched On and Off only one time over a fundamental period in Fundamental Frequency Modulation (FFM)' techniques. Basic FFM schemes can be described as follows:

- Multi-pulse converters in which multiple six-pulse converters are connected parallel on the dc side and with phase shifting transformers on the ac side. Selected harmonics are eliminated with transformer connections and complicated transformer connections are required for lower harmonic spectra.
- A multi-level converter is used in which the dc link capacitor is divided into the converters. AC side is connected to the selected converter by switching control and staircase waveforms are obtained with reduced harmonics. This topology allows the use of simpler transformer connections at the expense of complicated control systems to maintain capacitor voltage equalization.
- Each power semiconductor is switched at higher frequencies (250Hz-5kHz) to offer minimum harmonic spectra. The choice of the power stage depends on the system voltage, power ratings of required DSTATCOM.

The scope of this thesis is based on the 2 level, 3 leg Voltage Source Converter topology which is shown in Figure 2.5.

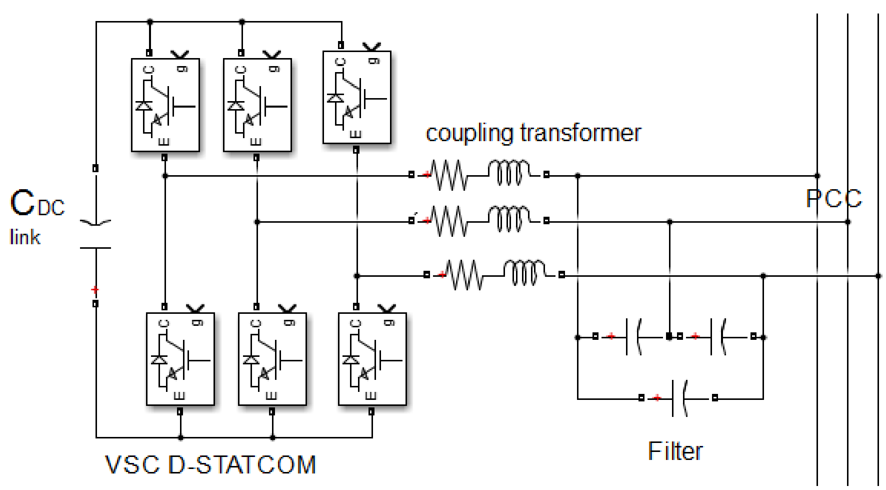


Figure 2.5 2 Level, 3 Leg Voltage Source With Filter

From Figure 2.5 input filter is used to filter out the switching harmonics of the converter. It can be designed as an inductance only filter or a low pass LC filter depending on the reactive power generation limits of the system and IEEE 519-1992 standard.

2.7.1 **Basic Elements of D-STATCOM**

The basic configuration of D-STATCOM consists of:

- Voltage Source Converter
- L-C Passive Filter
- Coupling Transformer
- Reactive power Control Block
- Dc link capacitor

The different components of D-STATCOM are as shown in Figure 2.6

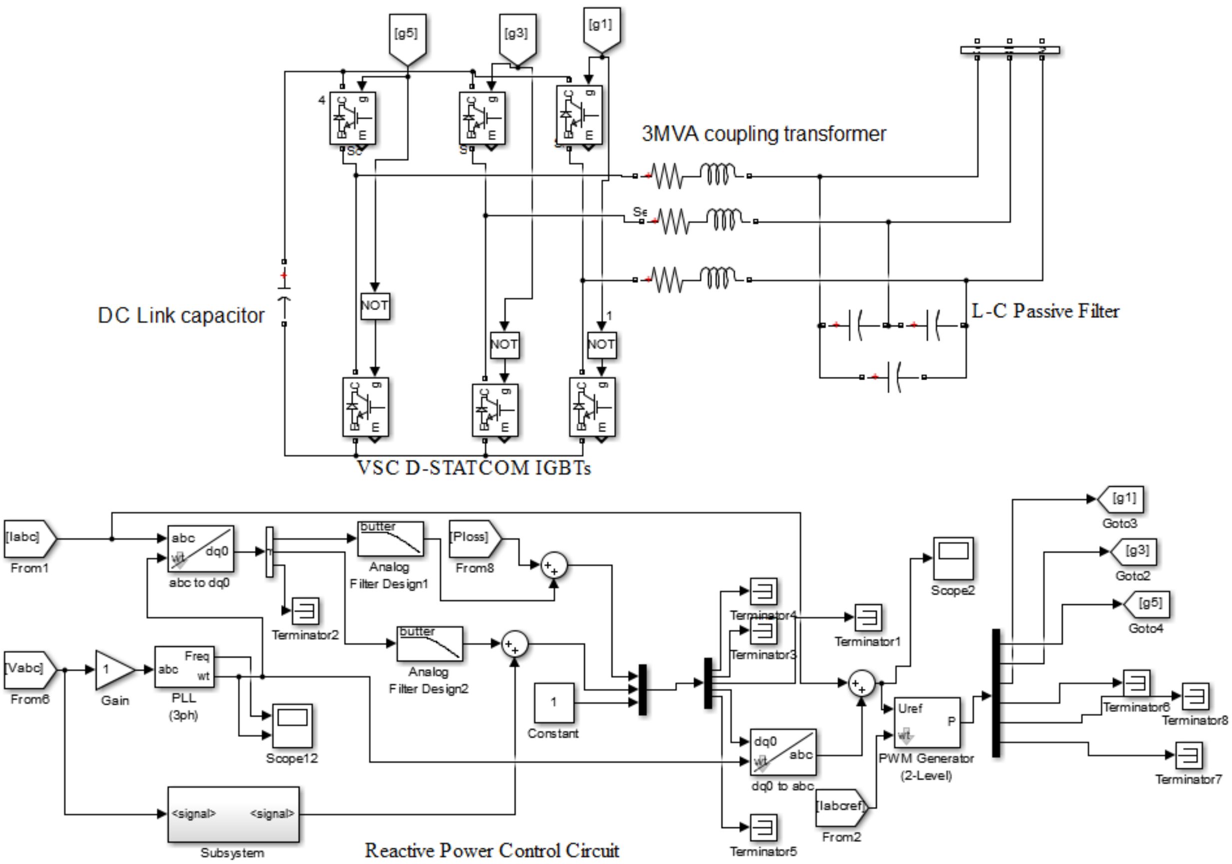


Figure 2.6 Components of D-STATCOM Device

i) Voltage Source Converter

A voltage source converter (VSC) according to the compensation required offers the regulated output voltage in terms of magnitude and phase angle to result in either leading or lagging reactive current. It uses semiconductor medium voltage IGBT technology to perform its operation. It helps in conversion of DC voltage stored in storage dc link capacitor to three-phase AC output.

Advantages of VSC-based transmission

- Independent control of reactive and active power
- Reactive control independent of other terminal
- Simpler interface with ac system
- Provides continuous ac voltage regulation
- Operation in extremely weak systems
- No commutation failures
- No polarity reversal needed to reverse power
- Variable frequency

Operating principle of IGBT based Self-commutated VAR compensator

The Self-commutated VAR compensator is meant for step less (smooth) and dynamic reactive compensation of a given load reactive power demand and is hence used in shunt with the Load. Self-commutated VAR compensators capable of generating or absorbing reactive power without requiring large banks of capacitors or reactors, instead it uses a capacitor with a regulated dc voltage. Self-commutated compensators are used to improve voltage regulation and correct power factor. The compensator uses pulse width modulated (PWM) voltage source converters (VSCs) based IGBTs as the self-commutated power device.

The VSC is a boost converter with output DC voltage greater than peak of the supply voltage.
The fundamental component of PWM voltage reacts with the input supply voltage to produce the desired capacitive or inductive current. The load current feedback from a load is given to the VSC, which calculates the reactive current component. The fundamental component of the PWM voltage is dynamically adjusted to offer exact compensation for the calculated reactive current component of the load current. This relieves the source from supplying any reactive current/VAR.
Neglecting the internal power losses of the overall converter, the control of the reactive power is done by adjusting the amplitude of the fundamental component of the voltage. Its principle of operation is similar to the synchronous machine.

ii) L-C Passive Filter

A passive filter component is a combination of capacitors and inductors that are tuned to resonate at a single frequency, or through a band of frequencies. In power systems, passive filters are used to suppress harmonic currents and decrease voltage distortion appearing in sensitive parts of the system.

Passive filters work by exhibiting different impedance values at the resonant frequency. A filter connected in series should present high impedance to the harmonic frequency that needs to be blocked. Although a series configuration is possible, it is more common to connect filters in parallel. Such a shunt configuration diverts harmonic currents to ground, and simultaneously provide reactive power, which may be used to correct the power factor. As such, passive shunt filters are designed to be capacitive at the fundamental frequency.

The LC filter helps in suppressing harmonics and couples inverter output impedance to that of inverter in order to partake current. The choice of LC filter is established on the grounds of the character of the system and the anticipated harmonics.

iii) Coupling Transformer

Coupling transformer is the medium to couple resultant voltage of VSC to the AC system. This purpose is served by the coupling transformer reactance. The coupling three-phase transformer is star delta connection. This connection of transformer removes harmonics by the delta-connected transformer and distributes the current unbalance.

iv) Reactive Power Control Block

The Control block performs the function of recognizing Power Quality problems like sags and swells in voltage due to load disturbance or fault and compensate for those problems by generating trigger pulses and terminating triggers when the disturbance instant has ended. These trigger pulses are fed to power electronics based PWM inverter.

The main objective of the control scheme is to sustain voltage at constant magnitude level at the Instant whenever a sensitive load is connected that leads to system disturbances. Control technique measures the voltage at the point of common coupling that is to be compensated as per the requirement. The switching pulses for the inverter are derived from the PWM hysteresis control technique. The input to the controller consists of an error signal obtained from the comparison of terminal voltage and reference voltage. Such error is processed by a PI controller the output is the angle δ, which is provided to the PWM signal generator. It is important to note that in this case, indirectly controlled converter, there is active and reactive power exchange with the network simultaneously: an error signal is obtained by comparing the reference voltage with the RMS voltage measured at the load point. The controller process the error signal generates the required angle to drive the error to zero, i.e., the load RMS voltage is brought back to the reference voltage.

Basic Hysteresis Controller

Among various PWM techniques, the hysteresis current controller is more used due to its simple implementation. It does not need any information regarding any load parameters. Its implementation is entirely based on deriving of switching signals from the fixed tolerance band and current error comparison [15]. In this, the actual phase current is compared with the predefined tolerance band. In this, the switching frequency can be varied depending upon the load conditions leading to inverter operations as irregular.

Hysteresis Controller

It is for the track down of reference current. Instantaneous source current and reference current are compared within the small hysteresis band and the resultant error signal is 1-5% of the current level. Here the logic used is as $I_{Sa}<i_{Sa}^{*}-h_{b}$

For better track down of source currents, a narrow hysteresis band is preferred with condition of higher switching frequency. Figure 2.7 shows Hysteresis Controller.

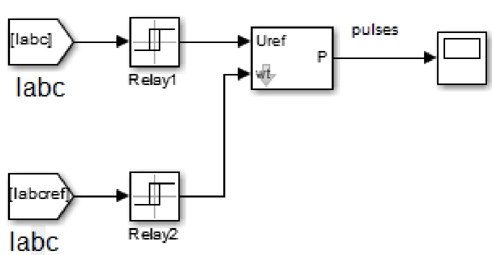


Figure 2.7 Hysteresis Controller

V) Dc-Link Capacitor

The dc-link-capacitor is a load-balancing energy storage element between the dc (battery) and ac (load) sides of a VSC. This component is connected parallel to the battery in order to maintain a stiff dc-link voltage across the VSC. In other words, a required amount of dc-line current ripple is needed to suppress the generated electro-magnetic interference (EMI) caused by pulsed inverter current and stray inductance and resistance of the dc-bus.

2.8 Principles of Reactive Power Control

Amplitude regulation of the D-STATCOM output voltage controls the reactive power exchange of the D-STATCOM with the AC system. Reference currents used to decide switching of D-STATCOM has real fundamental frequency component of load current, which is drawn with the help of IRP and SRF techniques. Here by controlling D-STATCOM reactive power needed by load is provided by D-STATCOM and hence voltage regulation at the load end is achieved and also the harmonic contents in the source currents are eliminated. In addition to IRP and SRF theories, two PI controllers are used one for DC bus voltage and other is for AC bus voltage control at the point of common coupling (PCC).

Simplified single phase Y equivalent model of D-STATCOM is given in Figure 2.8

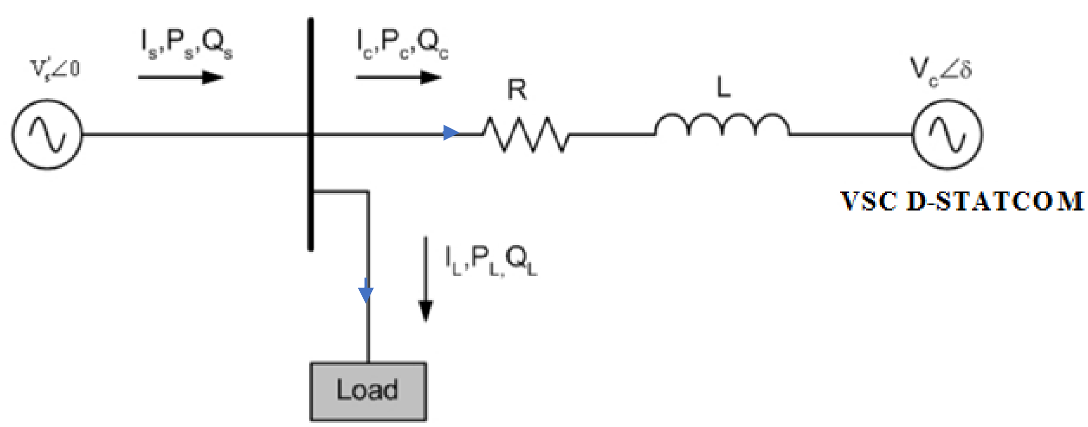


Figure 2.8 Simplified Model of D-STATCOM

V_s - RMS line-to-neutral AC grid voltage with a phase angle of zero referred to D-STATCOM side.

V_c - RMS line-to-neutral D-STATCOM fundamental voltages

I_s - RMS source current

I_{L}- RMS load current

I_c -RMS D-STATCOM current

Q_s- Source reactive power

Q_L- Load reactive power

Q_c - DSTATCOM reactive power

δ - Phase angle between fundamental voltage of D-STATCOM and AC grid

R-Y equivalent total loss resistance including coupling transformer losses, series inductor losses and converter losses

L - Y equivalent total inductance including source inductance, leakage inductance of coupling transformer and input filter inductance.

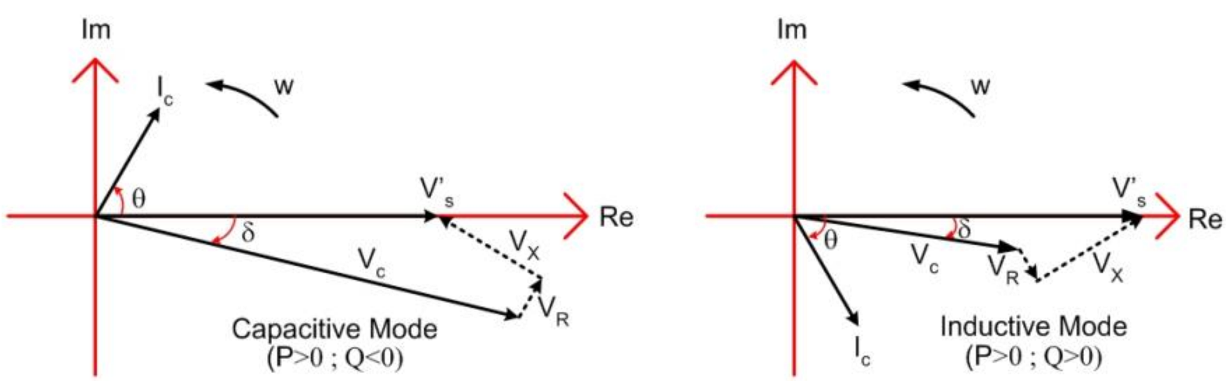


Figure 2.9 Phasor Diagrams of D-STATCOM Operating Systems

Kirchhoff's voltage equations for the circuit in Figure 3.4 can be written as follows.

$$\bar{V}_s = \bar{V}_c + \bar{V}_r + \bar{V}_x \qquad (2.3)$$

Where X=$2\pi f L$, $\overline{Vr}$=RIc , $\overline{Vx}$=jXIc

By resolving $\bar{V}_r$ and $\bar{V}_x$along Re and Im axes we can obtained.

$$V_s - V_c \ \cos\delta = (\mathrm{R}\cos\theta + X\sin\theta)I_c \tag{2.4}$$

$$V_c \cos\delta = (\mathrm{X}\cos\theta \ + R\sin\theta)I_c \tag{2.5}$$

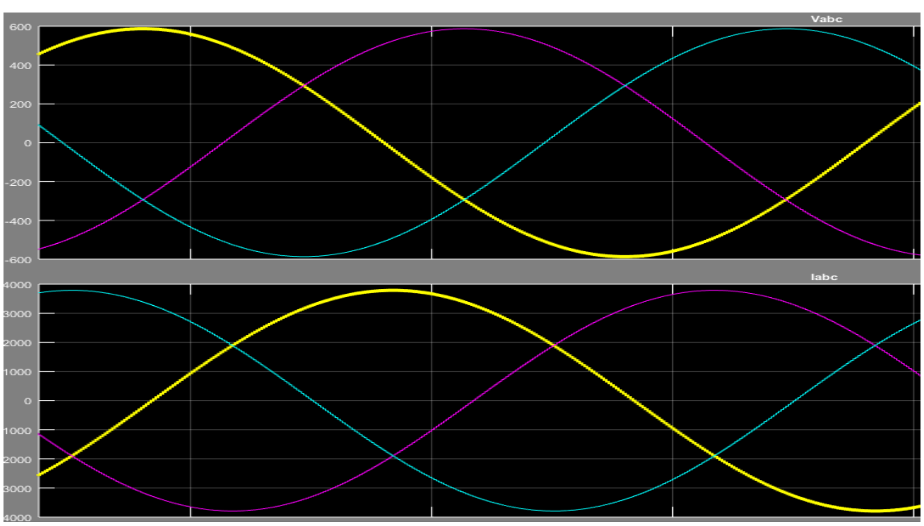
On the other hand, active and reactive power consumed by the D-STATCOM from the supply can be expressed as in below

$$P_c = V_s I_C \cos\theta \tag{2.6}$$

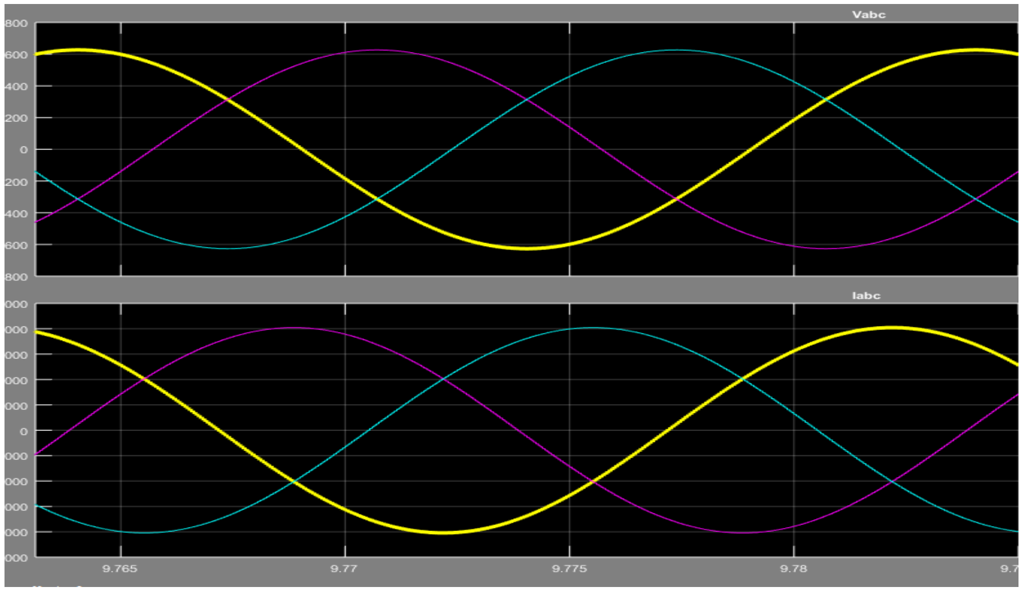
$$Q_c = V_s I_C \ \sin\theta \tag{2.7}$$

In the lossless system, D-STATCOM voltage is in phase with the AC line voltage and line current is purely reactive. If Vc is equal to Vs, reactive power generation is zero. If Vc<Vs, a current is induced which lags V_X. This current also lags Vs since V_X is in phase with Vs. Therefore, AC grid sees this current as inductive and D-STATCOM is said to be operating in inductive mode.

If $V_c > V_s$, a current is induced which lags V_X. However, this current leads Vs since V_X is in opposite direction with Vs. Therefore, AC grid sees this current as capacitive and D-STATCOM is said to be in operating capacitive mode. Voltage and current waveforms of AC grid and D-STATCOM is in Figure 2.10 for the ideal case.



Inductive Mode of Operation



Capacitive Mode of Operation

Figure 2.10 Inductive and Capacitive Mode of D-STATCOM opration

During operation of D-STATCOM in transient state, the DC link capacitor is to be charged and discharged periodically. Active power will flow from the supply to the DC link or vice versa through the converter. This condition makes necessary a finite load angle δ between V's and Vc although its value is small. Furthermore, input filter and VSC have their own losses which necessitates the flow from the supply for operation even in the steady state (DC link voltage is constant). For this case the following inequalities hold over the entire operating range (from full inductive to full capacitive).

$$\left.\begin{aligned} 0 \le\ & \delta \le 2.5^{\circ} \\ 89 \le\ & \theta \le 90^{\circ} \end{aligned}\right\}$$ in steady state condition

$-5 \le\ \delta \le 5^{\circ}$ in the transient state condition

Therefore, in the steady state following approximations can be made where ever

needed.

Sin$\delta \cong \delta$ where δ *is* expressed in radians

sin$\theta \cong 1$ and cos$\theta \cong 0$

These approximations yield alternative equation sets given below

$$\begin{bmatrix} P_c \cong \frac{V_s V_c}{X} sin\delta_c & Q_c \cong V_s \frac{V_s - V_c\ cos\delta}{X} \\ P_c \cong \frac{V_s V_c}{X}\ \delta & Q_c \cong V_s \frac{V_s - V_c}{X} \end{bmatrix} \quad (2.8)$$

It can be deduced from Pc and Qc that D-STATCOM absorbs active power even at zero reactive power because of converter losses. Let us assume the relationship between Vc and dc link voltage Vd is given in terms of a constant k.

$$V_c = KV_d \quad (2.9)$$

By substituting the above equation in

$$P_c \cong \frac{\acute{V}_S}{X} KV_d \sin\delta \quad (2.10)$$

$$Q_c \cong \frac{\acute{V}_S}{X} (\acute{V}_S - KV_d \cos\delta \quad (2.11)$$

In order to approximate input voltage of VSC to a pure sine wave at fundamental frequency, Pulse Width Modulation (PWM) or Pulse Amplitude Modulation (PAM) technique can be applied. For this case, peak value of fundamental component of VSC input voltage (line-to-neutral, Vc) can be related to dc link voltage in terms of modulation index ma as given in equation below by assuming a two-level line-to-neutral ac voltage.

$$V_C = m_a \frac{V_d}{2} \quad (2.12)$$

$$K = 0.35 m_a$$

$$P_C = 0.35 m_a \frac{\acute{V}_s}{X} V_d \sin\delta \quad (2.13)$$

$$Q_C \cong 0.35 \frac{V_s}{X} (\acute{V}_s - 0.35 m_a V_d \cos\delta) \quad (2.14)$$

Two different operation modes arise from Qc.

1. If 0.35 V_d m_a cos δ is smaller than Vs', then Qc becomes positive and hence VSC absorbs reactive power from the almeda textile load (inductive operation mode).

2. If 0.35 V_d m_a cos δ is larger than Vs', then Qc becomes negative and hence VSC delivers reactive power to the almeda textile load (capacitive operation mode).

Therefore, different control techniques can be applied in order to change 0.35 V_d m_a cosδ term. Since δ is smaller than 2.5° in the normal working range of D-STATCOM, cos δ ≅1 can be assumed.

2.9 Exchange of Active Power

There is a requirement of a DC capacitor to provide real power to the switching devices used in the D-STATCOM. When direct voltage control is required, real power exchange is demanded by an AC system in order to maintain capacitor voltage constant. In case of distribution system with very low voltage or faults, external DC source is provided in D-STATCOM to regulate voltage when there is a real power exchange with the AC system. If the system voltage lags the VSC voltage then real power form the DC source will be injected to the AC system in order to regulate system voltage or to maintain constant capacitor voltage as in (2.13).

2.10 D-STATCOM Control Strategies

i) Synchronously Rotating Reference Frame Theory

Synchronously Rotating Reference Frame (SRF) Theory is based on transformation of three phase a-b-c quantities to two d-q phase synchronously rotating reference frame quantities. Figure 2.11 shows the basic block diagram of SRF theory. The three phase load currents (I_{La} , I_{Lb} , I_{Lc}), are given to the Parks Transformation which gives two phase synchronously rotating reference frame currents (I_{Ld} ,I_{Lq})
Park's Transformation is given below,

$$\begin{bmatrix} I_{ld} \\ I_{lq} \\ I_{lo} \end{bmatrix} = 2/3 \begin{bmatrix} coswt & -sinwt & 1/2 \\ \cos\left(wt - \frac{2\pi}{3}\right) & -\sin(wt - \frac{2\pi}{3}) & 1/2 \\ \cos\left(wt + \frac{2\pi}{3}\right) & \sin\left(wt - \frac{2\pi}{3}\right) & 1/2 \end{bmatrix} \begin{bmatrix} I_{la} \\ I_{lb} \\ I_{lc} \end{bmatrix} \tag{2.15}$$

Where wt=θ which is transformation angle, calculated by using Phase Locked Loop (PLL) circuit. Inputs to the PLL is three phase AC voltages V_{sa},, V_{sb}, V_{sc} as shown in the Figure 2.11 Similar to the IRP theory, PI-controller I and PI-controller II are used for DC voltage regulation D-STATCOM and AC voltage regulation at the Point of Common Coupling (PCC) .phase synchronously rotating reference frame currents I_{ld} and I_{lq} has oscillatory as well as DC component, so that the Low Pass Filters (LPF) are used to separate them and only DC components are passed further.

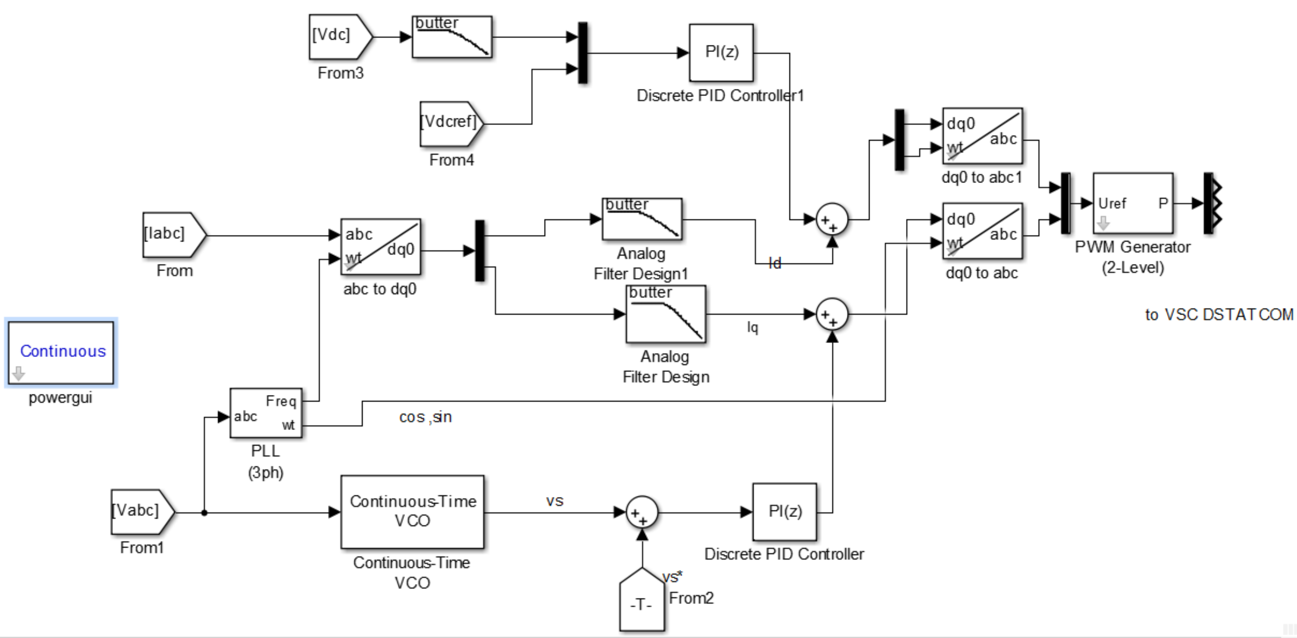


Figure 2.11 Block Diagram of Reference Current Generation Using SRF Theory

Again by using Inverse Park's Transformation, d-q reference frame currents are converted to a-b-c reference frame currents.

$$\begin{bmatrix} I_{la}^* \\ I_{lb}^* \\ I_{lc}^* \end{bmatrix} = 2/3 \begin{bmatrix} coswt & \cos\left(wt - \frac{2\pi}{3}\right) & \cos\left(wt + \frac{2\pi}{3}\right) \\ -\sin wt & -\sin(wt - \frac{2\pi}{3}) & \sin\left(wt + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} I_{ld} \\ I_{lq} \\ I_{lo} \end{bmatrix} \quad (2.16)$$

In addition, similar to IRP theory these three phase currents are given to Hysteresis Band Current Controller to generate gate signals to D-STATCOM IGBT.

2.11 PWM Techniques Employed in D-STATCOM Application

The ultimate purpose in the design of a D-STATCOM for medium voltage (MV) applications is to generate fully controllable sinusoidal line currents on the MV side of D-STATCOM system. Line current waveforms of D-STATCOM can be approximated to a sine wave, which should comply with IEEE 519-1992 primarily by the use of a proper PWM technique and secondly by carefully designing the input filter of D-STATCOM. In the case where reactive power control is based on the variation of modulation index ma and PWM becomes an indispensable part of the reactive power control algorithm.

i) Sinusoidal Pulse Width Modulation Technique

Sinusoidal Pulse Width Modulation (SPWM) technique is used to control the fundamental component of the line-to-line converter voltage. Three-phase converter voltages are obtained by comparing the same triangular voltage with three sinusoidal control voltages. The frequency of the triangular voltage (fs, carrier frequency) determines the converter switching frequency and the frequency of the control voltages determine the fundamental frequency of the converter voltage (f1, modulating frequency). Hence, modulating frequency is equal to supply frequency in DSTATCOM.

Amplitude modulation ratio m_a is defined as:

$$m_a = \frac{v *_{control}}{v *_{tri}} \quad (2.17)$$

where V* control is the peak amplitude of the control voltage and V* tri is the peak amplitude of the triangular voltage. The magnitude of the triangular voltage is kept constant and the amplitude of the control voltage is allowed to vary. Linear range of SPWM is defined for $0 \leq m_a \leq 1$ and over modulation is defined for $m_a > 1$.

Frequency modulation ratio mf is defined as :

$$m_f = \frac{f_s}{f_1} \tag{2.18}$$

m_f must be chosen as an odd integer to form an odd and half wave symmetric converter line-to-neutral voltage (V_{AN}). Therefore, even harmonics are eliminated from the V_{AN} waveform. Moreover, mf is chosen as a multiple of 3 in order to eliminate the harmonics at mf and odd multiples of mf in the converter line-to-line voltages.

Harmonics in the converter voltages appear as sidebands, centered on the switching frequency and its multiples. This is true for all values of main the linear range.

The frequencies of converter output voltage harmonics can be expressed as:

$$f_h = (jm_f \pm k)f_1 \tag{2.19}$$

The fundamental component of the converter line-to-neutral voltage varies linearly with the amplitude modulation portion ma irrespective of the frequency modulation ratio mf as in (2.18). Fundamental component of the converter line-to-line voltage is also expressed in (2.21).

$$V_{AN} = m_a \frac{V_d\text{v}}{2};\ m_a \leq 1 \tag{2.20}$$

$$V_{LL} = \frac{\sqrt{3}}{2\sqrt{2}} m_a V_d = 0.612 m_a V_d\ ;m_a \leq 1 \tag{2.21}$$

In SPWM, switching harmonics occur in high-frequency range around the switching frequency and its multiples in the linear range. Maximum available amplitude of the fundamental frequency component is 0.612maVd.

The constant value of DC link voltage is determined according to highest D-STATCOM fundamental voltage in the operation range from full inductive to full capacitive mode at minimum and maximum supply voltages.

Therefore, for $0 \leq m_a \leq 1$;

$$V_d > m_a \frac{V_{LL\prime max}}{0.612} \tag{2.22}$$

2.12 Software Tools

i) ETAP Software Tool

ETAP stands for Electrical Transient and Analysis Program (software program for electrical engineers) which is a full spectrum analytical engineering software company specializing in the analysis, simulation, monitoring, control, optimization, and automation of electrical power systems. ETAP software offers the most comprehensive and integrated suite of power system enterprise solution that spans from modeling to operation.

ii) MATLAB software tool

The name MATLAB stands for Matrix Laboratory. MATLAB was written originally to provide easy access to matrix software developed by the LINPACK (linear system package) and EISPACK (Eigen system package) projects. MATLAB [1] is a high-performance language for technical computing. It integrates computation, visualization, and programming environment. Furthermore, MATLAB is a modern programming language environment: it has sophisticated data structures, contains built-in editing and debugging tools, and supports object-oriented programming. These factors make MATLAB an excellent tool for teaching and research.

There are different applications present in MATLAB software; from the different applications, the thesis work used MATLAB Simulink to represent the Almeda textile factory in a short hand system. Using this software tools I draw the industry load system, the D-STATCOM system with its control circuit system in a precisely short form. For this it has been designed the D-STATCOM controller to improve the low power factor of the factory using MATLAB Simulink software.

Algorithms of MATLAB Simulink

The software components of this thesis are tasked with performing many mathematical functions, as well as the input-output actions that are required to accomplish them. When compiling the list of algorithms, we kept in mind the idea of modularity in that all systems should have the ability to perform an individual unit test for functionality without requiring the use of other source code.

Table 2.1 Different Algorithms Needed in the Control Circuit of D-STATCOM

Algorithm	Description
Data Acquisition	Samples input waveforms scaled to a maximum value of 3.6V and converts to a digital format to be handled by a conversion factor.
PLL	Provides ramp output locked to the peaks of phase A source voltage.
Forward Park Transform	Generates 3-phase sinusoidal data from the PLL input and various sinusoid data and computes the Park's transformation to produce d and q quantities for use in the control loop.
PI Control	Executes a PI controller function complete with anti-windup functionality to limit the value of output within physical limitations.
Control Loop	Uses calculated values and PI Control to execute the mathematical operation required for the decoupled current control.
Inverse Park Transform	Uses output from the Control Loop to compute the inverse Park's transformation on the data to generate sinusoidal data.
PWM	Compares sinusoidal data to a known threshold to generate a sinusoidal varying duty cycle which is given to a control register to update the high-speed PWM module on the dsPIC.

Phase Locked Loop (PLL)

The phase locked loop (PLL) is an important element in the D-STATCOM controller, used for tracking the line frequency. The PLLs used based on the PI controller and the Park’s transformation algorithm. The realization of PI controller with proper values of proportional gain (Kp) and integral gain (Ki) in Field Programmable Array (FPGA) will increase its processing time. To overcome this problem, the stationary reference frame based simple mathematical model is realized for the PLL. Mathematically realized PLL is more convenient to program the FPGA in hardware implementation. This is used to get the line frequency information for the synchronous reference frame transformation.

The PLL is used to obtain an accurate synchronization to the grid. It is required in almost all the equipment's connected to the grid to obtain the frequency information.

To transfer the variables from the abc frame to the synchronous reference frame (qd0), the transformation angle (θ= wt) is required. The transformation angle θ is the angle between the $\alpha\beta$ $-$frame and the qd0-frame.This transformation angle can be obtained by using the PLL, which ensures that the qd-frame is synchronized with the grid. If the voltage vector is defined in parallel with the q-axis in the qd-frame, the transformation angle can be defined using Equations

$$\bar{V} = v_a + jv_b \tag{2.23}$$

Transform angle θ can be defined using

$$\sin\theta = \frac{v_\alpha}{v} \quad \cos\theta = -\frac{v_\beta}{v}$$

$$v = \sqrt{v_\alpha^2 + v_\beta^2} \tag{2.24}$$

To get the transformation angle, the PLL is realized mathematically in the MATLAB. The three-phase instantaneous voltages are denoted by v_α and. The corresponding voltages are transformed in to $\alpha\beta$-frame and are denoted by vα, and v_β . For a balanced three-phase system, vα, and vβ will be present while the v_o component is zero. Figure below shows the block diagram of the mathematically realized PLL, which is used in this thesis.

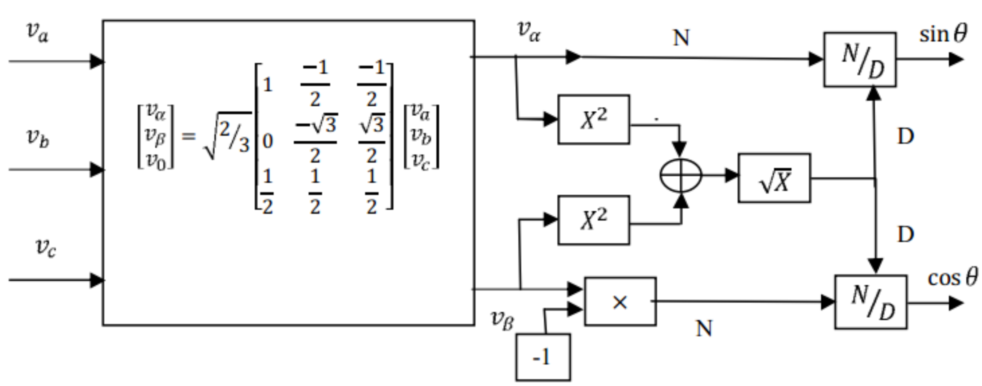


Figure 2.12 Mathematical Realization of the PLL Block

Analysis of the Basic Controller

The design of the controller is very important for proper operation of the DSTATCOM. As the DSTATCOM is connected in shunt to a three-phase system, it is necessary to control its real and reactive powers. Equations below give the real and reactive powers in the abc coordinate system

$$\mathrm{P} = V_a I_a \cos \mathrm{wt} + V_b I_b \cos(\mathrm{wt} - \frac{2\pi}{3}) + V_c I_c \cos(\mathrm{wt} + \frac{2\pi}{3}) \tag{2.25}$$

$$\mathrm{Q} = V_a I_a \sin wt + V_b I_b \sin(\mathrm{wt} - \frac{2\pi}{3}) + V_c I_c \sin(\mathrm{wt} + \frac{2\pi}{3}) \tag{2.26}$$

where, V_a , V_b, V_c are the phase voltages (V) I_a, I_b , I_c are the phase currents (A) and cos wt is the power factor.

From Equations above, it can be observed that the P and the Q can be controlled by controlling the phase voltages or phase currents or the angle between them (the power factor angle). Controlling the instantaneously varying three-phase quantities is challenging in the abc frame.

Total demand distortion

Current distortion levels can be characterized by a THD value, as has been described, but this can often be misleading. A small current may Total demand distortion Current distortion levels can be characterized by a THD value, as has been described, but this can often be misleading. A small current may

$$\mathrm{TDD} = \frac{\sqrt{\sum_{h=2}^{hmax} Ih^2}}{I_l} \tag{2.27}$$

$I_L$is the peak, or maximum, demand load current at the fundamental frequency component measured at the point of common coupling (PCC). There are two ways to measure I_L. With a load already in the system, it can be calculated as the average of the maximum demand current for the preceding 12 months. The calculation can simply be done by averaging the 12-month peak demand readings. For a new facility, I_L has to be estimated based on the predicted load profiles.

2.13 Methodology

i) Data Collections

The necessary data for the thesis are collected from different sources of Almeda textile factory. The necessary data's are:

- The average energy consumptions of the factory for the last twelve months (one year).
- The current production cost of the factory and energy bill.
- Measurements like 3-phase voltage, 3-phase current, power factor.

The performances of the whole data are analyzed quantitatively and qualitatively.

Depending on the assessed data opportunities to improve the power factor of the factory and to reduce loses are done. From the analyzed data, conclusion and recommendation have been forwarded.

The currently operating electrical parameters of Almeda textile factory displayed at EEU distribution substation are as in the table 2.2.

Table 2.2 Almeda Textile Load Profiles

	Bus Voltage, [KV]	Minimum line to line Current, [A]	Maximum line to line Current, [A]	Minimum apparent power due to the Min line current, [KVA]	Maximum apparent power due to the Max line current, [KVA]	Average power factor	Frequency In, [Hz]
The whole load of the factory directly recorded data at primary side of transformer	15	132	192	3429.5	4988	0.66	50

Samples of transformers data			
Type of recoreded data	Transformer$_2$ (1MVA)	Transformer$_9$ (1.25MVA)	Transformer$_7$(1.6MVA)
U_{12},[V]	397	396	390
U_{23},[V]	395	395	389
U_{31},[V]	396	395	388
V_1,[V]	230	230	226
V_2,[V]	228	228	224
V_3,[V]	227	227	223
I_1,[A]	568	571	863
I_2,[A]	558	559	845
I_3,[A]	549	550	831
Frequency(HZ)	50.05	50.02	50.03
PF_1(Power factor)	0.702	-	-
PF_2	0.675	-	-
PF_3	0.704	-	-
Average PF	0.694	-	-

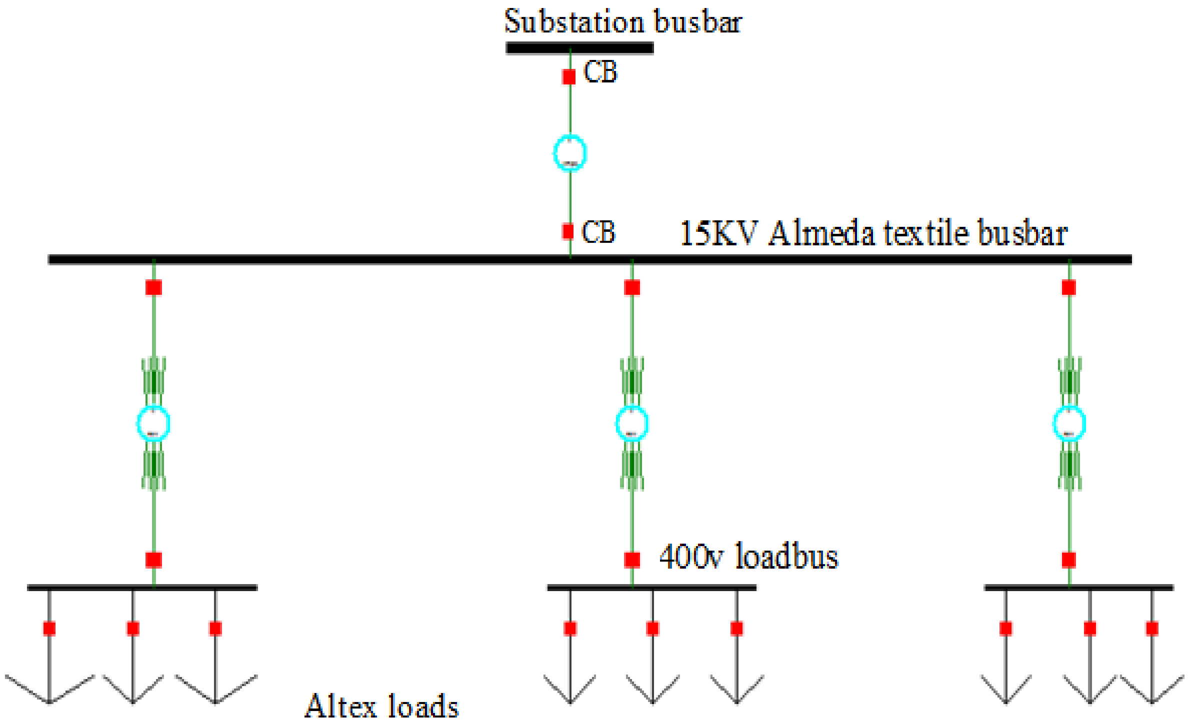


Figure 2.13 Power World Design of Single-Line Diagram Loads Connected to T_1(transformer), T_2 and T_3

Due to the operating of low power factor of the factory, EEU charges around 69000Birr monthly as indicated the samples of EEU bill of charged of the factory in table 2.3 and as the bills in appendixes A.

Table 2.3 Power Factor Charges of Almeda Textile Factory

No.	Sample bill of months	Amount of power factor charges	Operating Power factor
1	01/06/2016 G.C	68,592.03birr	0.66 lagging
2	01/09/2016G.C	69,914.14birr	

The total designed energy consumed by the factory as the tables in appendixe B is

W_T =2642186 + 1231306+ 876482.88+ 202373+ 71071+ 653869+ 233002+ 14394069+ 375022+201006=20.9TWh

$$\text{Energy} = \text{power} * \text{time}$$

$$\text{Power} = \frac{Energy}{time} \quad (2.28)$$

This energy is consumed by the factory within one hour period.

$$\text{So} \quad P = \frac{W}{t}$$

$$P_T = \frac{W_T}{t} = \frac{20.9TWh}{3600} = 5800\text{KW}$$

The total apparent power can be calculated using the total active power. Most of industrial application power factor is designed to operate near 0.9 and above, (IJETT) – Volume 4 July 2013 from this point of view the apparent power of Almeda textile factory is calculated as active power divided by internationally acceptable industrial power factor, which is approximately 0.9 lagging.

$$S = \frac{P_T}{PF} = \frac{5800}{0.9} = 6444.4\text{KVA}$$

From the designed apparent power the designed primary load current can be calculated as

$$S = \sqrt{3} \times V_L \times I_{PL}$$

$$I_{PL} = \frac{S}{\sqrt{3 \times V_L}} = \frac{6444.4KVA}{\sqrt{3 \times 15KV}} = 248\text{A}$$

This is the maximum primary load current of the total designed energy consumption of the factory.

CHAPTER THREE

Mathematical Design of Voltage Source Converter Based D-STATCOM

3.1 Design of Voltage Source Converter D-STATCOM parameters

On this chapter, depend on the factory data, designs the reactive power needed to improve the low power factor of the factory. Depend on the reactive power requirements the component rating of the D-STATCOM are designed. From the required reactive power for the power factor improvement the load reactive power rating, the component rating of the D-STATCOM such as the compensation current, medium voltage IGBT collector current, coupling transformer rating, DC link capacitor rating, filter ratings, energy transfer of the dc link capacitor are obtained. Depending on the designed parameters of D-STATCOM, the output power factor is designed mathematically as well as simulated using MATlab soft wares for both before and after correction of the factory power factor.

Table 3.1 Given Data from the Almeda Textile Factory

Types of Data	Amount
Input primary voltage(V_{LP})	15KV
Input primary load current(I_{LP},I_{L-L})	248A,
Currently operating power factor	0.66 or $\theta = 48.7^0$
Total energy consumption of the factory (W_T)	20.9 TWh

3.2 Mathematical Analysis of Electrical Parameters of Almeda Textile Factory

The Designed consumed total energy of the factory as indicated from the appendix B is

$$\text{Total consumed energy } (W_{T})=20880386.9\text{KWh}$$

$$\text{Designed total power } =\frac{energy}{time}$$

$$\text{Time } =1\text{hour}$$

The designed total power P_T is calculated as $P_T=\frac{W_T}{t}=\frac{20.9\text{TWh}}{3600s}= 5800\text{KW}$

Even if the IEEE standard acceptable power factor of an industrial application is above 0.85 lagging but in most of the world countries the acceptable load power factor is 0.9 and above . From this point of view the designed reactive and apparent power of the Almeda textile factory is calculated as

Apparent power (S) $= \frac{P_T}{PF}$ by setting power factor to 0.9 lagging

Apparent power (S)$= \frac{P_T}{PF} = \frac{5800\text{kw}}{0.9}= 6444\text{KVA}$ and the reactive power is

$Q=\sqrt{S^2-P^2}$, $Q=\sqrt{6444^2-5800^2}=2808\text{KVAR}$

From this the possible designed line current is calculated as

$S=\sqrt{3}\text{x}I_L\text{x}V_L$, $I_{PL}=\frac{S}{\sqrt{3\times V_L}}=\frac{6444.4KVA}{\sqrt{3\times 15KV}}=248\text{A}$

All distribution transformers of Almeda textile factory are connected in delta-star $(\Delta - Y)$ with a voltage ratings of 15kv/400v. Using transformation ratio of three phase transformer (($\Delta - Y$) the secondary load current can be calculated as

Primary line to line voltage (V_1) =15kv,

Secondary line to line voltage (V_2) =400V, V2 $=\sqrt{3}V_{phase}$

Primary line to line current (Ip) = $\sqrt{3}I_{phase}$

Secondary line to line current (Is)= I_{phase} , from this the secondary line current is calculated as

$$\frac{V_1}{V_2}=\frac{I_2}{I_1},\quad \frac{15000V}{400V}=\frac{I_2}{248},\quad I_2=\frac{15000\times 248}{400}=9300A$$

Therefore, the designed power parameters of Almeda textile factory are:-

S=6444KVA, P=5800KW, Q=2808KVAR, I_L=248A

The factory currently operating active and reactive powers are calculated as:

$P_1 = S\times\cos\theta$ Where $\theta = 48.7$

$P_1=S\times\cos\theta$ =6444kva×cos48.7=4253KW

$$Q_1 = S \times \sin\theta = 6444\text{kvar} \times \sin 48.7 = j4841\text{kvar}$$

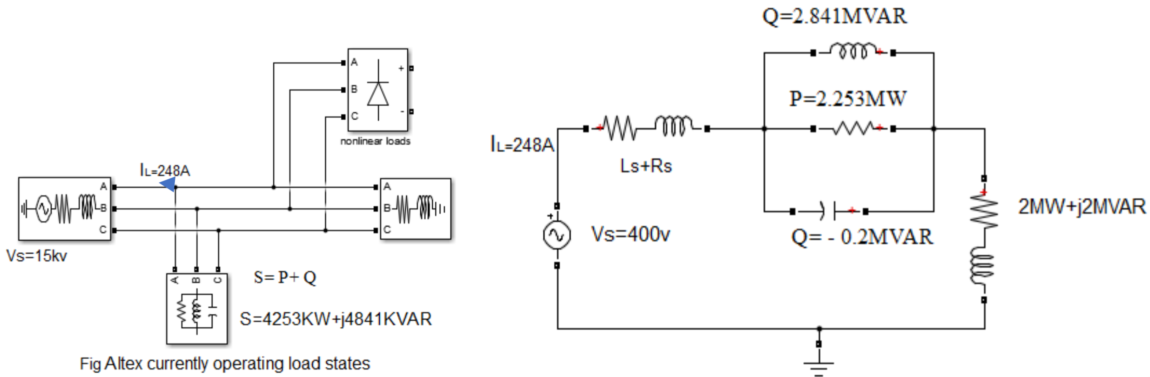


Figure 3.1 Almeda Textile Currently Operating Load States

3.3 Designing the Size of D-STATCOM Parameters for Almeda Textile

This thesis work designed to improve the power factor of the factory from presently operating 0.66 lagging to between 0.85 & 0.95 lagging . depend on IEEE standared in most of the world countries power factor correction is considered from 0.92 lagging and above (IJETT) – Volume 4 July 2013. From this concept designed power factor after correction is to get $0.92 \; or \; \theta_1 = 23$, from this the power parametries, when the power factor improved from 0.66 to 0.92 lagging are

$$P_2 = S \times \cos\theta 1 = 6444 \times \cos 23 = 5928.5KW$$

$$Q_2 = S \times \sin\theta 1 = 6444 \times sin 23 = 2518Kvar$$

From this the reactive power to be compensated is

$$Q_{new} = Q_2 - Q_1 = (2518-4841)\text{ kvar} = -2323\text{kvar}$$

As in (IJETT) – Volume-40 October 2016 giving 10% tolerance

$$Q_3 = Q_{new} \times 10\% = 2555\text{kvar}$$

The D-STATCOM size to compensate the reactive power of 2323kvar is 2555kvar.

Converters having a power level in the neighborhood of one mega volt amper use mostly high voltage (HV) power semiconductors. The voltage ratings of available HV power semiconductors for these power levels are 2500 V, 3300 V and 4500 V. Switching frequency of 3.3 kV HV IGBT modules should be kept around 1 kHz in order to have 1 % converter active power loss. The rating of the D-STATCOM is almost fully reactive power with on the D-STATCOM IGBT switches 1% active power dissipation.

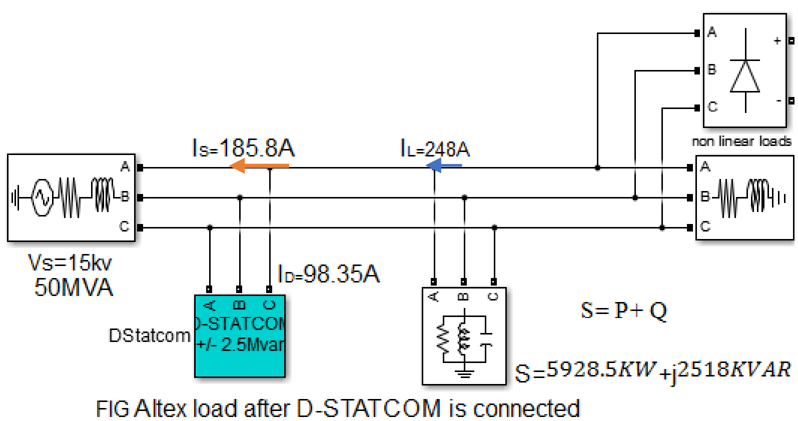
From this concept the active power of the D-STATCOM is calculated as

$$P = Q \times 1\% = 25.55\text{kw}$$

Apparent power of the designed D-STATCOM is

$$S = \sqrt{Q^2 + P^2} = 2555.13\text{KVA}$$

So 2555.13kvar rating of D-STATCOM is used to compensate the reactive power or the power factor to be corrected from 0.66 to between 0.85 to 0.95 lagging.



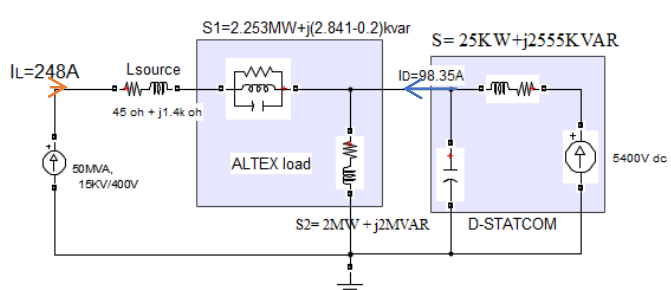


Figure 3.2 Simplified Electrical Circuit of Altex Load With D-StATCOM

Depending on the manufactured rating of VSC D-STATCOM, the rating of the IGBT can be calculated as follows:-

The D-STACOM primary coupling Transformer voltage is 15KV and depend on the operating voltage rating of collector to emitter voltage of the IGBT switches, the secondary transformer voltage is sated to 3.3kv.

To calculate the coupling transformer primary current

S=2555.13 KVA , Q=2555 KVAR , P=25.55KW,

$V_{primary}$=15kv, $I_{primary}$=?

So $S=\sqrt{3}\times Ip\times V_L$,

$I_{primary}=\frac{S}{\sqrt{3}\times VL} = \frac{2555.13KVA}{\sqrt{3}\times 15KV}$ = 98.35A=Current primary of D-STATCOM coupling transformer

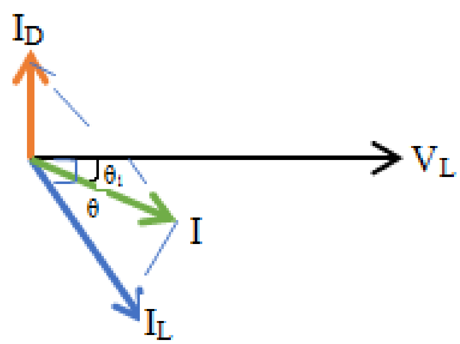


Figure 3.3-Phasor Diagram of Resultant Current After Power Factor Correction

From the phasor diagram above I_L is lagging load current, which is a current operating at an angle of ALTEX load which is:

$I_L<48.7^0$ = 248<48.7 A

I_D is D-STATCOM current, which is at angle of 90 degree, or leading current

That is I_D<90=98.35<90=j98.35A

I is the phasorically calculated resultant current or the current which gets after power factor correction or after the rated D-STATCOM is connected in shunt to the load. So the resultant current I is calculated as:

$I= I_L<48.7 - I_D<90 = (248\cos48.7+j248\times\sin48.7)\ A-(98.35\times\cos90+j98.35\times\sin90)$

$$= (163.68+j186.3)A-(0+j98.35A)=163.68+j(186.3-98.35A)$$

$$=163.68+j87.95, \quad I=185.8<28.2$$

From this $\theta_1 = 28.2^0$ and depending on this result the new power factor of the Almeda textile load is $\cos^{-1}(28.2^0)$ which is 0.88 lagging. From this point of view the load power factor is improved from the previously 0.66 to the newly improved power factor of .88 lagging.

After the power factor improves, the resultant load current on the primary 15KV transformer is reduced from 248<48.7 to 185.8<28.2

From this result we can conclude that, when the power factor improves:

- Power loss decreases (I^2R)
- Life time of the equipment increases
- The size of power cables decrease
- Reducing energy bill of charges

The new secondary load current of the factory is calculated as

$$\frac{V_p}{V_s} = \frac{I_s}{I_p}, \quad \frac{15kv}{400v} = \frac{I_s}{185.8}, \quad I_s=6967A$$

Which is reduced from 9300A<48.7 to 6967A<28.2. this is due to the improvement of the load power factor from 0.66 lagging to 0.88 lagging

Table 3.2 Mathematical Analysis Result of Almeda Textile Factory and D-STATCOM Size Designs

Name		Amount in number
Energy [KWH]		20880386.9
ALTEX designed electrical parameters	Apparent power S [KVA]	6444
	Active power P [KW]	5800
	Reactive power Q [KVAR]	2808
	Power factor [cosθ]	$\geq$ 0.9
Currently operating electrical parameter's of the factory	Apparent power S [KVA]	6444
	Active power P [KW]	4253
	Reactive power Q [KVAR]	4841
	Power factor [cosθ]	0.66
	Primary current [A]	248
	Secondary current [A]	9300
D-STATCOM electrical parameters	Apparent power S [KVA]	2555.13
	Active power P [KW]	25.55
	Reactive power Q [KVAR]	2555
	Primary current [A]	98.35
	secondary current [A]	447
	IGBT collector current [A]	447
After the D-STATCOM connected to the load the electrical parameters of Almeda textile factory becomes	Apparent power S [KVA]	6444
	Active power P [KW]	5928.5
	Reactive power Q [KVAR]	2518
	Power factor [cos$\emptyset$]	0.88
	Primary current [A]	185.8
	Secondary current [A]	6967A

Depend on the transformer transformation ratio formula the secondary current of the D-STATCOM coupling transformer can be calculated as:

$$\frac{V_p}{v_s}=\frac{I_s}{I_p}\ ,\quad \frac{15kv}{3.3kv}=\frac{I_S}{98.35A}=\mathrm{I_s}=\frac{15\text{kv}\times 98.35\text{A}}{3.3kv}=447\text{A}$$

The secondary current of coupling transformer is 447A and the line current of the medium voltage IGBT is 447A , Since on the manufacturer data sheet of IGBT, the calculated current is not available the next rating of medium voltage IGBT current of 800A is selected for the VSC based DSTATCOM. or from the data sheet of ABB IGBT rating up to 125°C temperature , 5SNA 0800N330100 3300v 800A Single IGBT is selected for the designed VSC DSTATCOM.

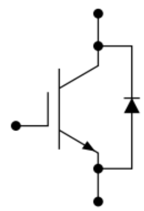


Figure 3.4 Selected Configuration of IGBT Symbol

Design of DC link Capacitor Voltage

The rating of the capacitor is decided based on the allowable ripple component on the DC-bus voltage. The minimum dc bus voltage of VSC of D-SATCOM should be greater than twice the peak of phase-to-phase voltage of system. The dc bus voltage is calculated using the modulation index m and is considered index as one and V_{LL} is the ac line output voltage of the D-STATCOM.

Using the secondary line-to-line voltage and the reactive power designed to generate the VSC D-STATCOM, the capacitance rating of VSC D-STATCOM calculated as

By taking modulation index of m_a =1

$$V_{DC}=\frac{2\sqrt{2}V_{LL}}{\sqrt{3}m_a}=\frac{2\sqrt{2}\times 3300}{\sqrt{3}\times 1}=5388.8\text{v}=5389\approx 5400\text{V}$$

So the DC link capacitor is selected with a 5400v rating to compensate the designed reactive power needed by the load.

Design of Input Filter

Input filter is used to filter out switching harmonics of the converter and to improve the voltage THD and current TDD at PCC. Input filter is formed either by a single inductor L or by inductance capacitance LC filter. The Use of a single L filter necessitates higher inductance values when compared to LC filter combination in order to reach the same voltage THD and current TDD specification. Higher inductance values cause higher voltage regulation on the DC link capacitor from full inductive mode to full capacitive mode and slow down the step response to a reactive power change. Input filter is designed with a reactive power rating of 10-20 % of the converter to filter out the switching harmonics and formed by power electronic capacitors. In other ways the filter capacitor designed by power capacitors as a tuned filter to filter out the harmonics of the load or as a detuned filter to prevent the risk of sinking of load harmonic currents. Usage of higher filter inductance also causes higher DC link voltages for a predetermined value of reactive power, which effect the rating of power semiconductors and DC link capacitor.

So using 10-20% reactive power of the IGBT power, the input filter capacitor calculated as:

$$Q_{IGBT}=2500KVAR$$

$$x_C = \frac{V^2}{0.15\times Q} = \frac{3300\times 3300}{0.15\times 2555000} = 28.4\ ohm$$

$$c=\frac{1}{2\pi\times fXc} = \frac{1}{2\times 3.14\times 50\times 28.4} = \frac{1}{8926.8} = 112\mu F$$

So three 112 μF single-phase input filter capacitors are needed to filter out the harmonics, which is generated by the IGBT switches.

The reactive power capacity of the input filter is calculated as

$$Q_{filter}= \frac{V^2}{X_c} = \frac{(15kV)^2}{28.4} =7.923kvar$$

So 7.9kvar capacitive reactive value is used to filter out the harmonic distortion produced from the D-STATCOM IGBTs at PCC.

DC link Capacitor design

There are two main considerations when choosing the DC link capacitor. It is required to be large enough to supply the VSC with a sufficiently stable DC voltage in order to avoid high harmonics in the D-STATCOM AC voltage output [7], and had to be able to supply the system with the required reactive power for power factor compensation. An undersized capacitor will result in high harmonics in the D-STATCOM AC voltage output [8], but an oversized capacitor will result in a slower response time for the DC link controller.

The D-STATCOM provides energy instantaneous to the system under transient operation. The response time of D-STATCOM is around 200 to 350μs (Hingorani and Gyugyi, 2000). If the DC voltage is lowered during load voltage regulation during transients then energy transfer from the capacitor to the system to provide reactive power is calculated as the value of dc capacitor (Cdc) of VSC D-STATCOM depends upon instantaneous energy available to the D-STATCOM during transients. The principle of energy conservation is applied as using equation below:

$$Energy\ transfer = \frac{1}{2} C_{dc}\ [(V_{dc2}) - (V_{dc12})] = 3\text{V}\ (\text{I} \times \text{a})\text{t} \qquad (3.1)$$

Where V_{dc} is reference dc voltage

V_{dc1} is minimum voltage level of dc bus

a is over loading factor,

V is phase ac voltage,

I is phase current and t is time by which the dc voltage is to recovered.

Considering the minimum voltage level of dc link Vdc1= 5380v,

V_{dc} = 5400 V, reference dc voltage

V_{ph}= 3300V, since the coupling transformer is in star-delta connection V_{LL}=V_{ph}=3300v

and the current in delta connection is the IGBT D-STATCOM collector current

$I_D = 447A$

The time by which the dc voltage recovered is calculated as.

Time= input resistance × input filter capacitor=3.125 × 112 micro farad = 350 micro seconds,

Over loading factor a is = 1.2

(3.1) becomes:

$$\frac{1}{2} c_{dc}\ [(V_{dc}^2)\text{-}(\ V_{dc1}^2)]\text{=}3\times\text{V}\times(\text{I}\times\text{a})\times\text{t}$$

$$C_{dc}=\frac{6Vph(Iph\times a)\times t}{[(Vdc^2)-((Vdc1^2)]}=\frac{6\times 3300(258\times 1.2)\times 350\mu s}{[(5400^2)-(5380^2)]}=9951\mu F$$

The calculated value of Cdc link is $9951\mu F$ micro Farad and giving 15% tolerance selected as 12000 micro Farad.

A number of eight (8) 1500 μF capacitors connected in parallel are needed for a D-STATCOM DC link capacitor to compensate the required 2.5MVAR reactive power of the load.

The inductor value needed to absorb a 2.5 MVAR reactive power of the D-STATCOM is calculated as :

$$X_L=\frac{V^2}{Q}=\frac{15000^2 v}{2500000\,VAR}=90\Omega$$ from this the inductor value is calculated as

$$X_L=2\pi f L\text{ , inductor(L)}=\frac{X_L}{2\pi f}=\frac{90\Omega}{314.159}=286.5\,mili\ henry\text{ (mH)}$$

So the series inductor connected with the coupling transformer is 286.5 mili henry

AC Inductor design

The selection of the ac inductance (L_{AC}) of VSC depends up-on currents ripple i_{cr} p-p, switching frequency fs dc bus voltage (V_{dc}). AC inductance is mainly these parameters and is calculated by using these parameters. The formula for calculation of AC inductance is given as

$$L_{AC}=\sqrt{3}\,\frac{m\times V_{dc}}{12\times a\times fs\times i_{ripple}} \tag{3.2}$$

Where m is the modulation index and a is overloading factor.

Peak current is $(I_{DP})=\sqrt{2}\times I_D=98.35\times\sqrt{2}=139A=I_{DP}$

$I_{ripple}=I_{DP}\times 20\%=139A\times 0.2=27.8A$

Consider the ripple current or i_{cr} (p -p)= 5%,

5% of $I_{ripple=}27.8A\times 0.05=1.39$

Switching frequency (fs) = 10 kHz,

Modulation index, m= 1,

V_{dc} = 5400V,

Overloading factor, a=1.2,

The L_{fAC} value is the required value

$$L_{fAC}=\sqrt{3}\,\frac{m\times V_{dc}}{12\times a\times fs\times iripple}=\sqrt{3}\,\frac{1\times5400}{12\times1.2\times10\times1000\times1.39}=L_f=\frac{9353}{200\times1000}=46.77\text{mH}$$

$$L_{fAC}=2\pi fL=2\pi\times50\times0.04677=14.69$$

$$L_{fAC}=14.69\ \Omega$$

Coupling transformer resistance is calculated as

$$R_{coupling}=\frac{\text{transformer rating}\times2\times\text{pi}\times\text{f}}{40}=\frac{50\times10^{\wedge}(-6)\times2\times\pi\times50}{40}=0.392\text{m}\Omega$$

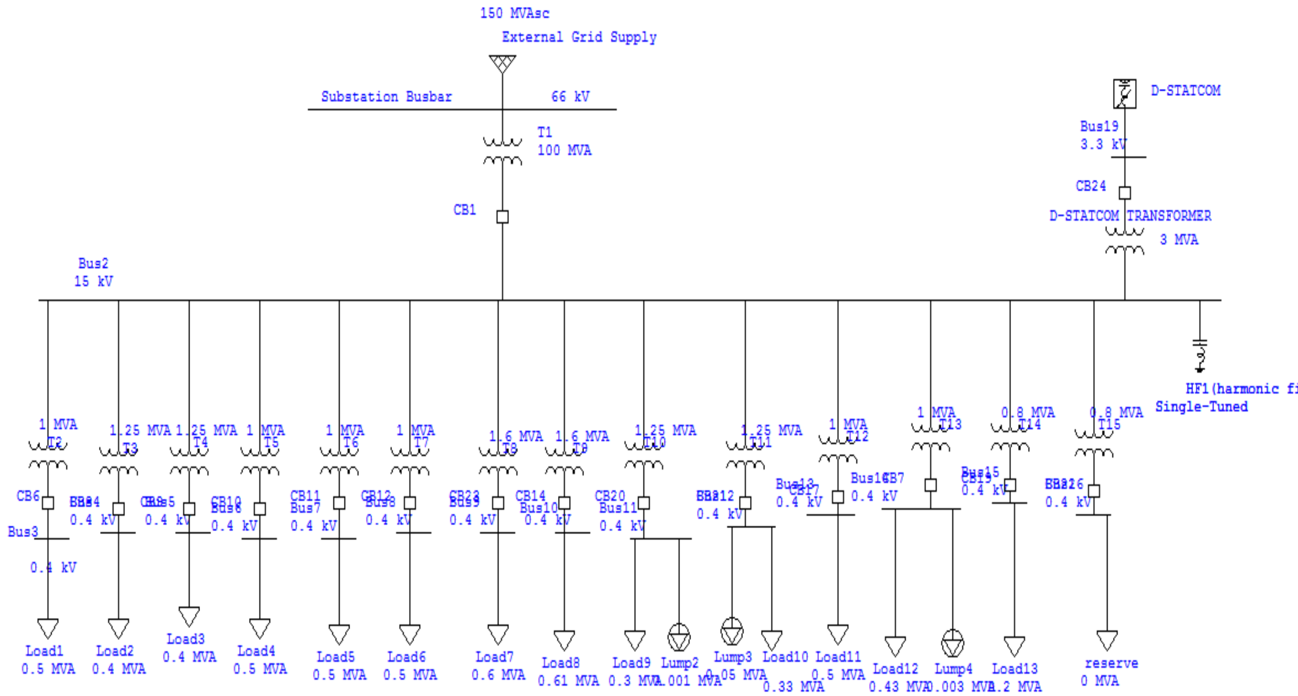


Figure 3.5 Complete Diagram of VSC D-STATCOM with Load Using ETAP

Table 3.3 Reactive Power Compensation Limits of D-STATCOM for Almeda Textile Factory

D-STATCOM Exchange of reactive power [KVAR]	Input filter [KVAR]	Coupling transformer		
		Rated power [MVA]	Primary voltage [KV]	Secondary voltage [KV]
$\pm$2.55MVAR	7.923	3	15	3.3
0	7.923			
D-STATCOM Voltage rating [KV]				$\geq$3.3
D-STATCOM Current rating [A]				$\geq$800
D-STATCOM Switching frequency [kHz]				$\geq$1

D-STATCOM components & their ratings		
1	Series inductor and Coupling transformer total AC Inductor [mH]	333
2	DC link Capacitor [mF]	12
3	DC link Capacitor Voltage [V_{DC}]	5400
4	Input Filter reactive power [KVAR]	7.923
5	Input Filter [μF]	112
6	Coupling transformer Resistance [mΩ]	0.392

3.4 Modeling of D-STATCOM

The basic circuit diagram and control of the D-STATCOM system are shown in Figure 3.6. It consists of a three phase voltage source converter (VSC), interfacing inductors, DC link capacitor, and control systems. In this Figure each VSC D-STATCOM IGBT switches represents a power semiconductor device and anti-parallel diode combination. The VSC D-STATCOM is connected to the network through the coupling transformer and interfacing inductors which are used to filter high-frequency components of compensating currents. The inductance L_f in this Figure represents the leakage inductance of the transformer and the interfacing inductors. The copper loss of the connecting transformer and loss of the interfacing inductor is represented by a resistance R_f. In this thesis, the D-STATCOM is used for power factor correction by injecting the reactive power to the Almeda textile load. Therefore, the control systems of the D-STATCOM consist of a current control, DC voltage control, and AC voltage control.

The primary control objective is to rapidly regulate the D-STATCOM currents to the reference values that are generated by the voltage controllers. A secondary control objective is to keep the DC voltage around a desired value, which is around 5400 dc voltage to keep the textile load bus voltage at constant value.

As seen in Figure 3.6, the D-STATCOM output AC voltage is represented by, Vt,abc. This voltage is generated by the converter and is assumed quasi-sinusoidal voltage waveform. Therefore, the voltage equation of AC system can be written as

$$L_f = \frac{di_{f,abc}}{dt} = -R_f I_{f,abc} - V_{t,abc} + V_{st,abc} \quad (3.3)$$

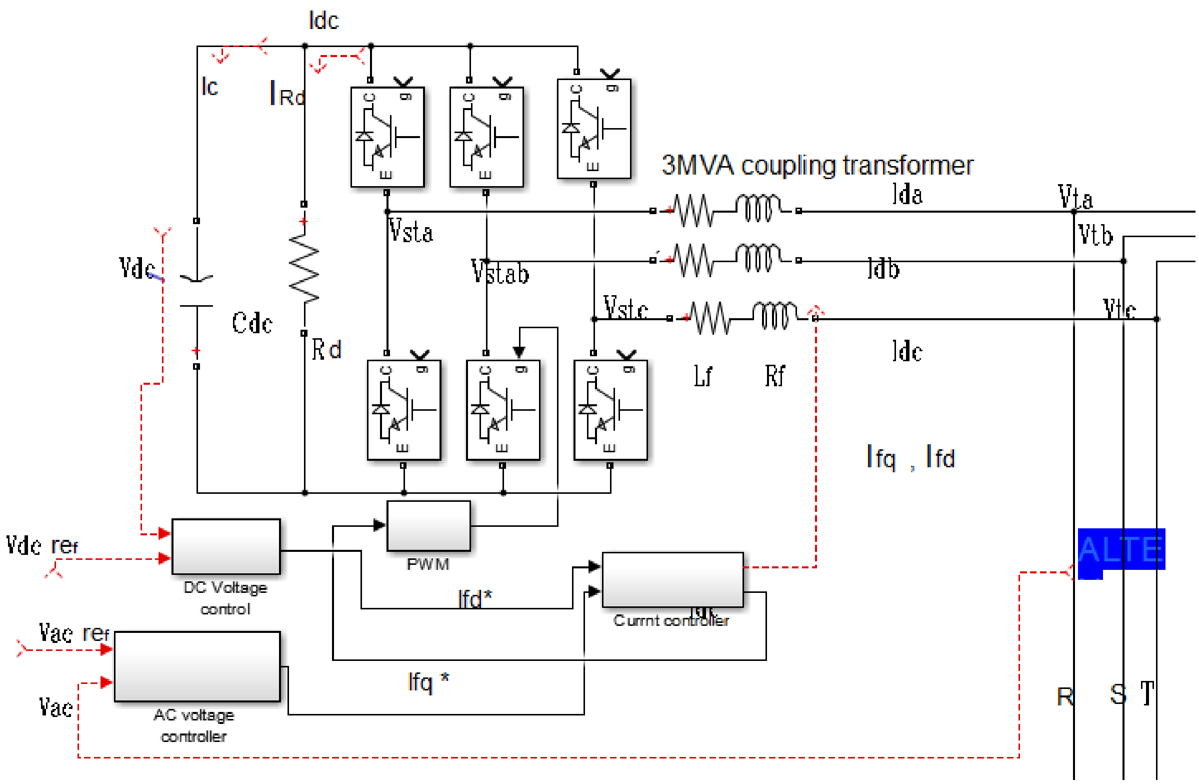


Figure 3.6 Basic Circuit Diagram And Control of the D-STATCOM System

Consider the DC system in Figure 3.6, the DC current (i_{dc}) consists of capacitor current (i_c) and resistor current (i_{Rd}). The resistor R_d represents losses in the IGBT converter. The power flow into the converters equals to the instantaneous power of the DC capacitor which can be described as

$$P_{dc} = -v_{dc}i_{dc} = v_{dc}(i_c + i_{Rd}) = P_{ac} = v_{st,abc}^{T}\, i_{f,abc} \tag{3.4}$$

Here, v_{dc} is the D-STATCOM DC voltage, if is the D-STATCOM output current, v_t is the load voltage, while the subscript "abc" implies vectors consisting of individual phase quantities. From Figure 3.6, the DC current can be expressed as

$$i_{dc} = C_{dc}\frac{dV_{dc}}{dt} + \frac{V_{dc}}{R_{dc}} \tag{3.5}$$

Where Cdc is the DC link capacitance. From Figure 3.6 the relation between DC power and AC power can be expressed as

$$v_{dc}\left(C_{dc}\frac{dV_{dc}}{dt} + \frac{V_{dc}}{R_{dc}}\right) = -\left(v^{T}_{st,abc}\, i_{f,abc}\right) \tag{3.6}$$

After applying the three-phase to two-phase transformation

$$v_{s,xy} = v_{sa}e^{j0} + v_{sb}e^{\frac{j2\pi}{3}} + v_{sc}\, e^{\frac{j4\pi}{3}} \tag{3.7}$$

followed by the rotational transformation with the chosen dq reference frame in

$$v_{s,dq} = v_{sd} + jv_{sq} = e^{-j\theta}v_{s,xy} \tag{3.8}$$

where the complex number , $v_{s,xy} = v_{sx} + jv_{sy}$. This is followed by the following

rotational transformation. From this the D-STATCOM dynamic equation can be rewritten as

$$\frac{di_{fd}}{dt} = -\frac{1}{T_f}i_{fd} + \omega i_{fq} - \frac{1}{L_f}V_{dt} + \frac{1}{L_f}K_p u_d v_{dc} \tag{3.9}$$

$$\frac{di_{fq}}{dt} = -\frac{1}{T_f}i_{fq} - \omega i_{fd} + \frac{1}{L_f}K_p u_q V_{dc} \tag{3.10}$$

$$\frac{dV_{dc}}{dt} = -\frac{V_{dc}}{T_{dc}} - \frac{3}{2C_{dc}}K_p u_d i_{fd} - \frac{3}{2C_{dc}}K_p u_q i_{fq} \tag{3.11}$$

where T_f is the time constant of the transformer and interfacing inductor, $T_f = \frac{Lf}{Rf}$

T_{dc} is the time constant of the DC system, $T_{dc} = C_{dc}R_{dc}$

Where $k_p u_d$Vdc and $k_p u_q v_{dc}$ represent the D-STATCOM output AC voltage on d-axis and q-axis ($v_{st,d}$ and $v_{st,q}$), respectively.

The ω is angular frequency of the system

v_{dc} , i_{fd} and i_{fq} represent the state variables of the D-STATCOM,

k_p is a constant value depending on the type of converter and transformer ratio (Marian et al., 2002). The D-STATCOM output AC voltage can be generated by controlling the converter. Therefore, AC voltage command on dq-axis (u_d and u_q) are the control inputs of the D-STATCOM.

3.5 Cost analysis of D-STATCOM

Due to the operating low power factor of the Almeda textile factory, the EEU charges an average of 69,000 birr per month and 828,000 per year. After the D-STATCOM is connected to the load bus of Almeda textile factory the power factor is improved from 0.66 lagging to 0.92 lagging, thus not only the monthly charged birr of 69,000 but also EEU saved 2323KVAR reactive power.

The total cost of the D-STATCOM to improve the power factor from 0.66 to 0.92 is around nine hundred fourty thousand birr. This birr is recovered the factory with one year of previously charged power factor bills. The D-STATCOM is operated from twenty to thirty years lifetime. So using a VSC D-STATCOM to improve the power factor and reactive power compensation system is better for reliably of the power system operation and minimization of loss and operating costs.

Table 3.4 Cost Analysis of D-STATCOM Component

D-STATCOM component specification and their price				
Name	Specification	Price per piece	No. piece needed	Total cost
Coupling Transformer (for 2.5 MVAR D-STATCOM)	15kv/3.3kv 3MVA ,oil immersed Outdoor installation	600,000 birr	1	600,000 Birr
IGBT switches	800A/3300V Indoor installation	1350-2700birr	6	6*2700= 16,200 Birr
Filter capacitor	7.5kvar Indoor installation	2,7000birr	3	3*2700birr=81000 Birr
DC link capacitor	2.5MVAR Indoor installation	180,000 birr	1	180,000 Birr
D-STATCOM controller	Indoor installation	50,000 birr	1	50,000 Birr
D-STATCOM cabinet	1.5m by 1m	10,000birr	1	10,000 Birr
Sub total cost of D-STATCOM				937,200 Birr

The location of the D-STATCOM is placed at the place where three phase power iterance of the factory is connected to the loads of the factory.

CHAPTER FOUR

Result and Discussion

A ±2.5 MVAr VSC D-STATCOM is designed and simulated according to the load reactive power requirement of Almeda textile factory. This VSC D-STATCOM power factor correction system performs, when the load power factor decreases below 0.85 lagging, the VSC D-STATCOM inject up to a maximum of -2.5 MVAR (capacitive reactive power) to the load results, the load power factor improves up to 0.95 and the bus voltage at PCC keeps constant at one per unit system. When the load power factor increases above 0.95lagging results, the load voltage increases above one per unit. This causes harmonics on the factory load system. In this case the VSC D-STATCOM absorbers up to a maximum of +2.5Mvar (inductive reactive power) from the load. If the load bus voltage is constant at one per unit, there is no need of absorbing and injecting of reactive power to the load. This means the load bus voltage at PCC and D-STATCOM bus voltage is the same. In this case, the D-STATCOM inject or absorb zero reactive power to the load. From this principle reactive power is directly related to the load voltage and load power factor.

The developed system is simulated to Almeda textile factory in order to provide power factor correction and reactive power compensation of the load. The complete load flow circuit diagram of D-STATCOM with ALTEX load system is shown in Figure 4.2 in MATLAB simulation and in Figure 3.5 using ETAP software's. The simulation result of MATlab shows that load flow analysis of the whole and power factor improvement of the load. In addition to this, the current unbalance of the factory is corrected automatically when VSC D-STATCOM connected in shunt to the load.

4.1 MATLAB Simulation Diagram and Result before the D-STATCOM connected to the load

In this Simulink, model of uncompensated system contains linear and nonlinear loads. The linear loads are series load of resistive and inductance and delta connected resistance, inductance and capacitance connected in parallel. The ALTEX load is modeled as in figure 4.1 below. On this simulation, the three-phase waveform of load bus voltage at PCC, current and operating load power factor are displayed and discussed briefly.

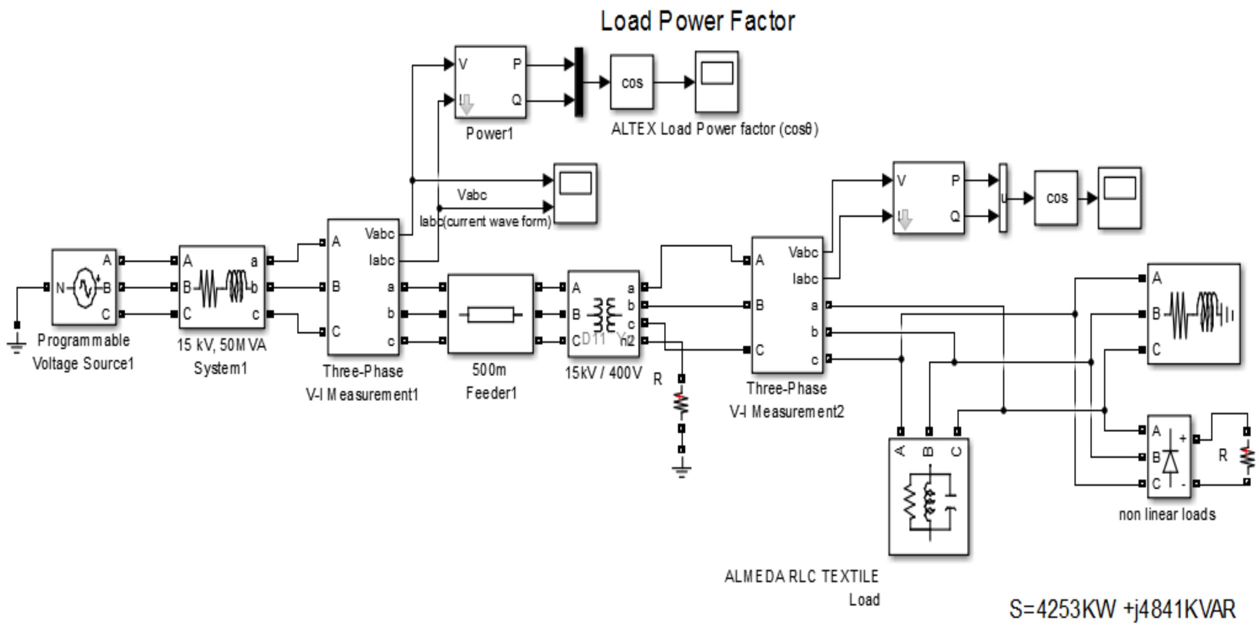
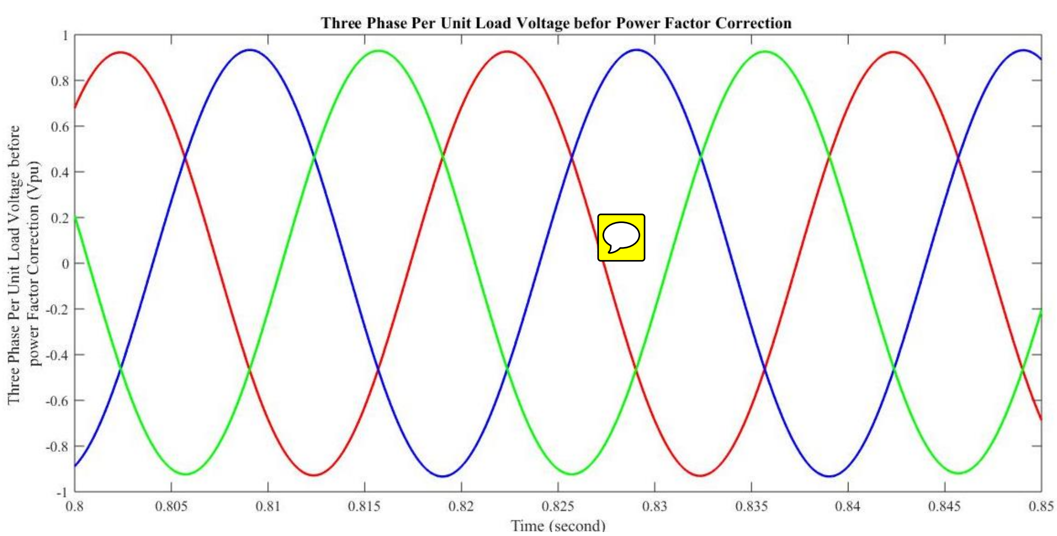


Figure 4.1 MATLAB Simulation Diagram of ALTEX Load before D-STATCOM Connection

Three phase MATLAB simulation result of uncompensated voltage, current waveforms



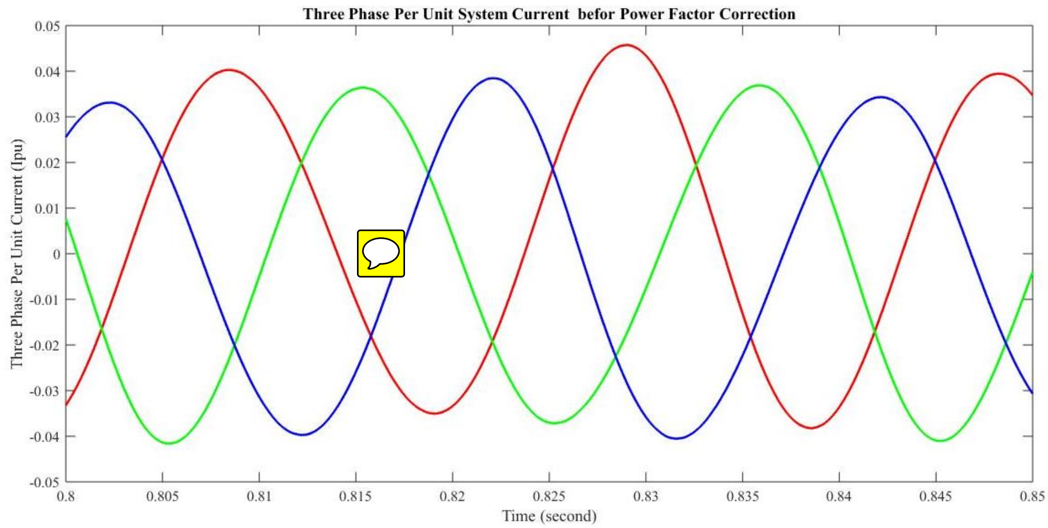


Figure 4.2 MATLAB Simulation Result of Voltage and Current Verses Time Waveform Before The D-STATCOM is Connected to ALTEX Load

As seen from Figure 4.2 the MATlab simulation result of voltage and current waveform, the three phase current waveform is unbalanced; this indicates there is unbalanced three phase load connections are here on the factory. This unbalanced three phase current is corrected by connecting VSC D-STATCOM in parallel to the ALTEX load.

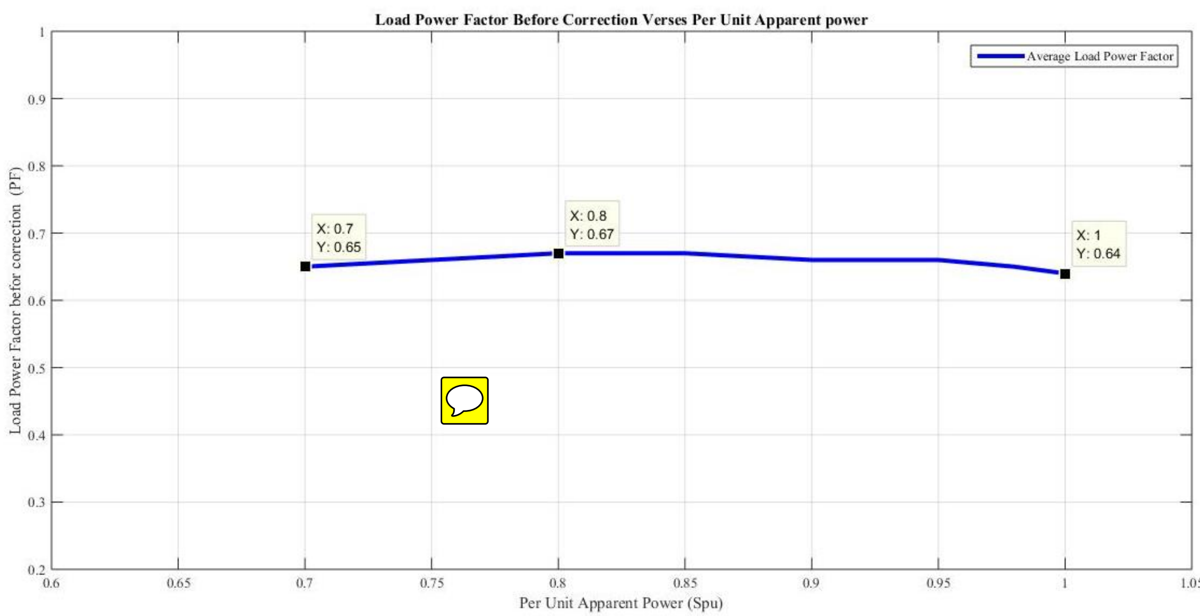


Figure 4.3 MATLAB Simulation Result of Load Power Factor Verses Per Unit Apparent Power Before the D-STATCOM Connected to Load

From Figure 4.3 MATLAB simulation result, ALTEX load vary from 0.7 pu up to 1 per unit or when the load vary from 70% load to peak load the output load power factor varies from 0.65 to 0.67 in some extent. most of the textile machines are induction type, as those machines operates in lightly loaded, their magnetizing current increases, which consume more reactive power from the system, which leads, the average load power factor to decrease. When those machines operate in nearly loaded condition, their reactive power consumption decreases which led to increase the average load power factor of the factory.

MATLAB simulation result figur of load power factor verses load current before VSC D-STATCOM connected to ALTEX load.

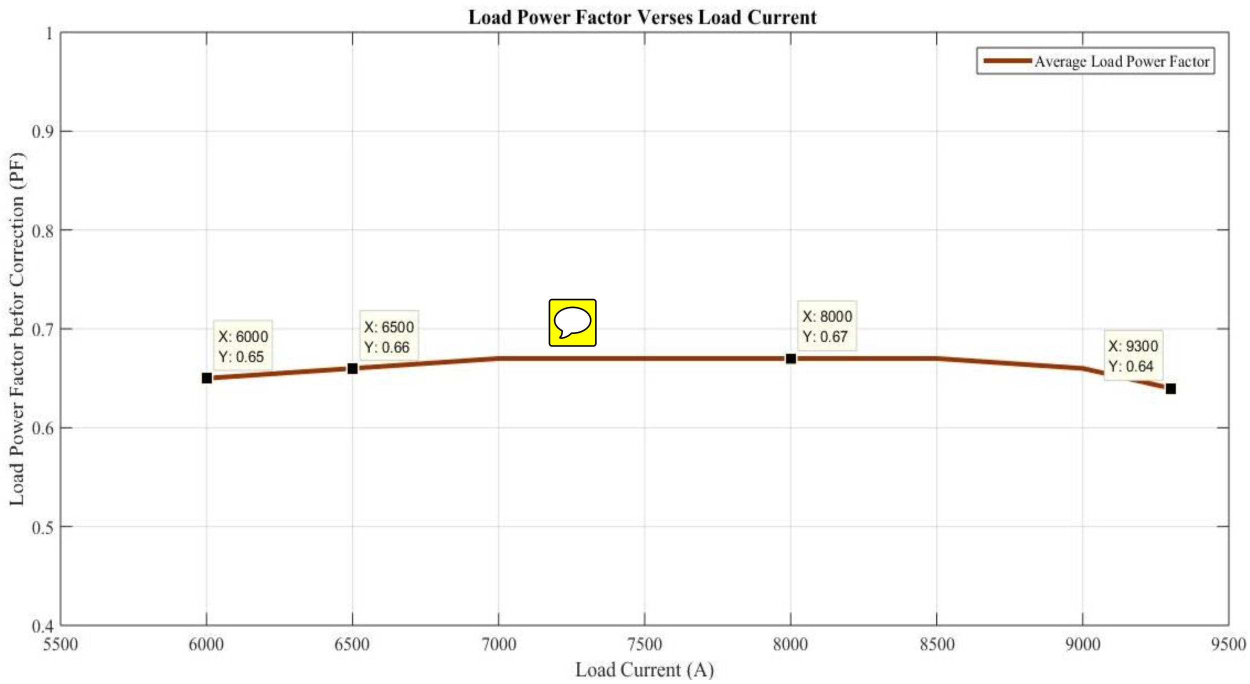


Figure 4.4 MATlab coding of Load Power Factor verses load current before VSC D-STATCOM connected to load

Figure 4.4 shows the power factor verses load current which is before the D-STATCOM connected to the load. From the simulation result when the load current increases the load power factor is in the range of 0.65 and 0.67 lagging. This indicates there is more consumption of reactive power and losses of energy with in the factory.

4.2 MATLAB Simulation Diagram and Results after VSC D-STATCOM connected to ALTEX load

In this Simulink, model of compensated system the Almeda textile factory load is modeled as in Figure 4.5. On this simulation, the three-phase waveform of load bus voltage, current and operating load power factor are displayed on each scope and discussed it.

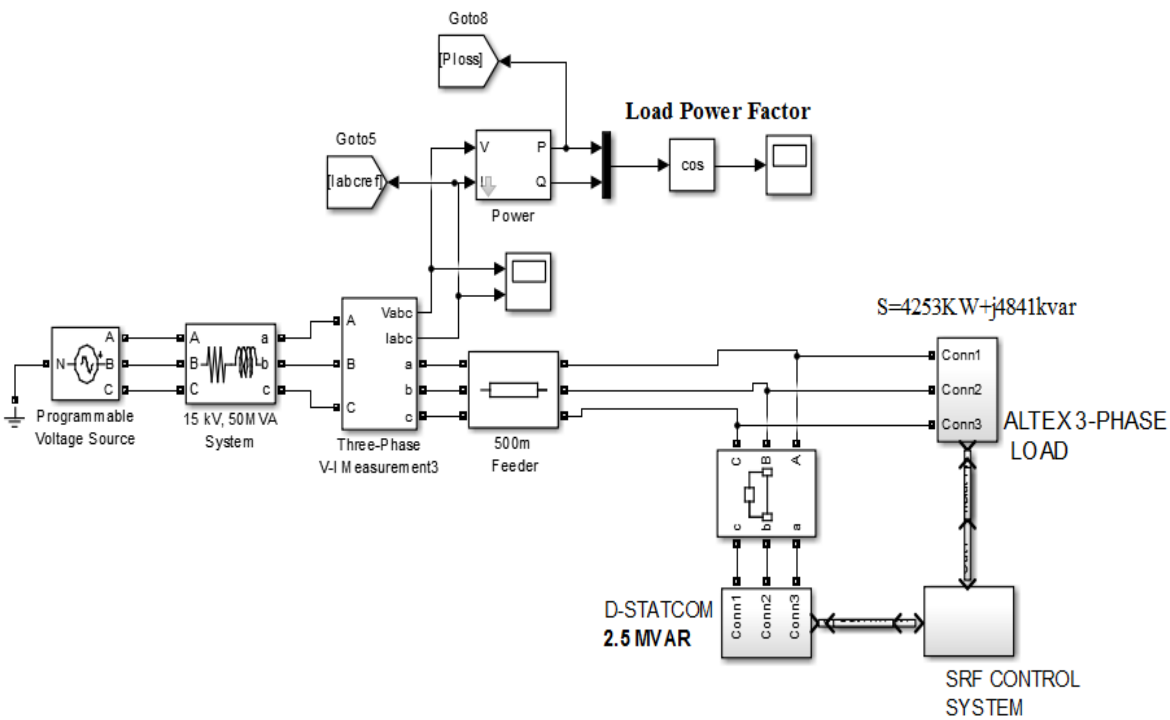
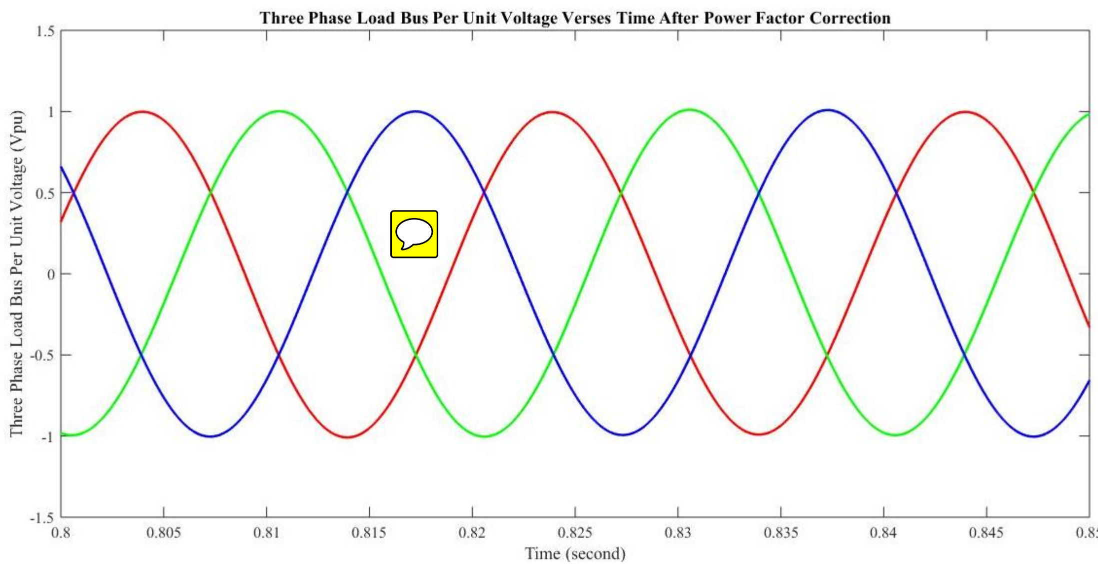


Figure 4.5 MATLAB Simulink of ALTEX Load With D-STATCOM and its Control Circuit

Figure 4.5 shows Almeda textile load, D-STATCOM and its synchronously rotating frame theory (SRF) are connected to each other. The SRF circuit gives a fast switching action to keep the load bus voltage at PCC constant, load current, load reactive power and load power factor by switching VSC D-STATCOM IGBT switches. The SRF control circuit is designed to control the Almeda textile load reactive current and load power factor by switching ON/OFF the VSC D-STATCOM IGBT switches. The SRF control system controls VSC D-STATCOM IGBT switching system with the help of PWM techniques. This means the load bus voltage, load current is connected to the control circuits of SRF control system in which, when load current increase the angle (θ) between load current and load voltage increases above 31^0 results the load power factor decreases below 0.85 lagging, at this time the SRF control circuit switches ON the VSC D-STATCOM IGBT gates 2,4 and 6 switches and the D-STATCOM injects capacitive reactive power to the load to increase the load power factor up to 0.95 lagging, and when the load current decreases the angle (θ) between load current and load voltage decreases below 18^0 results the load power factor increase above 0.95 lagging, in this condition the SRF control circuit switches ON the D-STATCOM IGBT gates of 1,3 and 5 switches and the D-STACOM absorbs an inductive reactive power from the load, this makes lowering the load power factor to between 0.85 and 0.95 lagging. Generally the VSC D-STATCOM SRF control circuit keeps the load power factor between 0.85 and 0.95 lagging by injecting and absorbing reactive current to the load.



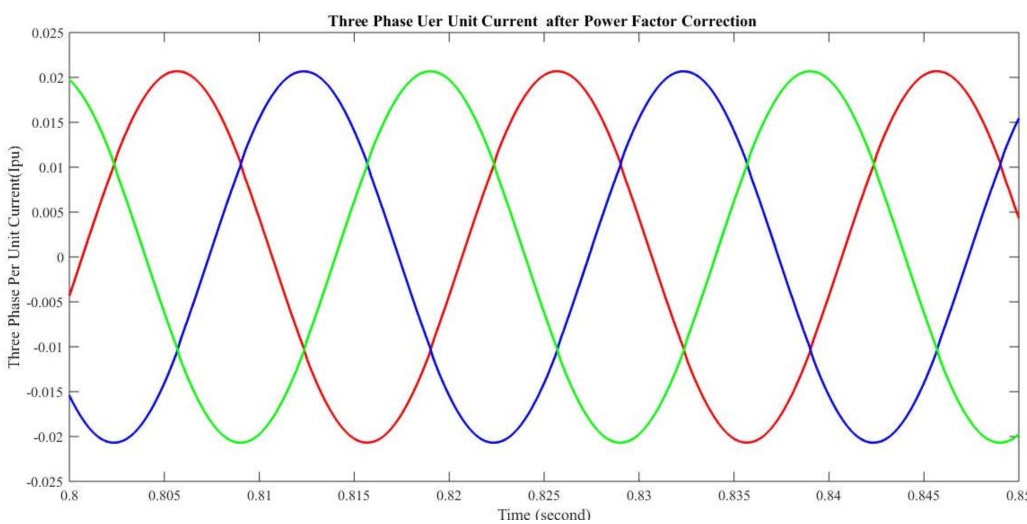


Figure 4.6 MATLAB Simulation Result of Voltage and Current Verses Time Waveform after the D-STATCOM is Connected to ALTEX Load

From the three-phase voltage and current waveform Figure 4.6, the unbalanced three phase load current in Figure 4.2 waveform is balanced by connecting the D-STATCOM in shunt to the Almeda textile loads and the load voltage is regulated and increase to one per unit value. From this the D-STATCOM gives a fast remedial action to control the unbalancing current, compensating reactive power and power factor correcting system in large customer loads.

The voltage and current waveforms are based on the per unit system with a base power of 50MVA and with base phase-to-phase voltage of 15kv system.

Table 4.1 Comparison of voltage and current wave form before and after power factor correction

Comparison of voltage and current wave form before and after power factor correction	
Voltage and Current Waveform Before Power Factor Correction	Voltage and current waveform after power factor correction
The load current waveform from Figure 4.2 is unbalanced and not purely sine wave	The current and voltage wave form from Figure 4.5 is purely sine wave and balanced signals. From this the unbalanced current in Figure 4.2 is balanced with the help of VSC D-STATCOM fact controller.
Due to low power factor operation the factory penalized by EEU	Due to the power factor, improvement of no penalty comes from EEU but saves an energy of 2323kvar every seconds.
Load per unit voltage is around 0.95 pu	The load per unit voltage improves its amplitude from 0.95 pu to one per unit.
Load current is about 9300A	Due to the improvement of load power factor, load current decreased from 9300A to 6967A, in this case the power factor have a great concern on energy losses.

Improved load power factor

The MATLAB simulation result displayed on the oscilloscope Figure 4.7 and MATLAB code result indicates that, ALTEX per unit apparent power verses load power factor. Before the D-STATCOM connected to the ALTEX load, the Almeda textile load power factor was 0.66 lagging, (MATLAB simulation result Figure 4.3) , after the designed VSC D-STATCOM connected in shunt to the load, the load power factor improves to 0.92 lagging. This power factor improvement indicates that, the factory reduces consumption of reactive power and energy losses. This acceptable load power factor gives the following advantages for the factory:

- Minimize electrical energy cost of bills.
- Reducing heating of equipment, this is due to reducing of line current.
- The equipment of the factory lives long lifetime due to reducing of reactive power consumption.
- EEU saves electrical energy
- The factory receives a sustainable and acceptable power for its application at any time.

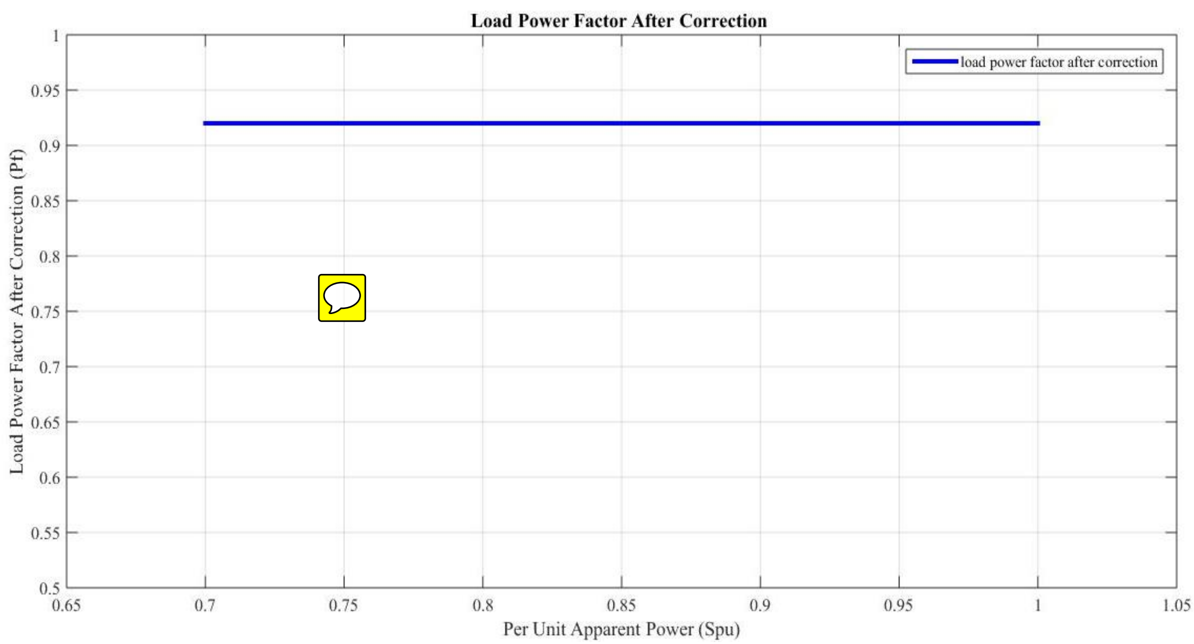


Figure 4.7 MATlab coding of Load Power Factor verses per unit apparent power after VSC D-STATCOM connected to the load

As seen from MATLAB coding in Figure 4.7 result, the load power factor is kept constant at 0.92 lagging, this is due to the fast compensation ability of VSC D-STATCOM application even in transient condition of large load switching. When the load vary even in transient condition the D-STATCOM performs the following actions to keep the load power factor at 0.92 lagging and load bus voltage at PCC one per unit:

A. When the load current increases, the load voltage at point of common coupling(PCC) decreases below one per unit and the load power factor decreases below 0.85 lagging then the D-STATCOM injects capacitive reactive power to the load, results the load bus voltage at PCC increases to one per unit system and the load power factor increases up to 0.95 lagging.
B. When the load current decreases, the load per unit voltage at PCC increases above one and in this case, the D-STATCOM absorbs the excess inductive reactive power from the load. This causes the angle θ between load voltage and load current led to increase and the load per unit voltage at PCC keeps constant at one per unit, this condition also keeps the load power factor around 0.9 lagging.

   From the two cases, load reactive (Q) power and load voltage are directly proportional to each other to keep the load power factor between 0.85 and 0.95 lagging.
C. If the load power factor is kept constant at 0.92 lagging results no reactive power exchange between the Almeda textile load and the paralleled connected VSC D-STATCOM.

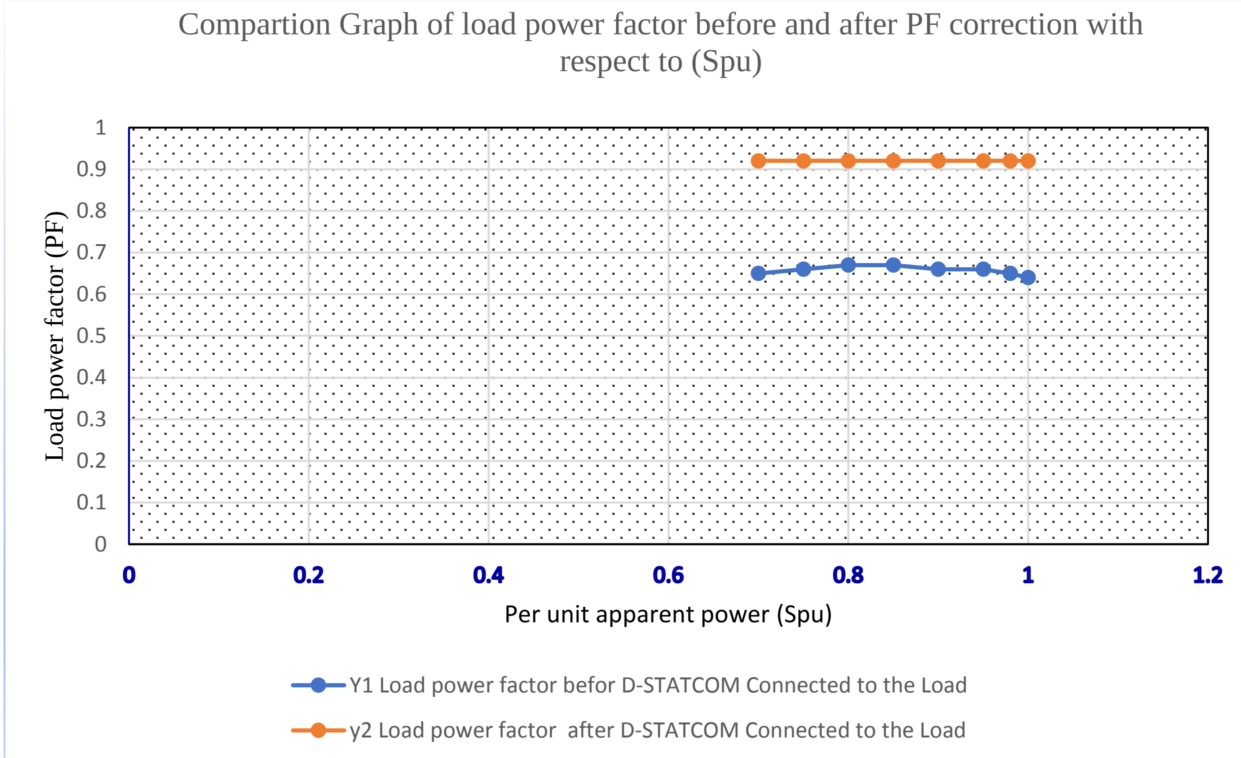


Figure 4.8 Comparison of Load Power Factor Simulation Result before and after the D-STATCOM connected to the load

Figure 4.8 shows comparison of load power factor before and after correction, thus the presently Almeda textile operating load power factor before power factor is around 0.66 lagging. Using fact controller VSC D-STATCOM the factory power factor is improved from 0.66 lagging to 0.92 lagging. This improvement of power factor solves the power losses and energy billing charges of the factory.

MATLAB coding result Figure of load power factor verses load current after VSC D-STATCOM connected to ALTEX load.

From Figure 4.9 when the VSC D-STATCOM connected to Almeda textile load the load current at a point of common coupling decreases from nine kilo ampere (Figure 4.4) to seven kilo ampere, this reduction of current is because of the shunted D-STATCOM that reduces the consumption of reactive power and loses. Due to the shunted VSC D-STATCOM the load power factor improved from 0.66 lagging to 0.92 lagging. The improvement of power factor aids the factory to overcome the power factor bill of charges as well as energy loses.

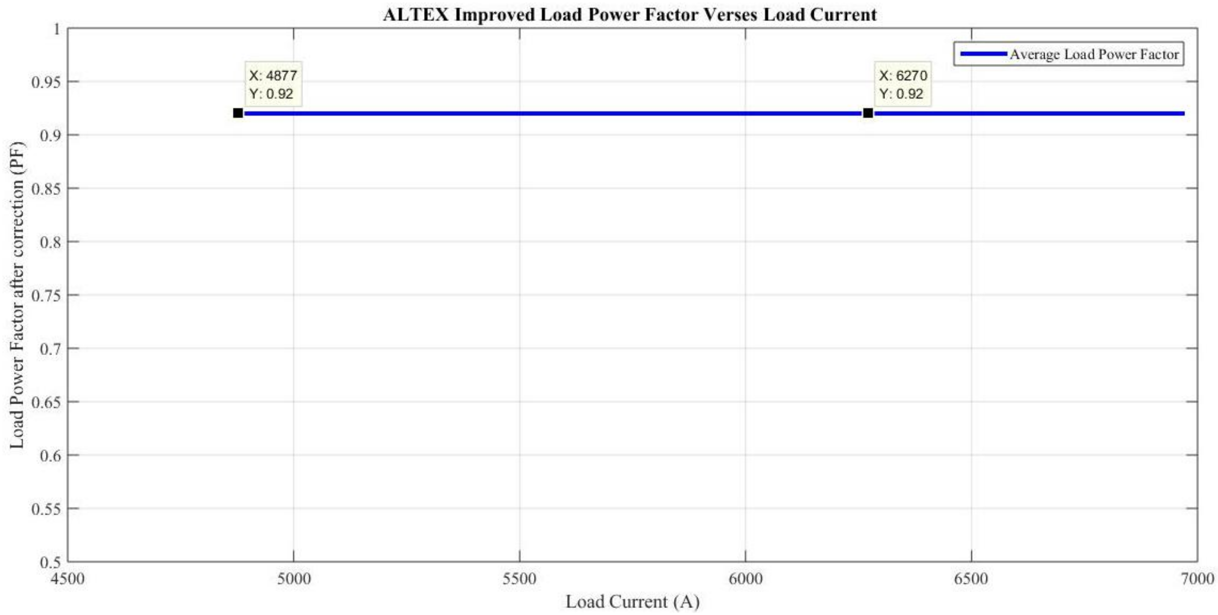


Figure 4.9 MATlab coding of Load Power Factor verses load current before VSC D-STATCOM connected to load

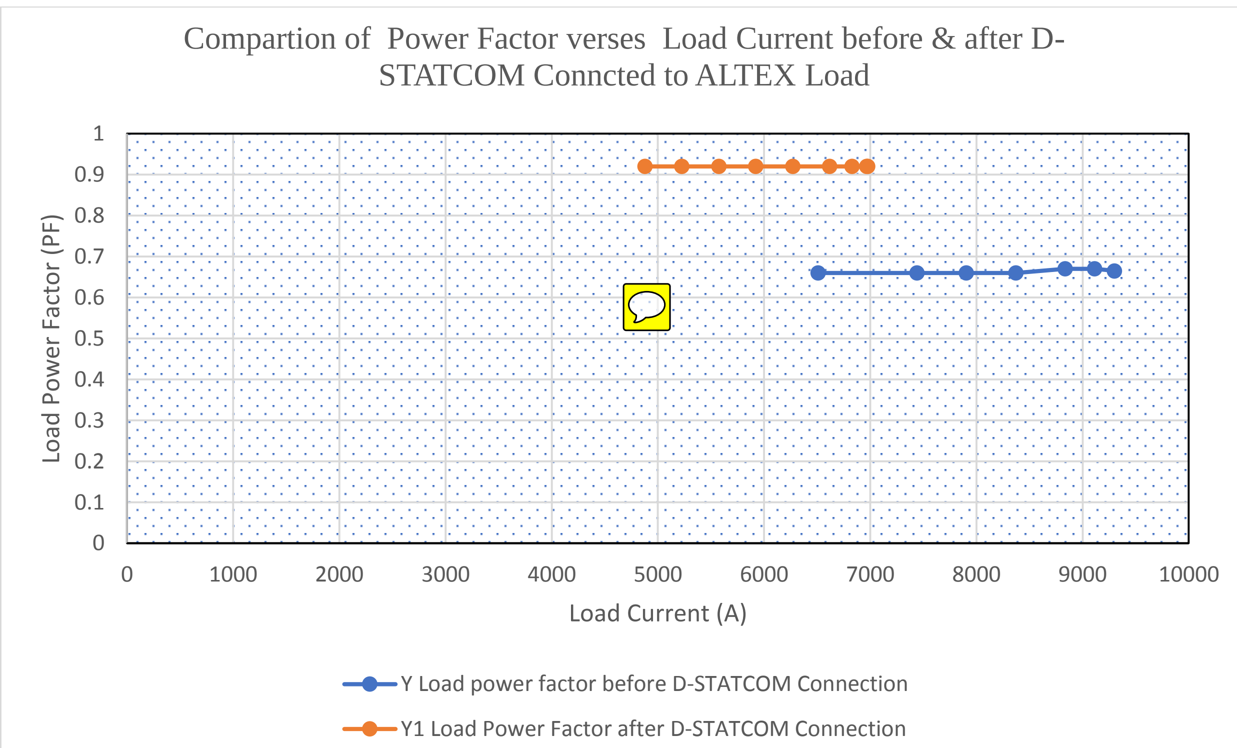


Figure 4.10 Comparison of Load Power Factor verses load current Simulation Result before and after the D-STATCOM connected to the load

Table 4.2 Comparison of Load Power Factor Simulation Result before and after the D-STATCOM connected to the load

Comparison of Load Power Factor Simulation Result before and after the D-STATCOM connected to the load as seen from Figure 4.10	
Power factor before the D-STATCOM connected to the load	Power factor after the D-STATCOM connected to the load
• From the Figure 4.4 operating power factor is in the range of 0.65 and 0.67 lagging	• From Figure 4.10 due to the injecting of leading current of VSC D-STATCOM, load power factor improved from the average 0.66 lagging to 0.92 lagging.
• The factory maximum load current at PCC reaches up to 9300A (Figure 4.4)	• Due to the addition of reactive (leading) current from VSC D-STATCOM to the load, the load current at PCC reduces below 7 kilo ampere(Figure 4.10)
• The factory pays a power factor bill of charges of 69,000 Birr each months to EEU.	• The previously power factor bill of charges of the factory solved after the D - STATCOM connected to the load and no bill of charges due to power factor problem.
• Energy losses and Unbalanced currents are present at the load (Figure 4.2)	• Due to the shunted VSC D-STATCOM, the energy losses and unbalanced currents are solved. Figure 4.10

4.3 D-STATCOM Voltage , Current, Dc Link Capacitor Voltage and Power Loss on the IGBT Switches

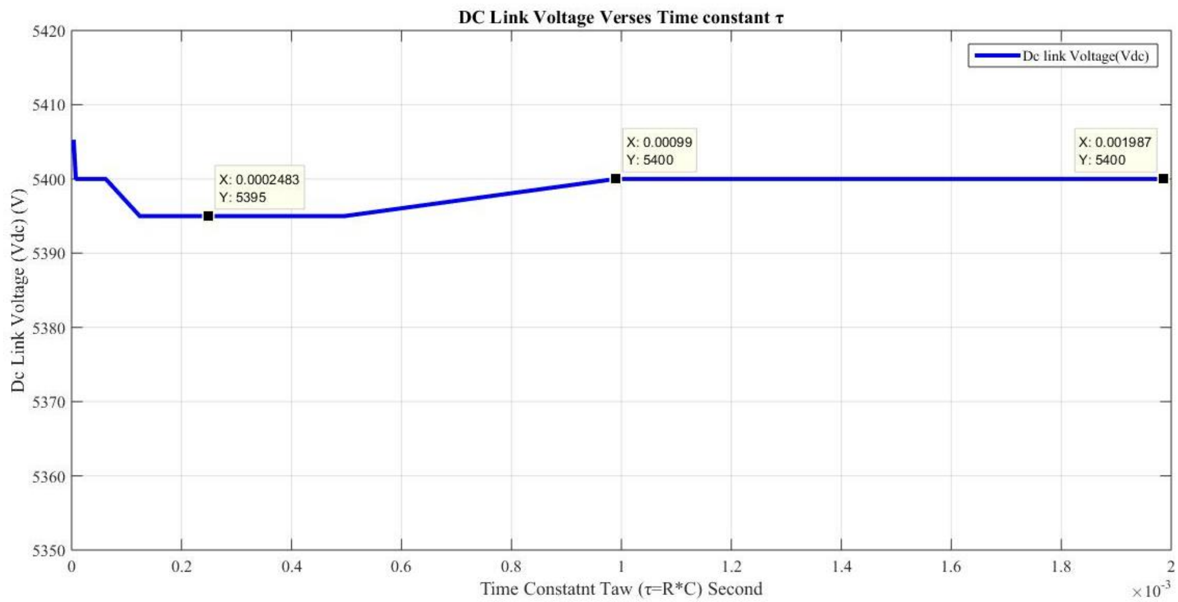


Figure 4.11 MATLAB Simulation Result of Dc Link Capacitor Voltage Verses Time (Time Constant $\boldsymbol{\tau}$)

The MATLAB code result Figure 4.11 shows DC link capacitor capacity of storing dc voltage. This capacitor stores a dc voltage at stable condition and when the load current increase the load power factor reduces below 0.9 lagging and per unit bus voltage lowers below one per unit. In this case the dc link capacitor injects voltage (negative reactive power) to the load results the load power factor improves its value up to 0.95 lagging and per unit load voltage at PCC increases up to one. When the load voltage per unit increase above one and load power factor improves above 0.95 lagging the dc link capacitor stores voltage or absorbs positive reactive power from the load to it. This condition keeps the load power factor below 0.95 lagging .When the load bus voltage and VSC D-STATCOM voltage is the same the dc link capacitor could not absorb or inject voltage to the load. on Figure 4.11 MATLAB coding the DC link voltage up to zero point one(0.1) millisecond time constant decreases its value, means when the D-STATCOM injects negative reactive power to the load the dc link capacitor voltage decreases its voltage upto 5395 dc voltage and after zero point one millisecond time the dc link capacitor voltage becomes increase it voltage up to one millisecond time constant means it absorves inductive ractive power from the load.after one millisecond time constant the DC link capacitor voltage stores 5400 v dc which is no exchange of reactive power between VSC D-STATCOM and ALTEX load. This indicates the load power factor and voltage at PCC are constant at 0.92 lagging and one per unit respectively.

The Figure 4.12 indicates the dc link current depends on reactive power exchange of the D-STATCOM with the load. This means when the load power factor decreases the D-STATCOM injects reactive power to the load results to decrease the dc link current and when no exchange of reactive power the dc link current Figure 4.12 of MATLAB code indicates a constant dc current, which indicates stable system.

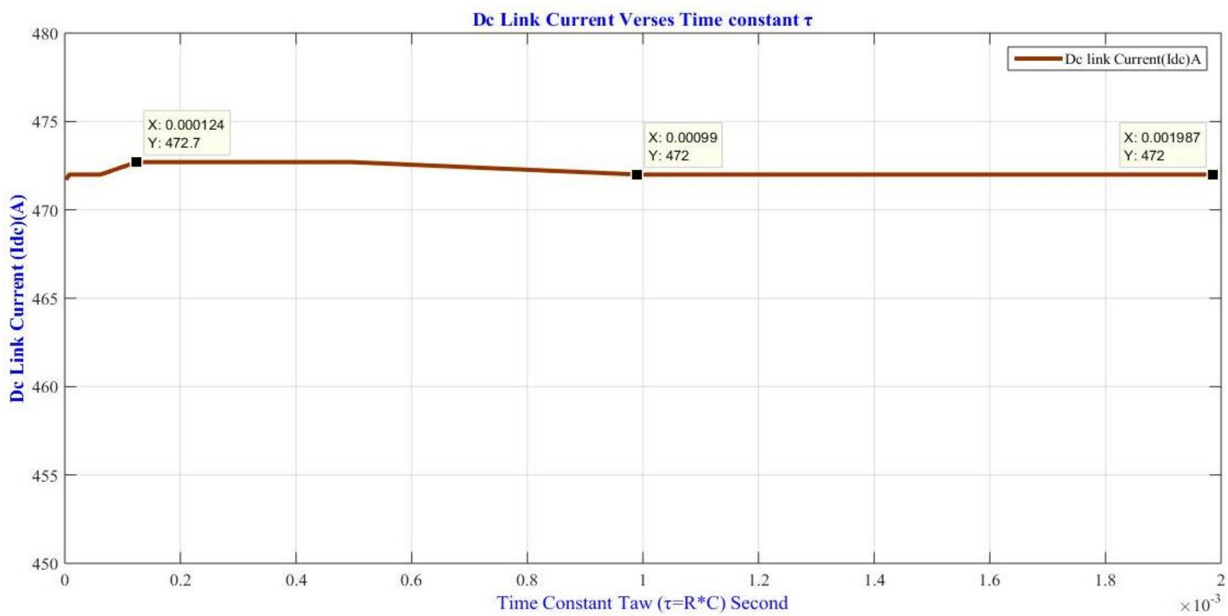


Figure 4.12 MATLAB Simulation Result of dc Link Current Verses Time

(time constant τ)

MATlab coding result of D-STATCOM IGBT Power Loss

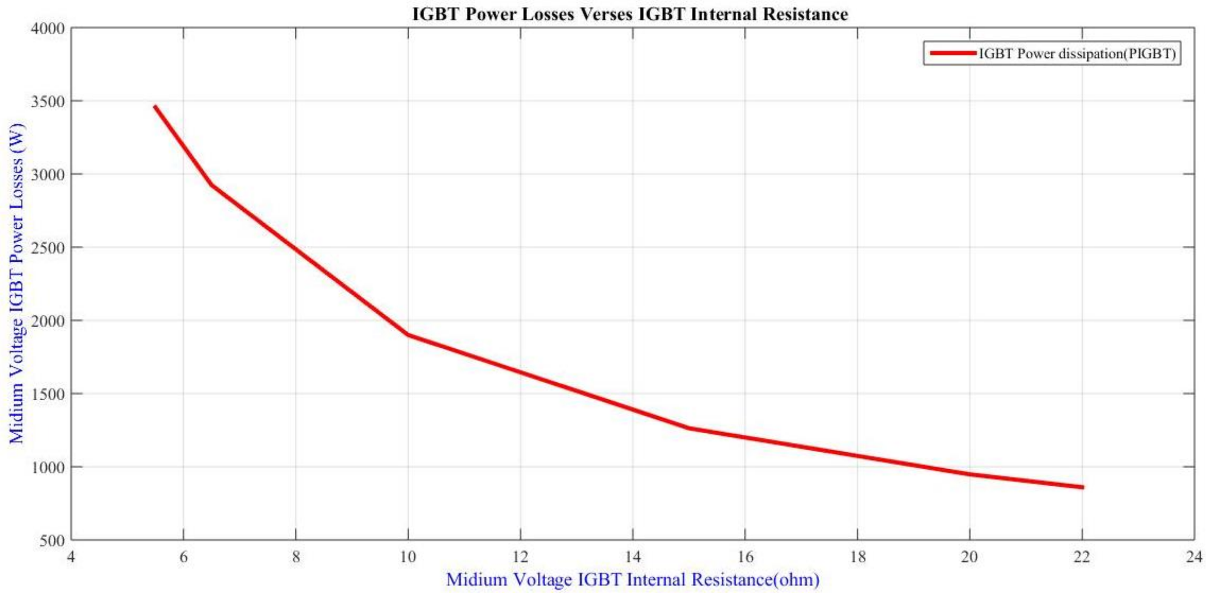
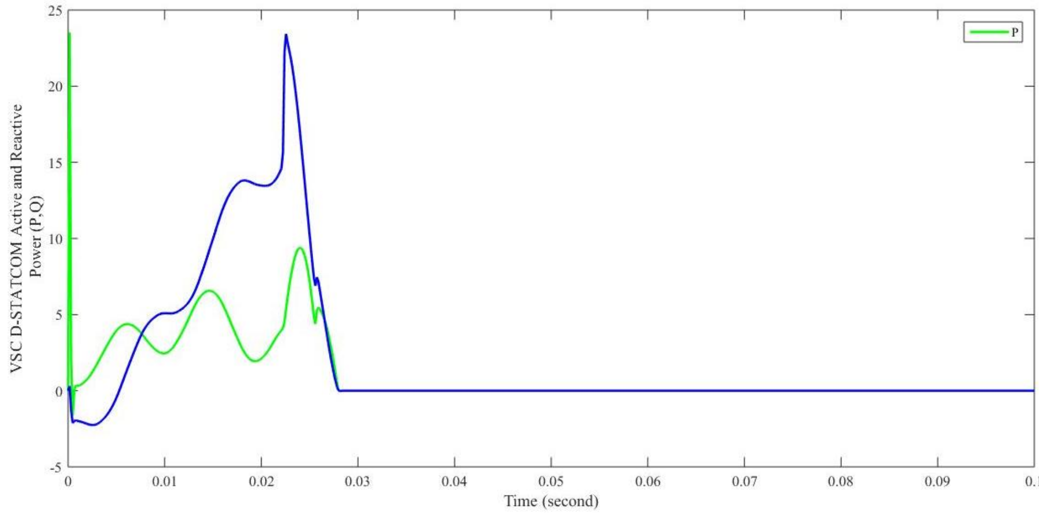


Figure 4.13 MATLAB Simulation Result of D-STATCOM IGBT Switches Power Loss

Even if the VSC D-STATCOM assumed fully reactive power but some losses are happen on the converter IGBT switches. From the data sheet of IGBT switches when the IGBT ON and OFF their internal (collector to emitter) resistance varies from 5.5 ohm fully ON state up to 22 ohm fully OFF state. At this condition, the power is lost in the form of heat as I_c^2R in the converter itself. This real power loss in the D-STATCOM is written in MATLAB code and drawn on the Figure 4.13 to indicate the active power loss on the D-STATCOM IGBT switchs.

MATLAB Simulation Results of D-STATCOM Current, Active and Reactive Power and Dc Link Voltage Level Verses Time



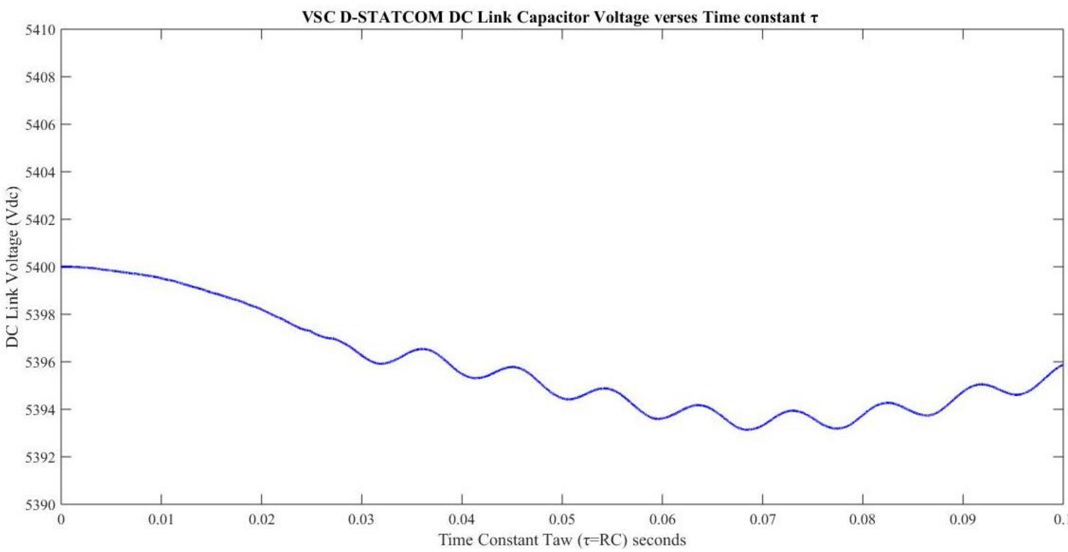


Figure 4.14 MATLAB Simulation Results of D-STATCOM Active and Reactive Power and Dc Link Voltage Level Verses Time

From Figure 4.14 MATLAB simulation result of DC link voltage is somewhat constant at the 5400v designed value of DC voltage, that designed to overcome the low power factor operating of the system load by injecting and absorving the necessary reactive power with the load. Thus, the dc link voltage output of the system is kept constant at 5400v dc, which is the designed value of the DC link capacitor voltage.

The decreasing and increasing DC link capacitor voltage of the Figure 4.14 is for the case of recovering the load bus voltage to be constant at one per unit system. This keeps the bus voltage constant, thus improves the load power factor to the designed, which is between 0.85 and 0.95 or 0.92 lagging. In addition to the active reactive and the D-STATCOM current are at stable conditions, this helps the D-STATCOM to regulate the bus voltage, load power factor and reactive power needed by the load of the factory with in short periods.

MATLAB Simulation Results of D-STATCOM (IGBT) Output voltage:

From the Figure 4.15 MATLAB simulation result of IGBT switches the output voltage is not pure sine wave, this is due to the nature of IGBT switches that generates harmonics on their switching system. The delta connected low pass filter at the input of the D-STATCOM removes this harmonic voltages and feed a pure sine wave and in phase with the source voltage to the load bus at PCC. This D-STATCOM IGBT output single phase voltage is around 1900v and with a three phase voltage of 3300 voltage ac. thus the voltage at the PCC is purely sine wave form or harmonic free and in phase with the load voltage.

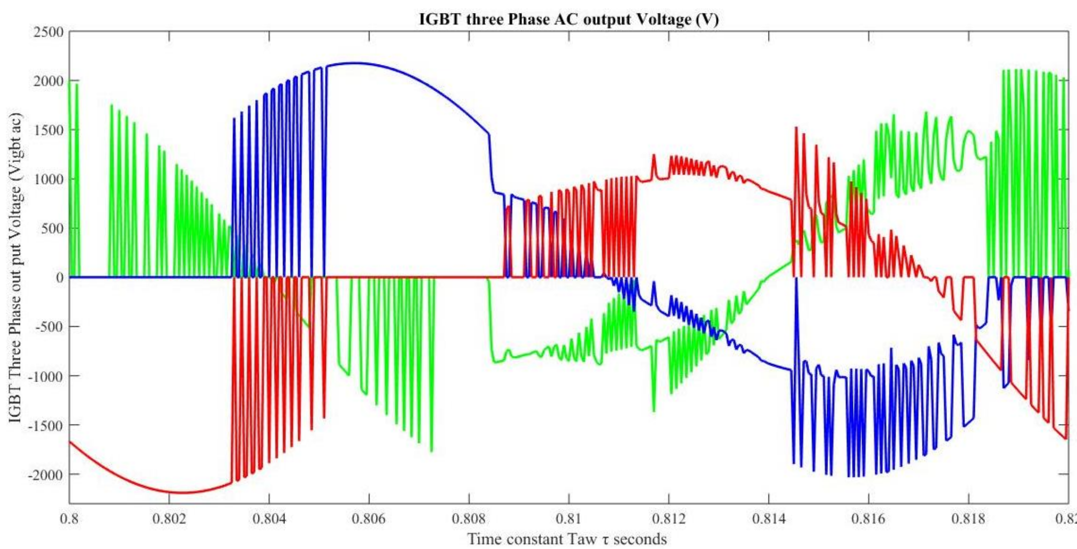


Figure 4.15 MATLAB Simulation Result of D-STATCOM IGBT Three Phase Voltage Output Signal Wave Form

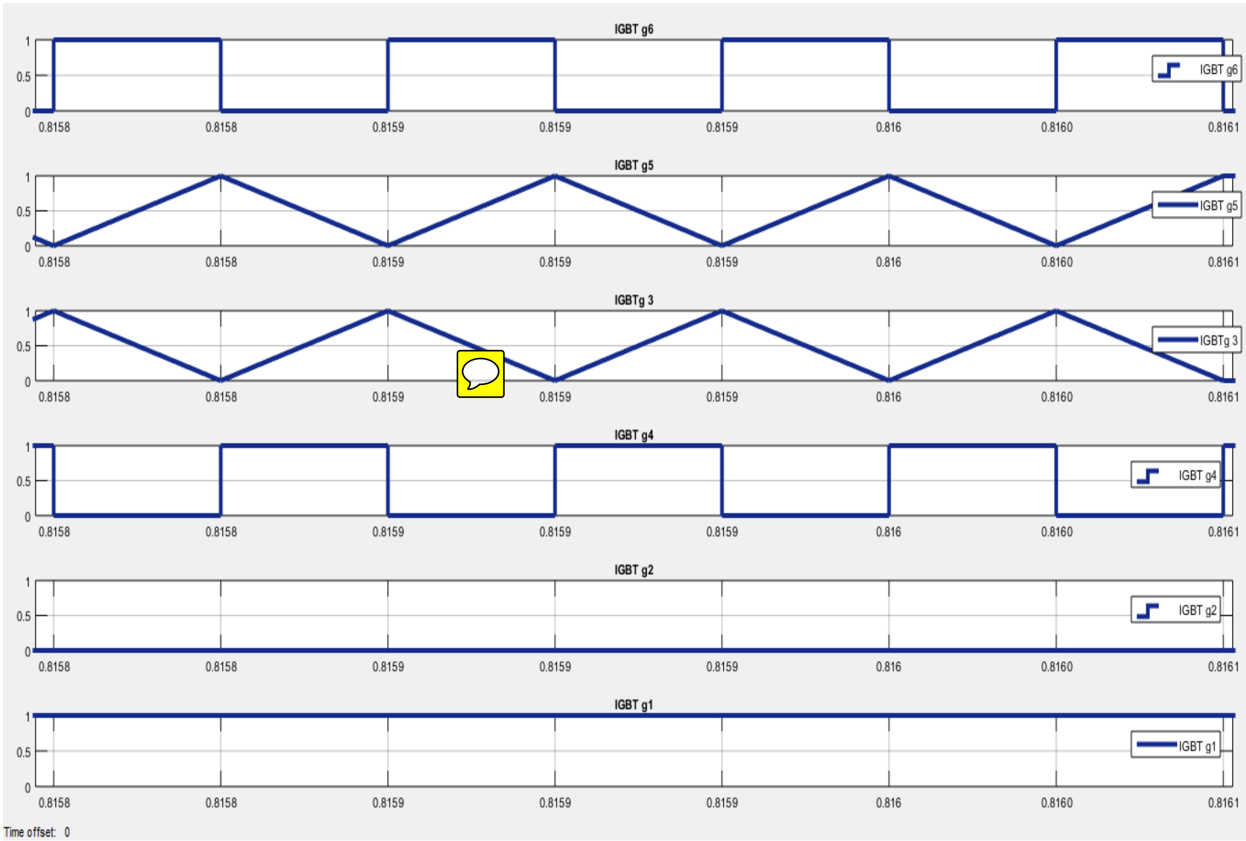


Figure 4.16 MATLAB Simulation Result of PWM Based SRF Switching D-STATCOM IGBT Pair of Converters

On this PWM based switching sequence of the D-STATCOM IGBT using the synchronous reference theory control circuits application and operation are addressed with simulation results. Figure 4.16 indicates that when IGBT switch g1 is ON the other pair of IGBT switch g2 is in OFF state and vise verse actions are takes place. The application of this switching system is to control the reactive current of the load resulting to control the load power factor of the Almeda textile load.

CHAPTER FIVE
CONCLUSION, RECOMMENDATION AND FUTURE WORK

5.1 **Conclusion**

On this thesis work, a D-SATCOM has been employed for compensation of reactive power and power factor improvement at Almeda textile factory using synchronous reference frame theory based control algorithm on three-phase load system. Various types of power factor correction methods have been studied and investigated from those methods D-STATCOM power factor correction method, is selected and thereby the factory lower power factor has been improved significantly from 0.66 lagging within the range of from 0.66 lagging to between 0.8[illegible]nd 0.95 lagging.

The SRF theory based control algorithm is used for extraction of balanced per phase active and reactive power for generation of reference currents in the factory load. The Various functions of D-SATCOM in linear and nonlinear distribution system such as harmonic elimination, source current compensation and load balancing have been demonstrated in power factor correction observed as per expected. The dc bus voltage of the D-SATCOM has been regulated to the reference dc bus voltage under all varying loads. The specification of the D-STATCOM components that used for this thesis work is designed depend on the reactive power requirement of the factory. Depend on the designs and MATLAB simulation results of D-STATCOM the Almeda textile low power factor is improved from the 0.66 lagging to 0.92 lagging. Due to this, the factory solves its power factor penalty bill of charges of sixty nine thousand per month. In addition to this the Ethiopian electrical utility (EEU) saves 2323KVAR reactive power which was consumed by Almeda textile every second.

Based on MATLAB simulation and MATLAB coding test results, it's concluded that the developed D-SATCOM and its control algorithm has been found suitable for power factor correction in a dynamic loads.

5.2 Recommendation

Efficient utilization of electrical power by reducing the quantity of power consumed and modifying the process of manufacturing provides sustainable development. For any country which is accelerating towards industrialization, efficient utilization of electrical power should be highly emphasized as it helps the economy growth smoothly. This thesis work has design and simulated D-STATCOM method of power factor correction for Almeda textile factory. From the power factor correction simulation results, more electrical energy is saved due to the improvement of low power factor of the factory. From this thesis work point of view it is , recommended that, the factory with the following points:

- ✓ Most of the machines on the factory are lightly loaded and since lightly loaded machines specially induction type machines consumes more reactive power from the system, so those machines should be operate from 0.7 to 0.9 % of their load to decrease their consumption of reactive power.
- ✓ Redesign of the load should be performed to solve the unloaded function of each induction machines.
- ✓ The induction machines should work at nearly fully loaded condition to minimize the loss.

5.3 Suggestions for future work

The results obtained in this thesis point to several issues where future research may be carried out. Some of these issues are:

- ✓ This thesis reflects study done on Almeda textile factory with regard to power factor correction only. Scope for further study exists in doing a detailed power quality issue.
- ✓ Current unbalance in the samples of transformers indicates that there is unbalanced load system within the system. This may needs further study.

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Appendixes A : Almeda Textile Factory Power Factor Charge Bill

Altex

ETHIOPIAN ELECTRIC UTILITY

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ELECTRICITY SALE BILL

ALMEDA TEXTILE FACTE
7392-262000, 0/0
UNKNOWN(ADWA DISTRICT) KEBE
ADWA

NO - ADAWA
CSC - ADWA DISTRICT
Tel:

7392262000003104
3511413

Contract No.: 597-5797 40257392-7392

Book-Itinerary No.: GR - 3 19

42
ICS - INDUSTRIAL -
Tariff Category

Bill No.: 611851310

Meter Reading Date: 01/06/2016

Meter Reading Sequence No.: 7392-262000 UNKNOWN (ADWA DISTRICT) KEBELE, ADWA ADWA

Electricity Supply Address:

Bill Items	Meter Number	Previous Reading	Present Reading	Meter Constant	Consumption KWh/KVA	Block Rate	CHARGE Birr
BAL. B/FWD							2,121,352.30
PAYMENTS							-767,352.04
ACTIVE - ENERGY	T-1111117	3663	3682	90000	1710000	0.4086	698,706.00
REACTIVE - KVAH		2515	2536	90000.00	1890000		
DEMAND MD		0	0	90000.00			
SERVICE CHARGE						54.0090	54.01
POWER FACTOR CH				(PF)	22.91	61.6340	68,592.03
		OUTSTANDING BALANCE					2,161,191.42

DEBIT ARREARS

Debit above 90 days	Debit within 60 days	Debit within 30 days	Current	PAYMENT DUE
1,354,000.26	0.00	0.00	767,352.04	2,121,352.30

Consumption Period: 01/05/16 to 01/06/16 (31 Days)

Estimated/Actual Bill: ACTUAL SENE 2008

Payment After No Shown 17/07/2016

Bill Preparation Date: 17/07/2016

Due Date: 17/07/2016

Contract Deposits: 410,415.00

Serial No.: 25223986

Collector   Date

IMPORTANT NOTES OVER LEAF

PLEASE DO NOT DETACH STUB

Payment Due: 2,121,352.30

Contract No.: 7392262000003104 3511413

ALMEDA TEXTILE FACTE
7392-262000, 0/0
UNKNOWN(ADWA DISTRICT) KEBELE, ADW
ADWA

Bill No: 611851310

Book-Itinerary No.: 597-5797 40257392-7392

Meter Reading Sequence No.: GR - 3 19

Bill Preparation Date: 17/07/2016

ETHIOPIAN ELECTRIC UTILITY

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ELECTRICITY SALE BILL

7392262000003104
3511413

MEDA TEXTILE FACTE
92-262000, 0/0
KNOWN(ADWA DISTRICT) KEBE
WA

NO - ADAWA
CSC - ADWA DISTRICT
Tel:

Contract No. 597-5797
40257392-7392

Book Itinerary No.: GR - 3
19

42
ICS - INDUSTRIAL -

632827868

Bill No.: 7392-262000, 0, UNKNOWN(ADWA DISTRICT) KEBELE, ADWA ADWA

01/09/2016

Electricity Supply Address:

	Meter Number	Previous Reading	Present Reading	Meter Constant	Consumption KWh/KVA	Block Rate	CHARGE Birr
L. B/FWD							2,116,011.89
Y NTS							-762,011.63
TIVE - ENERGYFT-1111117		3720	374390000	2070000		0.4086	845,802.00
ACTIVE - KVAH		2575	259890000.00		2070000		
MAND MD		0	090000.00				
RVICE CHARGE					54.0090		54.01
WER FACTOR CH			(PF)		19.29 61.6840		69,914.14
BAL 3027003							924,141.77
OUTSTANDING BALANCE							3,342,415.37

DEBIT ARREARS

	Debit within 60 days	Debit within 30 days	Current	PAYMENT DUE
2,278,142.03	0.00	0.00	915,770.15	3,193,912.18

01/08/16 to 01/09/16
(31 Days)

Estimated/Actual Bill: ACTUAL
MESKEREM 2009

Payment After: 12/10/2016

Due Date: 12/10/2016

Contract Deposits: 410,415.00

12/10/2016

28973332

Collector / Date

IMPORTANT NOTES OVER LEAF

PLEASE DO NOT DETACH STUB

Contract No. 7392262000003104
3511413

3,193,912.18

Collector / Date

Book Itinerary No.: 597-5797
40257392-7392

MEDA TEXTILE FACTE
92-262000, 0/0
KNOWN(ADWA DISTRICT) KEBELE, ADW
WA

Bill No: 632827868

CERTIFIED CHEQUES SHOULD BE MADE PAYABLE TO E.E.U. AND CROSSED

Meter Reading Sequence No. GR - 3
19

12/10/2016

842,222.45

Appendixes B: Energy Consumption of Almeda Textile Factory Machineries

Table B-1 : Energy Consumption Of Spinning Part of The Factory

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Uniflock	1	10.3	10.3
2	Uniclean	2	11	22
3	Unimix	3	7.16	21.48
4	Uniflex	3	13	39
5	Condenser	3	5.5	16.5
6	Mixing bale opener	2	6.97	13.94
7	Fine cleaner	1	4.25	4.25
8	Fan motor	7	2.2	15.4
9	Fan motor	11	4	44
10	Fan motor	1	7.5	7.5
11	Manual horizontal bell	1	4	4
12	Automatic horizontal bell	2	5.5	11
13	Fan motor	2	7.5	15
14	Fan motor	2	2.2	4.4
15	AC-A station total	1	119	119
16	Mixing opener	1	6.97	6.97
17	Cards	24	13.62	326.88
18	High speed draw frames	9	9.5	85.5
19	High speed draw frames	7	11.1	77.7
20	High speed combers	6	5.8	34.8
21	Speed frames	4	15.8	63.2
22	AC-2 station total	1	71.85	71.85
23	Lap former	1	13.6	13.6
24	Automatic open end	11	97	1067
25	Automatic open end	1	105	105
26	AC1 station total	1	179.9	179.9

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
27	AC station in laboratory	1	22.3	22.3
28	Winding	4	29.8	119.2
29	Twister old	4	22	88
30	Twister old	2	22	44
31	Twister new	3	29.8	89.4
32	Doubler old	1	7.4	7.4
33	Cone to cone	1	25.8	25.8
34	Doubler new	1	7.4	7.4
35	Yarn stripper	1	0.3	-
36	AC-3 station one	1	108.35	108.35
37	AC-3 station two	1	71.35	71.35
38	Ring frames	15	60.5	907.5
39	Yarn bundling press	1	22	22
40	Rewinding	1	10.3	10.3
41	Serie plan	1	2.1	2.1
42	Micromat	1	1.32	1.32
43	Uster tensor rapid	1	0.9	0.9
44	Micronaire	1	0.145	0.145
45	Termodetectore	1	1	1
46	Yarn striper	1	0.41	-
47	Flat wire mounting	1	1.94	1.94
48	Flat grinder	1	3.04	3.04
49	Flat end milling	1	2.21	21.1
50	Flat wire demounting	1	2.2	2.2
51	Waste sucker	1	3	3
52	Wire mounting	1	1.2	1.2
53	Cared wire grinder	1	0.7	0.7
54	Accotex grinder	1	1.8	1.8

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
55	Roving stripper	1	6.2	6.2
56	Air compressor	1	0.9	0.9
Total			1208	3932
			811692	2642186

Table B-2: Energy Consumption of Weaving Machines

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Warping creel	1	21	21
2	Sizing	1	48	48
3	Chemical mixer	1	14.5	14.5
4	Stirrer	1	5.1	0
5	Sectional warping creel	1	34	34
6	Looms for drill and twil	32	9.3	297.6
7	Poplin and sheetin	48	9.3	446.4
8	Looms for shirting	24	9.3	223.2
9	Looms for twil and dril	22	9.3	204.6
10	Looms for terry towel	5	8.4	42
11	Looms for canvas	5	8	40
12	Derolling and plaiting	1	4	4
13	Inspection	4	2.5	10
14	High pile plaiting	1	8	8
15	Storage crosousel	1	5.5	5.5
16	Steamer	1	6.6	6.6

No.	Name	Quantity	Designed capacity	Total
17	Harness cleaner	1	15.5	15.5
18	Beam lifter	1	1.5	1.5
19	Supply air unit	1	4	4
20	AC-B	1	47.5	47.5
21	AC-4	1	179.2	179.2
22	AC-5	1	179.2	179.2
23	Sanitary room,0ffice ,lighting for all	527	3.2	-
Total			625	1832
			419731	1231306

Table B-3 : Energy Consumptions of Finishing Part of Machines

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Yarn dyeing (hank dyeing)	2	19.4	38.8
2	Hydro extractor	1	6	6
3	Seinging/desizing	1	30.4	30.4
4	Batcher	2	10	20
5	Continuous scouring /bleaching	1	68.4	68.4
6	Open width washing range	1	41.8	41.8
7	Cylinder dryer	1	40	40
8	Mercerizing	1	91.2	91.2
9	Coustic recovery plant	1	7.5	7.5
10	Jiqqers	3	10	30
11	Stenters	1	175	175
12	Continuous dyeing range	1	202	202
13	Deying padder	1	27.75	27.75
14	Rotary screen printing	1	76	76
15	Backing /curing	1	30	30

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
16	Sanforizing	1	44	44
17	Calandering	1	34.5	34.5
18	Emerizing	1	75.38	75.38
19	Final inspection	4	2.5	10
20	Close rolling	1	2.5	2.5
21	Close rolling	1	4	4
22	Double folding	2	6.5	13
23	Baling	1	5.5	5.5
24	Pump house	2	15	30
25	Finishing and printing color kitchen	1	30.63	30.63
26	Mathis program dryer	1	9	9
27	Mathis lab mat	2	2.3	4.6
28	Micro wave	1	1.25	1.25
29	Padder	1	1	1
30	Loundary /washing m/cs	1	2.1	2.1
31	Lab dryer /binder	1	1.2	1.2
32	Lab dryer	1	2.1	2.1
33	Squeezer	1	0.9	0.9
34	Electrica balance	3	2.7	8.1
35	Stirrer heater	1	0.05	0.05
36	Tumple dryer	1	14.3	14.3
37	Emerizing	1	54.9	54.9
38	Polymerizer	1	14.4	14.4
39	Exposer	1	8.86	8.86
40	Coater	1	3.32	3.32
41	Dyeing colour kitchen	1	12	12

42	For screen cleaning	1	0.25	0
43	Hank lifter	1	4	4
44	Cabinet dryer	1	3.99	3.99
45	Exaust fan	2	5	10
46	Processing lighting	Set	13.86	13.86
Total			1213.19	1304.29
			815263.68	876482.88

Table B-4 : Energy Consumptions of Knit Dying Part Of Machines

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Sclavos	3	23.9	71.7
2	Sample sclavos	1	7	7
3	Squeezer	1	25	25
4	Dreyer 1	1	58	58
5	Dreyer 2	1	96	96
6	Compactor	1	27	27
7	Sewing /over lock/	3	0.55	1.65
8	Plater	1	1.5	1.5
9	Sample dying	1	2.3	2.3
10	Sample dryer	1	1	1
11	Sample heater	1	10	10
Total			252	301
			169512	202373

Table B-5 Energy Consumption of Circular Knitting Part of Machines

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Mayer & lie circular knitting	5	5.5	27.5
2	Pailung circular knitting	9	4.56	4.56
3	Flat knitting	6	0.92	5.52
4	Reeling	5	6.1	30.5
5	Inspection	1	1.2	1.2
Total			18	106
			12284	71071

Table B-6 Energy Consumptions Of Engineering Part of Machines

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Medium duty lathe	1	5.6	5.6
2	Light duty lathe	1	4	4
3	Universal milling	1	6.61	6.61
4	Power back saw	1	2.5	2.5
5	Power back saw	1	1.78	1.78
6	Drill	1	3	3
7	Drill	1	0.75	0.75
8	Drill	1	3	3
9	Tool grinder	1	0.37	0.37
10	Floor grinder	1	1.1	1.1
11	Cutting disk	1	2.2	2.2
12	Hydraulic press	1	7.5	7.5
13	Arc welding	3	59	177
14	Miqmaq wielding	1	5.39	5.39
15	Oxy acetylene	1	0	0
16	Circular	1	4.99	4.99

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
17	Planner	1	5.54	5.54
18	Drill	2	1.6	3.2
19	Oven	1	33	33
20	Auto coil former	1	3	3
21	Montier great sm-siller	1	0.55	0.55
22	Compressor	1	1.3	1.3
23	Rolling	1	1.6	1.6
24	Wheel balance	1	0.37	0.37
25	Feed water pump	6	5.5	33
26	Screw pump	3	2.3	6.9
27	Steam boiler	3	69.28	207.84
28	Dosing pump	1	0.2	0.2
29	Gearpump	1	0.3	0.3
30	Condensate pump	2	1.3	2.6
31	Screw spindle pump	2	1.2	2.4
32	Unloading pump	2	8.4	16.8
33	Circulating pump(thermal boiler)	1	12.6	12.6
34	Thermal oil boiler	1	78.7	78.7
35	Thermal oil reservoir	1	1.8	1.8
36	Refrigerant drier	2	3.7	7.4
37	Fuel oil depo(tankers)	6	17.2	103.2
38	Condensate tanker	1	1.5	1.5
39	Mixer	2	12.8	25.6
40	Mixer	3	4	12
41	Mixer	1	1.5	1.5
42	Mixer	4	1.3	5.2
43	Diaphragm pump	6	0.18	1.08
44	Diaphragm pump	1	1.3	1.3

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
45	Immersible aerator	1	14	14
46	Immersible aerator	2	14	28
47	Inline -lacerator	2	2.2	4.4
48	Counter current scraper	2	0.55	1.1
49	Rotary scruper	1	0.12	0.12
50	Submersible pump	1	1.21	1.21
51	Rotary scruper	2	0.12	0.24
52	Centrifugal pump	2	11	22
53	Centrifugal pump	2	5.5	11
54	Centrifugal pump	2	3	6
55	Centrifugal pump	3	7.5	22.5
56	Centrifugal pump	2	3	6
57	Displacement blower	1	9	9
58	Brine pump	1	0.86	0.86
59	E.H.R pump	6	3.45	20.7
60	E.H.R pump	3	9.2	27.6
61	Submersible pump	2	1.01	2.02
Total			466	973
			312836	653869

Table B-7 Energy Consumptions of New Garment (Woven) Part of Machines

No.	Name	quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Single needle	527	0.3	158.1
2	Double needle	26	0.425	11.05
3	Ms(feed of arm)	38	0.69	26.22
4	Bartaker	23	0.6	13.8
5	Button attach jucky	12	0.6	7.2
6	Button attach brother	6	0.4	2.4

7	Single needle	87	0.6	52.2
8	Double needle	13	0.6	7.8
9	Button hole	18	0.6	10.8
10	Button hole	5	0.6	3
11	5 thread(o'clock)	79	0.69	54.51
12	3 thread(o'clock)	26	0.69	17.94
13	Kansie	2	1.3	0
14	APW	4	0.35	1.4
15	Dice motor	2	0.44	0.88
16	Dice card	4	0.1	0
17	Belt loop	8	0.5	0
18	Top fusing	2	0.9	1.8
19	Coller press	3	2.3	0
20	Caf press machine	2	1.5	0
21	MH	18	0.7	0
22	Spreading m/c	4	2.1	0
23	Band knife	4	0.63	0
24	East man cutter	16	0.51	0
25	Rib cutter	4	0.4	0
26	Boiler for two iron m/c	4	7.1	0
27	Steam iron m/c	105	2.3	1.8
28	Dais cutter	1	1.8	0
29	Top fusing	4	0.5	2
30	Mini press	3	6.4	0
Total			11	560
			4487	233002

Table B-8 Energy Consumptions of New Garment (Knit) Part of Machines

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Piping m/c	10		0
2	Botton	21	0.644	13.524
3	Piping kansay	4	0.534	2.136
4	Over lock 4 thredd	67	515	34505
5	Over lock 4 thredd	7	0.913	6.391
6	Over lock 3 thredd	29	0.512	14.848
7	Sleave heame	7	0.34	0
8	Sleave heame	6	0.913	5.478
9	Rib cutter	1	0.215	0.215
10	Dice cutter	1	0.23	0
11	Pressing	4	5.6	0
12	Suction finishing	9	0.667	6.003
13	Table suction	6	0.345	2.07
14	Dray iron	9	1	9
15	Steam iron m/c	6	1.8	10.8
16	Single needle	45	0.55	24.75
17	Single needle	1	0.913	0.913
Total			524	34601
			217986	14394069

Table B-9 Energy Consumptions of New Garment (Utility and Supportive Area) Part of Machines

No.	Name	Quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Steam generator (steam boiler)	2	37.5	75
2	Turbo aspirator (vaccum motor)	2	30	60
3	Air compressor	2	18	36
4	Water pump	1	11.5	11.5
5	Daily fuel tank	1	0.13	0
6	Soft water plant	1	73.6	73.6
7	Canteen		0.2	
8	Office area	1	29.4	29.4
9	Toilet	1	23	23
10	Compound (street light)	35	0.15	5.25
11	Lightening production area (work area light)	42	1.624	68.208
12	High way light(reflection)	182	2.8	509.6
13	Lightening finishing area	6	1.656	9.936
14	Lightening cutting area	4	1.392	
Total			231	901
			95939	375022

Table B-10 Energy Consumptions of Computer Part of Machines

No.	Name	quantity	Power consumption (KWh)	
			Designed capacity	Total
1	Acer	2	0.98	1.96
2	Toshiba	34	1.034	35.156
3	Benq	5	0.96	4.8
4	Acer	2	0.98	1.96
5	Dell	133	1.78	236.74
6	Hp	3	1.78	5.34
7	Hanok	2	1.78	3.56
8	Waryt	16	0.6	9.6
Total			10	299
			6649	201006

Appendixes C: Transformer Ratings of Almeda Textile Factory

Table C-1 Transformer Ratings of Almeda Textile Factory

No.	Transformer rating
1	1000KVA
2	1000KVA
3	1250KVA
4	1250KVA
5	1000KVA
6	1000KVA
7	1000KVA
8	1000KVA
9	1600KVA
10	1600KVA
11	800KVA
12	800KVA
13	1250KVA
14	1250KVA (reserve)
Total	14550KVA

Appendixes D: Some Transformers Sample Load Reading on Power Stability Recorder

One transformer load profile of almeda textile factory displayed on power stability recorder

Figure A1.Transformer2 1mva transformer load profile displayed on power stability recorder

Figure A2 : Transformer9 1.25mva Transformer Load Profile Displayed On Power Stability Recorder

Figure A3 : Transformer7 1.6mva Transformer Load Profile Displayed on Power Stability Recorder

Figure A4 . Transformer2 1mva Transformer Load Power Factor Profile Displayed on Power Stability Recorder

From the above loads we have seen that there is a current unbalace on the three single phase systems of Almeda textile factory.

Appendixes E: MATLAB coding results of D-STATCOM Parametrs and power factor Figures

MATLAB coding to generate a graphical representation of low power factor operating of Almeda textile load.

```
clear;
clc;
base mva=6.44;
x= [0.64 0.65 0.66 0.66 0.67 0.67 0.66 0.65]; MATLAB simulation of PF result
y = [1 0.98 0.95 0.9 0.85 0.8 0.75 0.7];          Per unit apparent Power
plot (x,y)
y=legend ('Average Load Power Factor','per unit apparent power')
grid
function output txt = my function (obj,event_obj)
Display the position of the data cursor
obj currently not used (empty)
event_obj    Handle to event object
output_txt   Data cursor text string (string or cell array of strings).
pos = get(event_obj,'Position');
output txt = {['X: ',num2str (pos(1),4)],...
   ['Y: ',num2str (pos(2),4)]};
If there is a Z-coordinate in the position, display it as well
if length (pos) > 2
output txt{end+1} = ['Z: ',num2str(pos (3),4)];
end
```

MATAB code result for Improved ALTEX Load Power Factor

MATAB Code Generated a Graphical Representation of Corrected (Improved) Load Power Factor

```
clear;
clc;
base mva=6.44;
```

x=[1 0.98 0.95 0.9 0.85 0.8 0.75 0.7]; % Per unit apparent Power

y= [0.92 0.92 0.92 0.92 0.92 0.92 0.92 0.92]; %MATLAB simulation of PF result

plot (x,y)

y=legend ('load power factor','per unit apparent power')

grid

function output_txt = my function (obj,event_obj)

Display the position of the data cursor

obj   Currently not used (empty)

event_obj   Handle to event object

Output_txt   Data cursor text string (string or cell array of strings).

pos = get(event_obj,'Position');

output_txt = {['X: ',num2str(pos(1),4)],...

['Y: ',num2str(pos(2),4)]};

If there is a Z-coordinate in the position, display it as well

if length(pos) > 2

output_txt{end+1} = ['Z: ',num2str(pos(3),4)];

end

MATAB Code Result for Load Current Verses Power Factor before the D-STATCOM Connected to the Load

function create figure(X1, Y1)

Create figure(X1, Y1)

X1: vector of x data

Y1: vector of y data

Create figure

figure1 = figure ('Color', [0.678431391716003 0.921568632125854 1]);

Create axes

axes1 = axes ('Parent',figure1);

Box (axes1,'on');

Grid (axes1,'on');

Hold (axes1,'on');

Create plot

Plot(X1,Y1,'Display name', 'Average Load Power Factor');

Create legend

Legend (axes1,'show');

MATAB code result for Load Current Verses Power Factor after Power Factor Correction

Function create figure(X1, Y1)

Create figure(X1, Y1)

X1: vector of x data

Y1: vector of y data

Auto-generated by MATLAB on 07-May-2018 14:15:06

Create figure

figure1 = figure ('Color',[0.678431391716003 0.921568632125854 1]);

Create axes

axes1 = axes ('Parent',figure1,...

'ZColor',[0.153 0.227 0.373],...

'YMinorTick','on',...

'YTickLabel',{'0','0.1','0.3','0.5','0.6','0.7','0.8','0.9','1','1.1'},...

'YTick',[0 0.1 0.3 0.5 0.6 0.7 0.8 0.9 1 1.1],...

'YColor',[0.153 0.227 0.373],...

'XColor',[0.153 0.227 0.373],...

Uncomment the following line to preserve the X-limits of the axes

xlim(axes1,[4500 7000]);

Uncomment the following line to preserve the Y-limits of the axes

ylim(axes1,[0 1.2]);

Box (axes1,'on');

grid (axes1,'on');

hold (axes1,'on');

Create plot

Plot (X1,Y1,'DisplayName','Average Load Power Factor',...

```
'Marker Edge Color',[1 1 1],...
'LineWidth',3,...
'Color',[0 0.2 0.8]);
Create xlabel
xlabel('Load Current (A)');
Create ylabel
Ylabel ('Average Load Power Factor (PF)');
Create title
Title ('Load Power Factor verses Load Current after Power Factor Correction ');
Create legend
Legend (axes1,'show');
```

MATAB code result for dc link capacitor voltage

```
Start
clc
x= [0.0000039 0.0000077 0.00001552 0.000031 0.000062 0.000124 0.0002483 0.0004966 0.00099 0.00198656]; % time constant taw =R*C
y=[5405 5400 5400 5400 5400 5395 5395 5395 5400 5400]; % dc link capacitor voltage
plot (x,y)
y=legend ('Dc link Voltage(Vdc)','Time')
grid
function create figure(x1, Y1)
Create figure(X1, Y1)
X1:  vector of x data
Y1:  vector of y data
Create figure
figure1 = figure;
Create axes
axes1 = axes ('Parent',figure1);
 Uncomment the following line to preserve the Y-limits of the axes
Ylim (axes1,[5370 5420]);
```

Box (axes1,'on');

Grid (axes1,'on');

Hold (axes1,'on');

Create plot

Plot (x1,Y1,'DisplayName','Dc link Voltage(Vdc)','LineWidth',2,...

'Color',[0.200000002980232 0 0]);

Create legend

Legend (axes1,'show');

End

MATAB code result for DC link current

MATLAB cod of DC link current

Start

clc

x= [0.0000039 0.0000077 0.00001552 0.000031 0.000062 0.000124 0.0002483 0.0004966 0.00099 0.00198656]; % time constant taw R*C (τ)

y= [471.8 472 472 472 472 472.7 472.7 472.7 472 472]; % IGBT collector current

plot (x,y)

y=legend ('Dc link Current (Idc)','Time')

grid

function create figure(X1, Y1)

Create figure (X1, Y1)

X1: vector of x data

Y1: vector of y data

Create figure

figure1 = figure;

Create axes

axes1 = axes ('Parent',figure1);

box (axes1,'on');

grid (axes1,'on');

hold (axes1,'on');

```
Create plot
Plot (X1,Y1,'DisplayName','Dc link Current(Idc)');
 Create legend
Legend (axes1,'show');
end
```

MATLAB code result for power loss across the D-STATCOM IGBT switches from 'ON' up to 'OFF 'state

```
Start
clc
x= [5.5 6.5 10 15 20 22]; % IGBT resistance in (Ω) from on state to off state
y= [3455 2924 1900 1263 948 860]; % power loss across the IGBT switches from ON to OFF
Plot (x,y)
y=legend ('IGBT Power dissipation (PIGBT)','IGBT resistance')
Grid
Function create figure(X1, Y1)
Create Figure(X1, Y1)
 X1:  vector of x data
Y1:  vector of y data
axes1 = axes ('Parent',figure1);
Xlim (axes1,[2 24]);
Ylim (axes1,[500 5000]);
box (axes1,'on');
Grid (axes1,'on');
hold (axes1,'on');
Create plot
Plot (X1,Y1,'DisplayName','IGBT Power dissipation(PIGBT)','LineWidth',3,...
'Color',[1 0 0]);
Create legend
legend(axes1,'show');
end
```