



UNIVERSITY OF RWANDA
COLLEGE OF SCIENCE AND TECHNOLOGY

AFRICAN CENTER OF EXCELLENCE IN
ENERGY STUDIES FOR SUSTAINABLE DEVELOPMENT (ACE-
ESD)

**Design and Modeling of D-STATCOM for Power Factor
Improvement (Case Study: Gatare Tea Factory)**

A thesis submitted

In partial fulfilment of the requirement for the degree of
Master of Science in Electrical Power Systems

By

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October, 2022

DECLARATION

I hereby state that this MSc Thesis I have submitted for graduation at University of Rwanda is entirely unique work of mine, and that all sources of information included in the thesis have been properly cited.

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ACKNOWLEDGEMENTS

First, I would like to thank my Almighty God for the control during all my accomplishments especially in this thesis. My thanks goes also to University of Rwanda for facilitating this thesis work Next, I would like to sincerely thank my advisor, Dr. Ing. Getachew Biru, for his guidance, support, and understanding throughout this research as well as for his unwavering belief in me and his priceless contributions to my professional development.

I am also thankful to show my appreciation to Dr. Emmanuel MUDAHERANWA for his help & reinforcements from the proposal to the final report of my thesis.

In addition, I want to thank the staff at the Gatare Tea factory for their assistance in every way, especially the team from the electrical department, who assisted me in gathering the information I needed for my thesis.

Finally, I would want to thank both sides, my parents and my family for their sacrifice, support, and untiring encouragement.

ABSTRACT

Electricity is the widely used form of energy all over the world. Industries are using electricity to power the machines which are usually driven by induction motors. When these induction motors are operating, the system's power factor drops, which is a huge concern for the utilities that provide electricity since it results in increased losses from the reactive power that are used those induction motors and which is not paid. The system with low power factor is subjected to a number of problems such as voltage drop, voltage instability and high investment for buying larger generators, transformers and cables. Industries owners also face the problem of paying high bill due to high maximum kVA demand as the power factor varies inversely proportional to the reactive power of supply, and the increased reactive power result in increased kVA rating of the system.

Gatare Tea Factory, like other industries, struggles with a low power factor that averages at 0.54 if power factor is not corrected. A Distribution Static Synchronous Compensator (DSTATCOM), which boosted the factory power factor from 0.54 to 0.96 and above, was designed and modelled to improve this power factor. Various techniques were employed to complete this work, including factory-based data collection and analysis, analysis of other authors' writings on power factor improvement, selection and modeling of DSTATCOM, with power and control circuit modeling and simulation in Matlab/Simulink, and finally discussion of findings and cost analysis.

With the simulation in Matlab/Simulink, the DSTATCOM supply the reactive power in the system to be absorbed by the load which results in the increase of power factor from 0.54 to 0.96 and above. From simulated results the Voltage source converter DSTATCOM was shown to be a reliable and economical fact device to improve the power factor.

Key words: DSTATCOM, Power factor improvement, reactive power and MATLAB/Simulink.

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LIST OF ABBREVIATIONS

| | |
|-----------|---|
| AC | Alternative Current |
| DC | Direct Current |
| D-STATCOM | Distribution Static Synchronous Compensator |
| ETAP | Electrical Transient and Analysis Program |
| FACTS | Flexible Alternating Current Transmission System. |
| IGBT | Insulated Gate Bipolar Transistor |
| Kp | Proportional Gain |
| Ki | Integral Gain |
| KWh | Kilo Watt hour |
| KVAr | Kilo Volt Ampere reactive |
| IEEE | International Electrical Electronics Engineering |
| LCL | inductor-capacitor-inductor Passive Filter |
| MATLAB | Matrix Laboratory |
| PLL | Phase Locked Loop |
| PCC | Point of Common Coupling |
| PI | Proportional Integral |
| PWM | Pulse Width Modulation |
| S | Apparent Power |
| STATCON | Static Synchronous Compensator |
| SVC | Static VAR Compensator |
| VA | Volt-Ampere |
| VAR | Volt-Ampere-Reactive |
| VL12 | Line one to Line two Voltage |
| VL13 | Line one to Line Three Voltage |
| VL23 | Line Two to Line Three Voltage |
| Vp1 | Phase one to Neutral Voltage |
| Vp2 | Phase Two to Neutral Voltage |
| Vp3 | Phase Three to Neutral Voltage |
| V | Voltage |
| VSI | Voltage Source Inverter |

| | |
|-----|--------------------------|
| VSC | Voltage source converter |
| P | Active Power |
| Q | Reactive Power |

CHAPTER 1. INTRODUCTION

1.1. Background

Industries and factories employ induction motors to complete their tasks, and because of the way that these motors operate, which requires the consumption of reactive power in the system, and are the main source of low power factor. Working with low power factor results in system losses because reactive power consumption raises current in the line, which produces a voltage drop and energy loss from heat dissipation[1]. Low power factor is a big problem to utilities as it causes the performance at low efficiency. To avoid this low efficiency performance, utilities request all industries to improve their power factor for avoiding system losses and being penalized due to that low power factor.

The improvement of power factor is accomplished by using different methods such as shunt capacitors or FACTS devices[2]. Each method has its advantages and disadvantages and D-STATCOM is the one of suitable devices used in power factor improvement.

Due to the increase in a range of loads that contaminate the power system, maintaining quality power in electrical network is now more important than ever. Reactive power is needed by inductive loads like induction motors, transformers, and arc furnaces in order to magnetize them, and this reactive power consumption from the grid results in poor power quality. In an electrical power system, active and reactive power must be balanced between the sending end and the receiving end. If this is not kept up with, a voltage and frequency imbalance may happen, making the power system unstable. Active and reactive power control is necessary for a reliable power system.

One of the most cutting-edge power electronic devices, the static synchronous compensator (STATCOM) technology makes it possible to quickly and continuously compensate for capacitive and inductive reactive power.

Inductive loads make up the majority of the electrical power system's loads and draw lagging power factor currents. The increased demand for reactive power decreases the active power flow and raises feeder losses.

For large users and utilities, power factor correction at the distribution level is a crucial element to take into account. Power factor is given as the ratio of watts to Volt-Ampere ratings of the system. Reduced power factor on the consumer side requires utilities to boost the VA rating of their distribution transformers and switchgear in order to provide more reactive power, which causes disorder in the electrical supply network.

Capacitor banks were once employed by utilities to rectify the power factor, but they were bulky and inflexible. Due to the growing number of motors with rectifier control and the general rise in harmonic and inter-harmonic content, power quality issues in industrial facilities are becoming more and more problematic. These loads result in industries low power factor which causes inefficient use of electricity, which has an impact on both the plant's overall energy use and bill costs. Due to an imbalance between machine size and driving loads, which leads to significant reactive power consumption, the factory operates at a low power factor. This incorrect use of reactive power caused the factory's power factor to decrease, which has an impact on the nation's overall electric consumption.

This thesis work has designed and simulated a three-leg two level voltage source converter (VSC) D-STATCOM to compensate reactive power of Gatare Tea Factor hence to boost its power factor.

D-STATCOM can work in three different modes as follows: If the utility voltage is less than the its output voltage, it behaves as capacitor and supply reactive power to the system. If utility voltage is greater than the D-STATCOM output voltage, it behaves as a reactor and consume Reactive power from the system and if the utility voltage is equal to the D-STATCOM voltage, there is no supply and no absorption of Reactive power by the D-STATCOM; then it is reportedly operating in a floating model in this scenario[3].

The method of D-STATCOM was chosen to replace Shunt capacitors at GATARE Tea factory for three reasons: Capacitors have poor voltage regulation, and beyond a certain threshold of compensation, they do not reach a stable operating point. Their supplied reactive power depend on the square of terminal voltage which causes the VAR support to drop during low voltage conditions. On the other hand, D-STATCOM has a better characteristics, when the system voltage drops, it supply more voltage to attain the normal system voltage and its maximum reactive output is independent from the magnitude of the system voltage [4].

After designing a D-STATCOM to boost the power factor of Gatare Tea factory, the results were simulated by using Mat-lab Simulink. The data on GATARE Tea Factory load have been collected and analyzed together with the documentation to accomplish this research.

1.2. Statement of the Problem

Nowadays electricity is becoming the most used form of energy in all domains. Heavy tasks are performed by induction motors. The operation of induction motors and other inductive devices cause the power factor of the system to decrease as they consume reactive power. GATARE Tea Factory faces this problem of low power factor as it uses induction motors to perform different tasks in the factory.

The low power factor causes different problems on both sides, consumers and utilities. Some of the problems caused by working with low power factor are:

- i) **High apparent power equipment rating:** system equipment like alternators, transformers, and switchgear, are all rated in KVA. Since the equipment's KVA rating increases when the power factor was reduced, the decreased power factor results in the high apparent power rating of equipment. As a result, the KVA rating of the equipment is increased at low power factor, increasing the equipment's size and cost.
- ii) **High conductor size:** At low power factor, the conductor must carry more current than it would at higher power factor in order to carry out the equivalent amount of power at constant voltage. Large conductor sizes are required as a result, which raises the price on the utility side.
- iii) **High copper losses:** More I^2R losses occur in each component of the electrical network. And at low power factor the current increases and results in high losses in all equipment. Hence Equipment efficiency decreases as a result.
- iv) **Poorly regulated voltage:** Alternators, transformers, transmission lines, and distributors have significant voltage drops due to the high current at low lagging power factor. Due to the reduced voltage at the supply end as a result, user's devices performance is reduced. An additional piece of equipment (a voltage regulator, for example), which adds to the cost, is needed to maintain the receiving end voltage within acceptable bounds.

v) **Penalties on the consumer side:** Consumers with low power factor are penalized by distributes which results in larger amount of money paid. In Rwanda REG recommend users to work with power factor not less than 0.8, otherwise they are penalized. In this thesis, a DSTATCOM is Designed and Modelled to improve the power factor at Gatare Tea Factory.

This study is done to assess the potential of DSTATCOM over Static capacitors which are currently in use at the factory. The current method presents disadvantages over the new one such as: poor voltage regulation compared to DSTATCOM; this causes the damage of sensitive loads. The supplied reactive power of Static capacitors depends on system terminal voltage which leads to insufficient VAR compensation during low voltage conditions in the system which is not the same case to DSTATCOM. They have a short lifespan of 8 to 10 years, are readily damaged if the voltage is higher than the rated value, and once broken, are expensive to repair.

These disadvantages of low power factor result in higher losses for more payment of electricity. The use of D-STATCOM to improve power factor at Gatare Tea Factory is a solution for the stated problems.

1.3. Objectives

1.3.1. Main Objective

To design, model and simulate D-STATCOM for studying the potential improvement of the power factor of GATARE Tea factory

1.3.2. The Specific Objectives

The following specific objectives have been accomplished in order to reach the overall objective

- Collection of data on the factory and evaluate the performance gap.
- Design a D-STATCOM that can increase the factory power factor from 0.54 to 0.96.
- Modelling and simulate a system that to improve the factory power factor from 0.54 to 0.96 and evaluate the performance improvement.
- Estimate the cost of implementation and the cost recovery period.

1.4. Scope of the study

The study involved reviewing related literature, collection and analysis of data from GATARE Tea factory located in Western province of Rwanda to boost the factory power factor from 0.54 to 0.96 and above. In this thesis, a three leg, two level voltage source converter based D-STATCOM have been used and the simulation was done using MATLAB/Simulink software.

1.5. Significance of the Study

As explained below, improving power factor is crucial for both consumers and generating stations.

- **For consumer side:** In addition to the units consumed (kWh), customers are required to pay power fees based on their maximum KVA demand.

If the consumer increases power factor, his maximum KVA demand decreases, which results in a reduced maximum demand charges and in annual money savings. Even though power factor improvement requires additional annual spending for buying equipment to improve the power factor, getting the power factor to the right level leads to a net annual savings of the consumers.

- **For generation side:** Power factor improvements affect generating stations just as much as they do on consumers. Although a power plant's generators are rated in KVA, their useful output depend on kW output as is expressed as $kW = kVACos\Phi$. Therefore kilowatt hours supplied by it depend on its power factor. If the power factor is increased at high level, active energy supplied by the generation to the customers increases, which leads to the conclusion that a power plant's ability to make more money is increased by improved power factor of the system.

1.6. Methodology

Various techniques were employed to accomplish this thesis and are discussed below.

- **Literature review:** Different published suggestions for increasing power factor have been reviewed and used to write literature review.

- **Data Collection:** Different types of data have been collected in order to complete this work, such as rated power, daily energy consumption, system voltage, and operating power factor.
- **Data analysis:** the collected data at the factory have been analyzed to identify the gaps.
- **Design and Modelling:** DSTATCOM is integrated in the power grid for validating the improvements.
- **Simulation:** The Simulation has been done in the Simulink with MATLAB software to observe and validate the impacts of the DSTATCOM.

1.7. Description of the Study Area

Gatare Tea factory is situated in the Nyamasheke District of western province of Rwanda, 22.7 kilometers from the district headquarters and 185.8 kilometers from Kigali. Its coordinates are 2°18'09.1"S and 29°12'37.0"E. Tea is grown between 1,500 and 2,500 meters above sea level on highlands and marshlands with good drainage. Highlands and well drained marshlands describe the land of 1,000 hills pretty accurately [1].



Figure 1.1. Gatare tea factory location

The factory is supplied by one distribution transformer with rated capacity of 630kVA, 30/0.4kV, 50Hz, which is connected on 30kV line from Kibogora substation.



Figure 1.2. Gatare Tea Factory Building

The factory was designed to process and export tea. It is Equipped with more than 200 induction motors with the specific tasks such as blowing hot air on flesh tea to reduce quantity water in the leaves, to drive the conveyers, to crush tea leaves and to ferment and separate the quantities of tea. To boost the overall factory's power factor, the bank of static capacitors is used with controller to switch on the required capacitors according to the load reactive power in the circuit.

1.8. Organization of the work

This work is divided in six chapters and each one is briefly explained as follows.

Chapter 1: Is an introduction about power factor improvement and focuses mainly on background of the study, problem statement, objectives, significance, methodology and scope of the work.

Chapter 2: It includes theoretical background and comprehensive literature review of different related works about power factor improvement.

Chapter 3: this chapter deals with data collection and its analysis.

Chapter 4: It deals with design and modeling of DSTATCOM for improving power factor of the factory.

Chapter 5: Deals with simulation results and their discussions. The simulation results with MATLAB/Simulink were discussed.

Chapter 6: Discussed about conclusions and recommendations.

CHAPTER 2. THEORETICAL BACKGROUND AND LITERATURE REVIEW

This thesis describes how the Distribution Static Compensator (D-STATCOM) improved the GATARE Tea Factory's low power factor and reactive power compensation and Voltage Source Converter D-STATCOM principle serves as the foundation for the idea.

The D-STATCOM introduces reactive power into the network to lower the distortion of harmonics and increase power factor. The methods used to improve power factor have been studied by various writers from various angles, and various power factor correction approaches have been discussed. The low power factor of the GATARE Tea factory was improved in this thesis by using a three leg two level voltage source converter D-STATCOM. Different studies have been conducted about improvement of power quality and power factor in general and have been reviewed in this work to write literature review.

2.1. Power Factor

The power factor is defined as the quotient of the produced kW to the produced kVA of the system. It is also determined by the cosine of the system's voltage and current phase angle [5].

When the power factor of the customer is low, the current increases in the system and the losses increase and the capacity of the system has to be increased also. To reduce these losses and this increment of system equipment, the consumers are requested to increase the power factor of their load by adding the power factor improvement devices in shunt with the load[6]. If the consumers do not increase their power factor closer to unit, penalties are applied to them.

2.2. Sources of Low Power Factor

Low power factor is mainly caused by inductive load connected in the system. Due to high angle of phase difference between system current and voltage in purely inductive load which is which is 90° , it causes the power factor to decrease to a very low value approximately to zero.

The sources of low Power factor include the followings;

- a) **Single phase and three phase induction Motors:** Induction motors often operate at low power factors, in the range of 0.8 to 0.9 when loaded at full, little load, 0.2 to 0.3 with small load and the power factor may reach zero when working at no load.

- b) **Load variation in Power System network:** As usual, the load consumption of electricity changes with the time. In the case there is a small demand or no demand, the supply voltage increases which increases the magnetizing current and decreases the power factor of the system.
- c) **Industrial heating furnaces:** these furnaces are made by inductors which when carrying A.C current, induce eddy current to the metal to be heated and heats it up. As they draw a lagging current they lower the system's power factor to which are connected.
- d) **Electrical discharge lamps:** (Lighting using high-intensity discharge) Arc lighting lamps when operating their power factor becomes very low.
- e) **Transformers:** As transformers are made by coils, they decrease the power factor in the circuit. And
- f) **Harmonic Currents:** Nonlinear loads in the system are the main sources of harmonic current which result in decreased power factor [6].

Devices that are used to overcome these problems are installed in the system to supply reactive power. Thus, GATARE Tea factory experience this problem of low power factor, and in this thesis the voltage source converter based DSTACOM was designed and simulated to supply the required reactive power to improve the power factor to the value above 0.96.

2.3. Drawbacks of low power factor

The power is important factor to consider in power systems as energy consumed by the load depends on this factor. Expressions of three phase power and line current are shown in equations (2.1) and (2.2) respectively while the expression of power factor is shown in equation (2.3)

$$P = \sqrt{3} V_L I_L \cos\theta \quad (2.1)$$

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

$$\cos\theta = \frac{P}{S} \quad (2.3)$$

According to the equation (2.2), for a fixed amount of power and voltage, the current of load increases as the power factor decreases and vice versa. P is active power of load, I_L is the three phase line current, V_L is the three phase line voltage, S is the load apparent power, θ is the phase angle between load voltage and current and $\cos\theta$ is the power factor. The drawbacks of a low power factor are presented here below:

- 1) **High KVA Rating of equipment:** Electrical machines and equipment (e.g. switchgear, alternators and transformers) are rated in KVA. As the rating kVA of equipment increase with the decrement of power factor, the decreased power factor results in high kVA rating of equipment. This results in large cross sectional areas of conductors and larger sizes of equipment. All these issues cause the increase of cost on the utility side.
- 2) **High conductor size:** At low power factor, the conductor must carry more current than it would at higher power factor in order to transmit the same amount of power at constant voltage. Large conductor sizes are required as a result, which raises the price on the utility side.
- 3) **High copper losses:** at low power factor, the current increases in all equipment of the system. As the copper losses are direct proportional to the square of the current flowing (I^2R) and increases heat of equipment; these reduce efficiency of equipment.
- 4) **Poorly regulated voltage:** The large current caused by low lagging power factor results in greater voltage drops in generators, transformers, and transmission and distribution lines. This causes the terminal voltage at the load side which weakens the performance of connected devices. To avoid this problem, the consumers are required to install voltage regulators devices which result in addition costs.

2.4. Review on the Current Power Factor Correction Techniques

The major cause of poor power factor is the lagging currents flows in inductive loads. Its improvement is achieved by installing in shunt to the load the devices that draws the leading current to cancel the effects of lagging currents of inductive load. To improve the power factor, Different devices are used. Most used devices are capacitors, static VAR compensators, synchronous condenser, modulated power filter capacitor compensator, static synchronous compensator, etc. different devices used to improve power factor are discussed as below.

2.4.1. Capacitor bank

Static capacitors are used to generate capacitive reactance, canceling out the inductive reactance of the lagged current. These banks support both star and delta connections. Typically, a control system is used to monitor the power factor by turning on and off these ones.

In [7], N. P. Jampalwar et al. present a review on induction motor automatic power factor improvement. Static capacitors are used and installed in parallel with an induction motor to increase its power factor. Advantages of power factor correction are stated and researchers conclude stating that Power factor improvement techniques can be used to stabilize industries, power systems, and family unit. As a result, the system becomes stable and both system and device productivity rise. However, it's important to avoid overcorrecting because doing so would increase the voltage and current, which will make the appliance or power system unsteady and shorten the life of the capacitor banks.

In [8], H. K. Channi present overview of power factor correction techniques. He discusses the technics of power factor correction and including Static capacitors by comparison of technics giving advantages and disadvantages. He shows that capacitors can be used in power factor improvement in factories, concluding stating that the power factor is enhanced and plant efficiency is increased by adding power capacitors of the appropriate size to the circuit. He concludes by highlighting several drawbacks of employing capacitors to increase power factor, such as their short life of service of 8 to 10 years, ease of damage from voltages beyond their rated value, and expensive repair once are damaged.

In [9], F.-G. Popescu et al. presents the financial and technical benefits of power factor adjustment. They demonstrate how power factor correction technologies boost electricity supply efficiency and provide immediate cost savings. The authors continue by stating that it is imperative to keep in mind that the capacitor bank represents an "installation expense" that must be fairly dispersed across the installation's years of use using one or more economic coefficients. In reality, the cost of installing the capacitor bank can be recovered during the first few years of operation. In addition, excessive capacitors in an AC circuit, like excessive inductance, will cause a poor power factor. Therefore, in order to avoid over-correcting the circuit, we must be careful when dealing with power factor correction.

Advantages of capacitor bank

- Capacitors operation exhibit Low losses
- Their maintenance require low cost
- Easy to transport due to their fewer weight
- Their installation is simple

Disadvantages of capacitor bank

- They have short lifespan ranging from 8 to 10 years
- During overvoltage time, they are damaged easily.
- In case they are damaged, their repair requires high costs. Hence there are not economical.
- Due to their switching set-up, harmonics and surges are produced..

2.4.2. Synchronous condenser

In [10], X. Zhou et al. Present A Review of Reactive Power Compensation Devices. They demonstrate that when employed with the appropriate automatic exciter circuit, the device can continuously adjust reactive power. At distribution voltage levels as well as transmission voltage levels, synchronous condensers have been utilized to maintain and enhance voltage stability within specified limits under a variety of loads and emergency situations [4]. Synchronous condensers are still used occasionally, but they are rarely used because they require large foundations and a lot of starting and safety equipment. They cannot be managed quickly enough to make up for sudden changes in load, and the short-circuit current is likewise influenced by them. Furthermore, compared to static compensators, their losses and costs are substantially higher. However, their great capacity for brief overloads is a benefit.

In [11], A.H.M. Iftokharul Ferdous et al. present Synchronous Condenser power factor monitoring and control. The researchers show advantages of synchronous condenser in power factor correction over capacitor as this one reduces harmonics which is not the case with capacitor bank.

They conclude by stating that due to the synchronous condenser's extended lifespan, it is essential to employ synchronous condenser in high voltage systems rather than capacitor bank.

In [12], A. Zaw Latt discusses synchronous motor's application to boost power factor for industries loads. The researcher explains how connecting an overexcited synchronous motor in parallel with industrial loads that have a lagging power factor can improve power factor. In this study, the synchronous motor (condenser) is rated appropriately to make up for reactive power and increase the rice milling plant's power factor from 0.7 to a range between 0.95 and unity.

In his conclusion, he states that although synchronous motors, static capacitors, and phase advancers are typically utilized as load compensators, major enterprises often use synchronous condensers to increase power factor due to their advantages over other compensators. Within the boundaries of its design and load, synchronous motors can have their power factor controlled.

In [13], S. Fahiz et al. investigate the automatic power factor controller using synchronous condenser. The researchers show that Electrical load power factor correction is a problem that affects all industrial enterprises, and in the past, power factor correction was accomplished by manually adjusting the capacitance bank.

In their research they propose to use automated synchronous condenser to increase the system power factor of the due to its low maintenance cost and long life compared to capacitors. Additionally, the synchronous condenser reduces harmonics, which is impossible with a capacitor bank.

2.4.3. Static VAR Compensator (SVC)

In [4], M. Noroozian et al., the researchers present advantages of SVC and STATCOM for applications in power utilities.

They demonstrate that SVC can control load voltage up to roughly 0.25 p.u. Both compensators reach their limits over this threshold.

SVCs and STATCOMs work as a shunt capacitor and a constant current source collectively. It was demonstrated that STATCOMs contribute more to the voltage regulation than SVCs by a factor of roughly 1.7%. They also demonstrate that STATCOMs disconnect to protect the valves if the voltage exceeds above limit.

They continue showing that for the same amount of reactive power of the system, STATCOMs contribute more to the voltage regulation than SVCs during under-voltage cases. As this case is almost common in Rwanda, STATCOMs can be a long-lasting solution for this issue.

In [10], X. Zhou et al. presented a review on devices used in compensation of reactive power. They highlight SVC's benefits, including its ability to maintain network voltage at a predetermined reference point and some of its other control features, including control of voltage , reactive power management, dampening of power oscillations, imbalance control, and quick

reaction. The STATCOM, however, is up to 1/3 the size and 1/5 the volume of Static Var Compensator.

In[14], F. Ali et al. described an SVC controller for improvement of power quality of a heavily loaded Grid. The researchers show that the device improves the quality of power in the system including power factor correction at a sufficient level. They show how SVC is best over capacitor banks which require voltage an installation of regulators in the circuit which is not the case to SVC. They conclude stating that SVC is a good FACT device for power quality improvement but introduces harmonics in the system which cannot be reduced completely in the system.

Static VAR Compensator Benefits

- It improves the transmission lines' capacity for power transmission.
- It increases the system's transient stability.
- It regulates both momentary overvoltages and steady states.
- It raises the load power factor, which decreases line losses and enhances system performance.

2.4.4. Static Synchronous Compensator (STATCOM)

A Static Synchronous Compensator is a modern FACT device used in reactive power compensation of the electrical system. According to designs of systems with equivalent dynamic ranges, the STATCOM can occupy up to 1/3 of the space and 1/5 of the volume of an SVC. Due to the lack of capacitors or reactors needed to provide reactive power, the STATCOM requires less installation space. STATCOM features more controllable variables and greater dynamic behavior. Due to these benefits, STATCOM will soon be more widely accessible device[10].

The use of STATCOMs or SVCs does not generally appear to be hindered by the footprint issue, however on occasion, STATCOM has been chosen because of the expected reduced footprint.

SVCs function as shunt capacitors, while the STATCOM acts as a constant current source. When parallel lines go down, for instance, the terminal voltage drops to one-third of its nominal value, STATCOMs contribute 1.7% more to voltage regulation than SVCs do. According to the aforementioned examples, STATCOMs contribute to voltage regulation more effectively under

under-voltage conditions than SVCs with the same reactive power rating, and SVCs more effectively under overvoltage conditions than STATCOMs [4]. As a result, STATCOM is good in power factor improvement than SVC.

In [15], M. Mbae and N. Nwulu present Impact of hybrid FACTS devices on the steadiness of power system in Kenya. The researchers show how FACTS devices can be employed singly or in combination to boost the stability of a power system. They have extensively researched the usage of the SVC for improving rotor angle stability as well as voltage steadiness in power systems both when the system is functioning normally and when there are system disturbances like line outages and line faults.

They demonstrate that the voltage varies inversely with the reactive power and as a result, their usefulness in a power system declines when the demand increases.

A key advantage The STATCOM is that it offers all required reactive power compensation without the influence of the system voltage, which is a significant benefit over the SVC. Numerous studies have been conducted on the STATCOM to increase rotor angle stability and voltage. When the SVC and STATCOM were compared, it was found that the latter performed better in terms of enhancing transient stability and system voltage profiles. They end by demonstrating that, regardless of the system voltage, the STATCOM provides full reactive power adjustment. Compared to the TCSC and the SVC, which both feature capacitor correction and whose output decreases with system voltage, this is a significant improvement.

In alternating current electrical transmission networks, a static synchronous compensator (STATCOM), sometimes known as a static synchronous condenser (STATCON), is a regulating device. It can supply or drain reactive AC power to a network of outlets and is based on a voltage-source converter for power electronics. If it is connected to a power source, it can also give active AC power. It belongs to the family of FACTS devices and is already power and modular [16]. Voltage source converter and current source converter are shown in the Figure 2.1 [15,16].

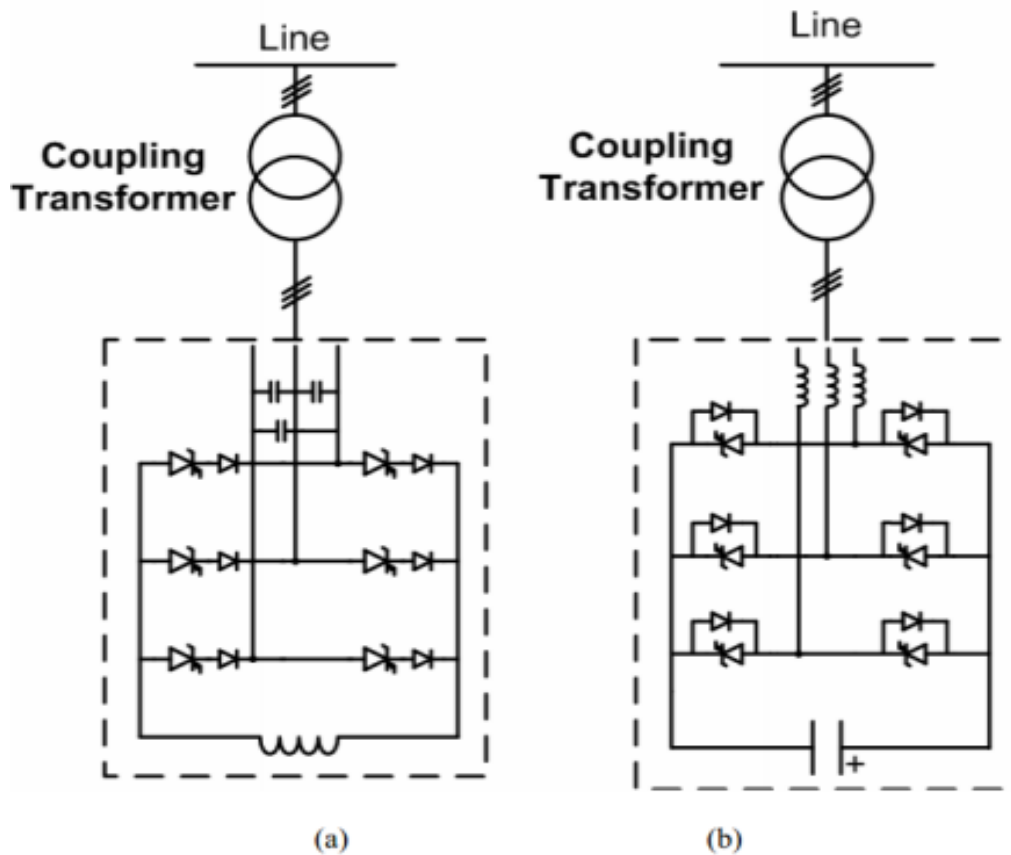


Figure 2.1. Current Source Converter (a) and Voltage Source Converter (b)

A synchronous condenser with static power electronics is known as a STATCOM. It is a piece of reactive power compensation equipment that is shunt connected, and it exhibits performance traits akin to those of a rotating synchronous condenser. STATCOM in systems are categorized as Distribution STATCOM and Transmission STATCOM and even though they share the same structure.

2.5. Power Factor Improvement by Distribution STATCOM

The STATCOM is known as D-STACOM (Distribution STATCOM) when it is used in a distribution system, and it has the same configuration as transmission STATCOM. Given that the research location is a factory, the poor power factor, voltage sag, swell, and unbalanced load current issues at the GATARE Tea facility were resolved using the VSC based distribution-STATCOM. An effective solution to the distribution system's issues with reactive power compensation, power factor correction, voltage control, load balancing, and harmonic filtering is achieved by a shunt compensation device called a D-STATCOM.

To remove imbalances or distortions in the appliance current or system voltage, D-STATCOM may be able to inject unbalanced and harmonically distorted current in the system. A controller, coupling inductor or transformer, DC capacitor, and voltage source converter make up the device (VSC). The D-STATCOM is connected to the grid on the Common Coupling point via a coupling inductor and is managed such that it only trades reactive power with the grid. The current is injected in quadrature with the grid voltage to achieve this. A GTO or IGBT based Voltage source inverter coupled to electrical network through a coupling transformer or inductor makes up a D-STATCOM. Typically, STATCOM-level transmission applications requiring high power use GTOs.

IGBTs are commonly used in medium- to low-voltage power applications in D-STATCOM. It either uses a voltage source converter or a current source converter, with a capacitor or an inductor serving as reactive power storage, respectively. Because of their smaller diameters, reduced heat dissipation, with the same rating, voltage source inverters are typically employed extensively than Current Source Inverter which use expensive inductor compared to capacitors used in VSI. A Voltage Sourced Converter D-STATCOM linked to the grid is shown in Figure 2.2[17].

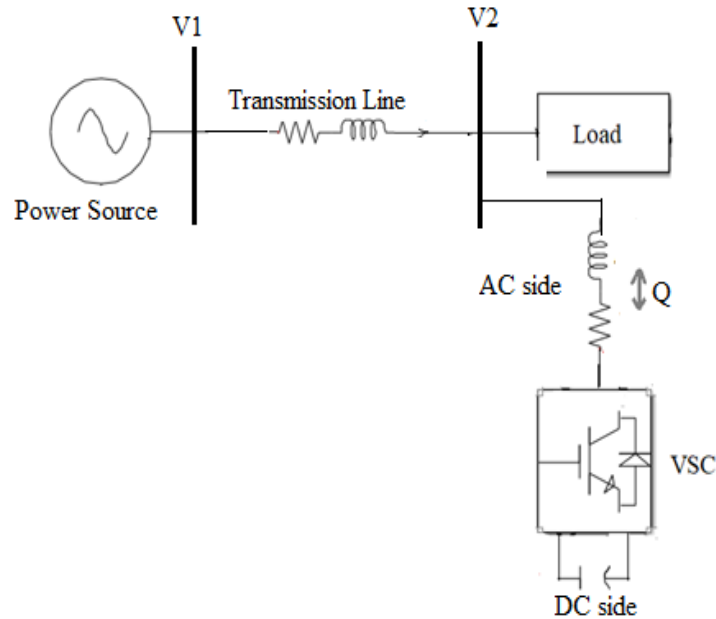


Figure 2.2. VSC D-STATCOM connected in the power system

The following are benefits of D-STATCOM power factor correction over other power factor correction techniques. [18].

In contrast to the synchronous condenser, it operates with a very fast temporary response, giving the impression that it has almost no inertia. It also offers nearly steeples compensation for reactive VARs and automatically maintains the desired power factor taken as reference, despite load fluctuations. If plant load increases, adding more units in parallel can enhance compensation capacity. It can be managed to deliver leading or lagging VARs and adapts itself automatically based on the load VAR demand. It has better dynamics, zero inertia, less expensive to install and maintain than synchronous condenser.

It Enables complete grid control; continuous and dynamic voltage regulation, it effectively improve power factor than other alternative power factor correction techniques. It has High dynamic and quick step reaction between 8 and 30 ms. As active power regulation is available with a DSTATCOM, it supports in system stability control. It a highest reactive current across a wide voltage range, able to regulate unbalanced load using a single phase and has no possibility of creating a resonance point.

The method of power factor correction using D-STATCOM is the best for power factor adjustment in the distribution level circuits and big consumers among the several power factor correction techniques previously addressed.

That is why the D-STATCOM was chosen to improve the power factor in my thesis work at GATARE Tea factory. The gap in power quality improvement is that the response time of capacitors is long and these ones generally have low performance compared to DSTATCOM. To overcome this, the neural network system will be used with back propagation algorithm in this research.

2.6. Principles of operation of D-STATCOM

A Distribution STATCOM is nothing other than a STATCOM used at the distribution level of an electrical network. For reactive power compensation, it is connected at the load side. Either it is used to improve the power factor or to regulate the voltage. It is a three-phase power electronic device connected in shunt. When the inverter is operated using the D-STATCOM controller, the angle of phase between the inverter output voltage and the line voltage is adjusted, allowing the D-STATCOM to generate or absorb the appropriate reactive power at the Point of connection of DSTATCOM to the system. If the voltage of DSTATCOM is equal to that of the system, there is no exchange of reactive power in the system.

The current I_c of collector, that flows in the coupling inductor from D-STATCOM to the point of connection with the system in case the inverter voltage is greater than that of the system, indicates that the device introduces the current to the system and produces reactive power in the form of capacitive. When the D-STATCOM receives current from the ac system because the output voltage of inverter is lower than the system voltage, the device absorbs inductive reactive power [19].

Six IGBT switches with anti-parallel diodes are used to construct a three-phase voltage source converter (VSC). It's possible for three phase loads to have a trailing power factor, be imbalanced, or be nonlinear. The system has a filter linked in parallel with the load and the compensator to reduce ripples produced during IGBTs switching process at the point of connection to the Grid.

To decrease compensating current ripples, interface inductors (L_f) are utilized on the AC side of the voltage source converter. To eliminate the harmonic/reactive power component of the load currents, the D-STATCOM supplies harmonic/reactive currents to PCC. As a result, the source currents have no harmonics.

The sizing of switches is determined by the needed compensation's current and voltage rating. When two AC sources of the same frequency are connected together through a series inductor, the flow of active power is from the capacitive circuit to the inductive circuit and the reactive power flows from high voltage AC source to the AC source with low voltage.

The flow of Reactive power in system is governed by the difference in voltage amplitude between those sources, whereas active power flow is determined by the difference in phase angle between the sources. The choice of the voltage source converter's power stage is influenced by the design's preferred control strategy, harmonic reduction methodology, reactive power compensation, and load characteristics. The voltage source converter two level, 3 leg based D-STATCOM connected to the Grid is shown in Figure 2.3.

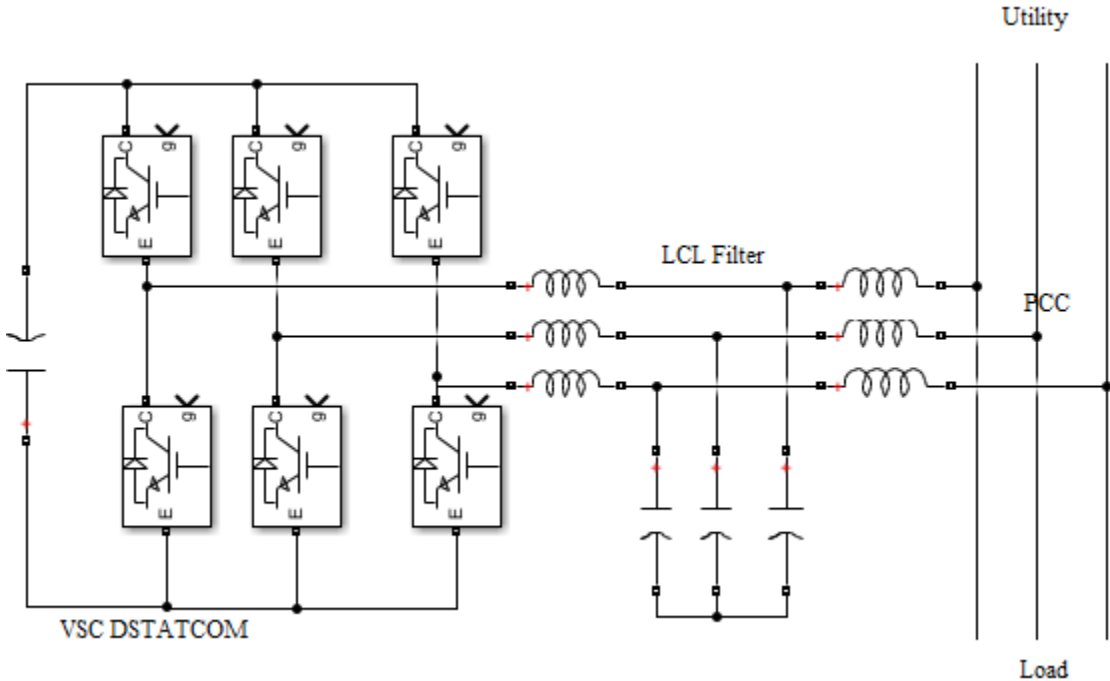


Figure 2.3. Two-Level, three-Leg Voltage Source Converter with Filter

2.7. Main elements of D-STATCOM

The main elements of DSTATCOM are as follows:

- Voltage Source Converter
- Inductor –Capacitor-inductor Passive Filter
- Control block for reactive power and
- Dc link capacitor

i) Voltage Source Converter

The DSTATCOM converter produces the controlled output voltage referred to the magnitude and phase angle to supply the lagging or leading current according the required compensation in the system. It operates by utilizing semiconductor low voltage IGBT technology. It facilitates the transformation of DC voltage present at the terminals of dc link capacitor into three-phase AC output voltage.

Benefits of Voltage Source Converter

- Reactive control is independent of other terminals,
- providing for separate control of reactive and active power
- Offers constant ac voltage regulation
- Use of incredibly fragile systems
- No failures in the commutation
- Power may be reversed without changing the polarity.
- Adjustable frequency

ii) Reactive Power Control Block

In order to correct for Power Quality issues like voltage sags and swells brought on by load disturbances or faults, the Control block generates trigger pulses and ends triggers after the disturbance instant has passed. These trigger pulses are routed to a PWM inverter that is powered by power electronics. When a delicate load is attached and causes system disruptions, the primary goal of the control strategy is to maintain voltage at a constant continuous magnitude level at instantaneous time.

The voltage at the point of system's connection that needs to be corrected according to the requirements is measured by the control approach. The PWM hysteresis control method is used to produce the switching pulses for the converter. The error signal that results from comparing the terminal voltage of the system and desired reference voltage is the controller's input. Such an inaccuracy is dealt with by a PI controller, which produces the angle and gives it to the PWM signal producer. It's crucial to keep in mind that in this instance of an indirectly controlled converter, there is concurrence in the exchange of active and reactive power in the network.

A signal error is produced by comparison between load voltage and reference voltage [6].

iii) L-C-L Passive Filter

Capacitors and inductors are combined and adjusted to resonate at a same frequency or across a scope of frequencies make up a passive filter component. In order to prevent voltage distortion and suppress harmonic currents, passive filters are utilized in power systems. Passive filters function by displaying various value of impedances at the resonance frequency. The frequencies with harmonics that are needed to be eliminated should have a high impedance when a filter is coupled in series.

Although connecting filters in a series configuration is an option, parallel connections are more typical. This type of shunt design generates reactive power that should be used to change the power factor while also discharging harmonic currents to the ground. To achieve this, passive shunt filters have to be designed to behave as capacitive circuit at the fundamental frequency [20].

iv) Dc-Link Capacitor

A load-balancing energy storage component between the dc (battery) and ac (load) sides of a VSC is the DC-link capacitor. To maintain a rigid dc-link voltage across the VSC, this component is linked in parallel with the battery. It means that, a particular level of dc-line current ripple is required to suppress EMI brought on by pulsed inverter current, stray inductance, and dc-bus resistance.

2.8. Techniques of PWM used in D-STATCOM

The main goal of a D-STATCOM system is to produce fully regulated sine wave of line currents on the medium voltage side of the D-STATCOM system for medium voltage (MV) and low voltage applications.

The waveform of D-STATCOM line current have to be transformed in a sine wave, which should be in accordance with IEEE 519-1992, first and foremost through the use of an appropriate PWM approach, and secondly through the carefully designed D-STATCOM input filter. Pulse Wave Modulation becomes an essential component of the required control algorithm of reactive power which is based on the change of the modulation index, m_a .

2.9. Software Tools

2.9.1. ETAP Software

Electrical Transient and Analysis Program (ETAP) is a full-spectrum analytical engineering software company with a focus on analysis, electrical power system simulation, control, supervision, modeling, management, and automation. The most comprehensive and integrated range of power system business solutions, from modeling to operation, is offered by ETAP software[6].

2.9.2. MATLAB Software

The word MATLAB is in full Matrix Laboratory. MATLAB was initially developed to make matrix software established by the linear system package (LINPACK) and EISPACK programs accessible. It is a high-execution language for technical computation that combines calculation, graphics, and a programming background. Secondly, MATLAB offers a state-of-the-art programming language background with addition of built-in editing and debugging tools, support for object-oriented programming and sophisticated data structures. These features elevate MATLAB as a research and educational tool.

The MATLAB software has a variety of uses; for this thesis study, the Gatare Tea factory load was simulated using MATLAB/Simulink. The power and control circuits were built and simulated using this software raise the factory's low power factor.

CHAPTER 3. DATA COLLECTION AND ANALYSIS

In this chapter different collected data from the factory are presented and analyzed. The collected data are those which related to the energy consumption, power factor and installed capacity.

3.1. Electrical Parameters of Gatare Tea factory

Before the design of DSTATCOM to raise the factor's power factor, different electrical parameters were collected at the factory. In this chapter the tables showing all required data collected from the factory are presented.

Table 3.1. Rated capacity, working voltage and power factor of the factory

| Types of Data | Quantity |
|---|-------------------------|
| Distribution transformer rating | 630kVA, 30/0.4kV |
| Power factor | ≤ 0.75 |
| Maximum daily energy consumption/hour | 254kWh & 390 kVarh |
| Total daily energy consumption | 3812kWh & 244.65KVARh |
| Average daily energy consumption/hour | 158.8 kWh & 244.6 kVarh |
| Total installed capacity of the factory | 1021.84 kW |
| V _{p1} | 233.6V |
| V _{p2} | 234.4V |
| V _{p3} | 234V |
| V _{L12} | 403.3V |
| VL13 | 403.2V |
| VL23 | 403.2V |

Table 3.2. Detailed Load of Gatare Tea factory

| S/N | Machinery section/Apartment | Rated electrical power in kW |
|------------|-----------------------------------|------------------------------|
| 1 | Withering section (3floor levels) | 337.7 |
| 2 | Rolling section (2 lines) | 222.2 |
| 3 | CFM/CFU (2 lines) | 38.37 |
| 4 | Drying section(2 lines) | 153.59 |
| 5 | Sorting section (2 lines) | 19.65 |
| 6 | Packing | 6.75 |
| 7 | Boiler | 91.84 |
| 8 | Tea processing area lights | 6 |
| 9 | Street lights | 6 |
| 10 | Offices | 20 |
| 11 | Factory canteen | 10 |
| 12 | Residential apartments | 110 |
| Total load | | 1021.84 |

Total installed capacity of Gatare Tea Factory is 1021.84 kW whereas the existing transformer has a 630kVA rating. It means that the factory cannot run all loads at the same time which a big problem for the factory and to solve it they are planning to purchase a new transformer that can allow them to run the factory at full. In our design we have been based on the installed transformer and once they change the transformer, the parameters could be updated.

Table 3.3. Monthly Energy consumption of Gatare tea factory

| Month | Energy in kwh | Energy in kVArh |
|----------|---------------|-----------------|
| January | 146610 | 20840 |
| February | 133523.6 | 17442.5 |
| March | 117672 | 14045 |
| April | 154148 | 17463 |
| May | 154058.8 | 54468.8 |

| Month | Energy in kwh | Energy in kVArh |
|-------|---------------|-----------------|
| June | 127668.8 | 39520.8 |
| July | 100984.4 | 16516.4 |

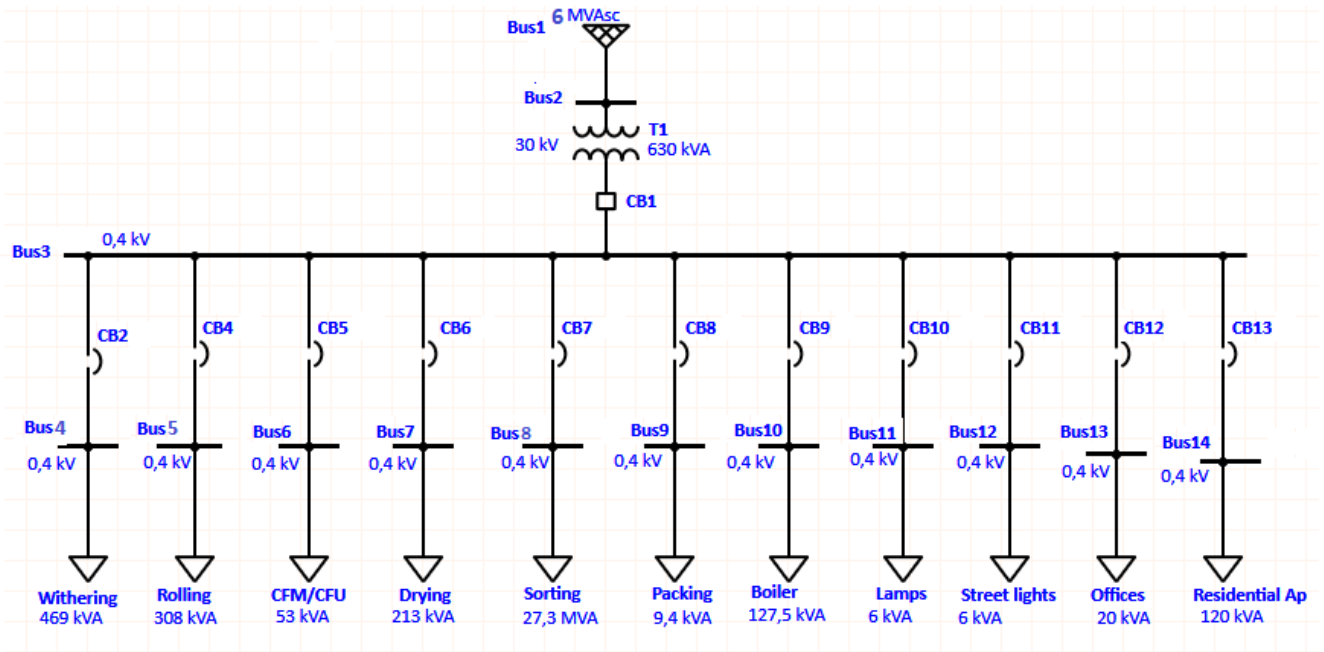


Figure 3.1. Single line diagram of installed load at Gatare Tea factory

3.2. Analysis of Electrical Parameters of Gatare Tea Factory

As Rwanda Energy Group (REG) recommends electricity consumers to work with the power factor not less than 0.8 lagging, different consumers raise their power factor to reduce their maximum kVA demand charges. Consequently the targeted power factor of Gatare Tea Factory is 0.96 and this is achieved by using capacitor bank. The used distribution transformers rating capacity is 630kVA and unable to supply the installed loads of the factory.

3.2.1. Load and Power factor variation at the factory

In the factory the load is not constant due to the behavior of activities and active and reactive power change hour per hour which results in the continuous change of power factor., the variation of load in the factory during the day is shown on the Figure 3.1 and the power factor variation during the day is also shown on the Figure 3.2.

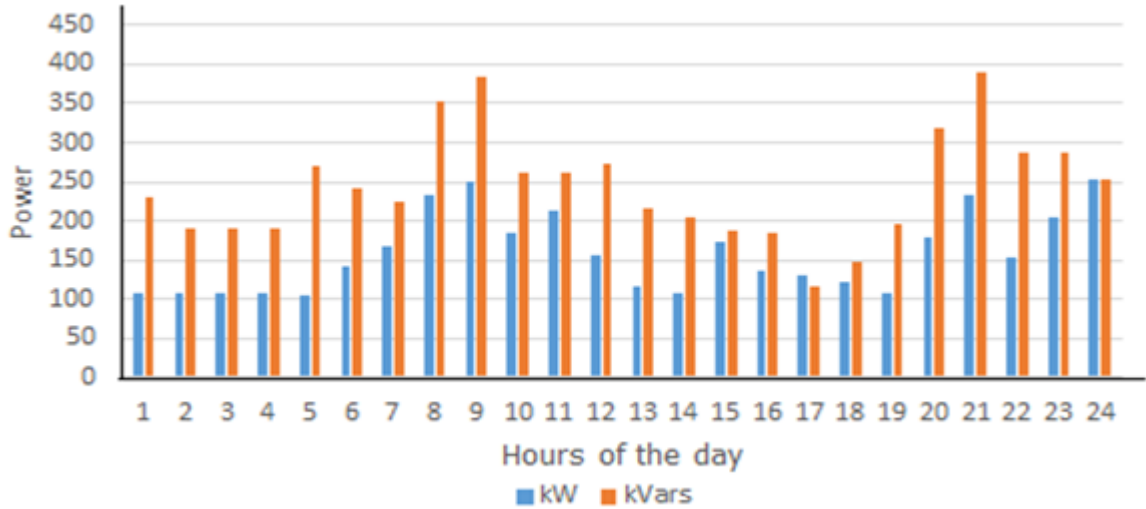


Figure 3.2. Load variation during the day at Gatare Tea Factory

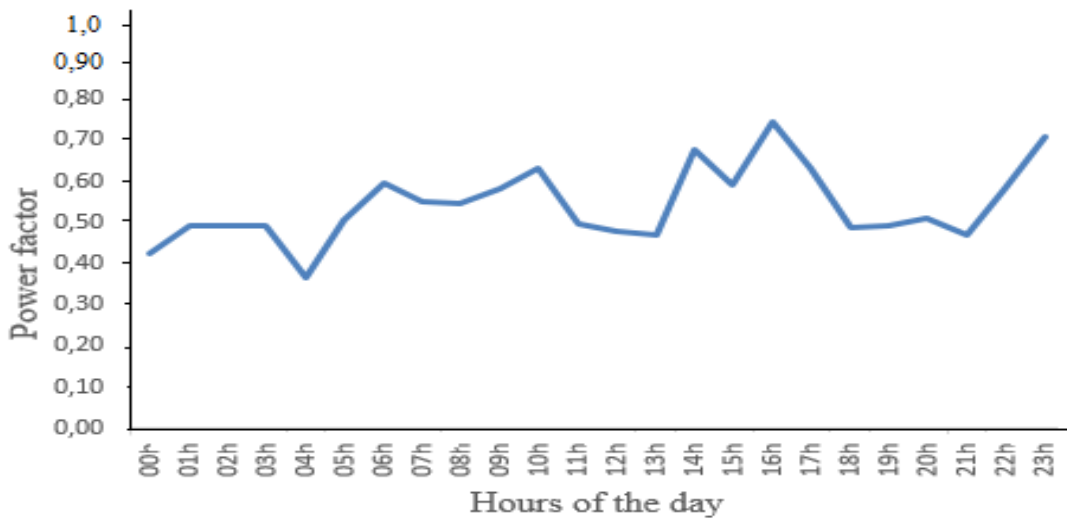


Figure 3.3. Power factor variation during the day at Gatare Tea Factory

From the values recorded at the factory, the average power factor during the day is 0.54

3.2.2. Calculation of Reactive Power Required to Improve the Factory Power Factor

The calculations were based on maximum kVA recorded during the day, and that is 459.59kVA with 251kW and 385kVAr.

This mean that the factory takes the reactive power ($Q=385\text{kVAr}$) from the national grid if there is no power factor improvement device used and apparent power in three phase system is given by equation (3.1).

$$S = \sqrt{3} V_L I_L \quad (3.1)$$

Where S represent apparent power of the load, V_L load line voltage and I_L is the load line current which is derived from equation (3.1) and calculated as below:

$$I_L = \frac{S}{V_L} = \frac{459.59 \text{ kVA}}{\sqrt{3} \times 400V} = 663.36A$$

When the factory runs the this load (251kW and 385kVAr) without power factor correction, power is 0.55 and the phase angle between system voltage and current θ_1 , is given by equation (3.2);

$$\theta_1 = \cos^{-1} 0.55, \theta_1 = 56.63^\circ \quad (3.2)$$

After power factor improvement from 0.55 to 0.96, the phase angle is calculated in equation (3.3).

$$\theta_2 = \cos^{-1} 0.96, \theta_2 = 16.26^\circ \quad (3.3)$$

New apparent power is calculated as, $S_{New} = \frac{P}{PF_2} = \frac{251}{0.96} = 261.49\text{kVA}$

New reactive power taken by the load from the grid is given by equation (3.1).

$$Q_{New} = \sqrt{S_{New}^2 - P^2} \quad (3.4)$$

$$Q = \sqrt{261.49^2 - 251^2} = 73.07\text{kVAR}$$

Where S_{New} and Q_{New} are new apparent power and new reactive power taken by the load from the Grid, P is the load active power and is constant.

The new line current is, $I_{LNew} = \frac{S_{New}}{\sqrt{3} V_L} = \frac{261.58\text{kVA}}{\sqrt{3} \times 400V} = 377.5A$.

It is remarked that the current increases by 285.86A in the event that the same load is utilized without power factor correction.

After the power factor correction, the added reactive power in the circuit of Gatare Tea Factory is given by calculating the difference between reactive powers of the factory before and after power factor improvement as shown by equation (3.4) and Q_{add} represent added reactive power to the system by DSTATCOM, Q_{before} , load reactive power taken from the Grid before power factor improvement and Q_{New} is the new reactive power taken by the load from the Grid.

$$Q_{add} = Q_{before} - Q_{New} \quad (3.5)$$

$$Q_{add} = 385\text{kVAr} - 74.07\text{kVAr} = 311.93 \text{ kVAr}$$

To increase the power factor of Gatare tea factory from to 0.96 lagging, it requires an installation of DSTATCOM with capacity to supply 311.93 kVAr.

CHAPTER 4. DESIGN AND MODOLING OF VSC BASED D-STATCOM

4.1. Parameters Design of VSC based D-STATCOM

Reactive power needed to raise the factory's power factor was designed in this chapter based on data from the factory. Based on the working voltage and reactive power requirements of the plant, the D-STATCOM components rating was created. The component ratings of the D-STATCOM, such as the compensation current, medium voltage IGBT collector current, DC link capacitor rating, filter ratings, and AC inductor, are designed based on the required reactive power to enhance the factory's power factor. The output power factor was mathematically designed and then simulated using MATLAB software for both before and after factory power factor correction, depending on the designed parameters of D-STATCOM.

4.2. D-STATCOM Parameters Design for Gatare Tea Factory

This thesis aims to increase the power factor to 0.96 lagging. As shown in the collected data from the factory, the maximum load during the day to be 251kW and 385kVAr with an average power factor of 0.54 lagging; to increase the factory's power factor to 0.96 lagging, 311.93 kVAr have to be injected in the system by a DSTATCOM and is calculated in equation (4.1).

$$Q_{add} = Q_{DST} = Q_{before} - Q_{After} \quad (4.1)$$

$$Q_{add} = 385kVAr - 74.07kVAr = 311.93 \text{ kVAr}$$

Q_{add} is the kVAr added in the system by DSTATCOM and is symbolized as Q_{DST} and the rated apparent power of DSTATCOM is symbolized as S_{DST} .

The size of D-STATCOM to recompense the reactive power of 311.93 kVAr is 343.12kVAr.

As the volume 40, October 2016 of IJETT giving 10% tolerance $Q_{DST} = Q_{Add} + 10\% \times Q_{Add}$

$$Q_{DST} = 343.12kVAr.$$

4.3. VSC D-STATCOM parameters and Its Elements Design

Low voltage (LV) power semiconductors are mostly used in converters with power levels in the hundreds of kilovolt ampere range. For a 1% converter active power loss, the converter's voltage rating is 400V with a switching frequency of 20 kHz.

The rating of D-STATCOM seems to be pure reactive power with D-STATCOM IGBT switches losses equivalent to 1% active power dissipation.

4.3.1. DSTATCOM Capacity Design

From the concept of 1% active power dissipation of the D-STATCOM; its size is designed as below;

$$P_{DST} = Q_{DST} \times 1\% = 3.43\text{kW}$$

Apparent power of D-STATCOM is given as follows

$$S_{DST} = \sqrt{Q^2 + P^2} = 343.13\text{KVA}$$

343.13KVA rating of D-STATCOM is used to recompense the reactive power of the factory from 0.54 to 0.96 lagging.

Depending on the industrial rating of VSC D-STATCOM, the current rating of the IGBT are calculated as follows:

Line voltage = 400V,

$$I_L = \frac{S}{\sqrt{3} V_L} = \frac{343.13\text{kVA}}{\sqrt{3} \times 400\text{V}} = 495.2\text{A}$$

I_D is the line current of D-STATCOM, and is at an angle of 90 degree, or lagging current, it means that is $I_D = 495.2 \angle 90^\circ = -j495.2\text{A}$. The collector current of IGBTs is 495.2A.

4.3.2. Design of DC link Capacitor Voltage

The permitted ripple component on the DC-bus voltage is used to determine the capacitor's rating. The phase-to-phase voltage of the system should be greater than twice the minimum dc voltage available at the DC bus side of D-SATCOM. V_{LL} is the DSTATCOM ac line output voltage, and the calculation of DC voltage of DC bus is performed by using modulation index, m_a and is taken to be 1. Using DSTACOM line voltage and modulation index, the dc bus voltage is calculated as follows;

Considering modulation index, $m_a = 1$, V_{DC} is calculated as below.

$V_{DC} = \frac{2\sqrt{2} V_L}{\sqrt{3} m_a} = \frac{2\sqrt{2} \times 400\text{V}}{\sqrt{3} \times 1} = 653.2\text{V}$ to be selected as 700V. Hence the voltage of DC link is taken to be with 700V rating to supply the needed reactive by the load

4.3.3. Ripple Filter Design

Ripple filtering is used to reduce voltage THD and current TDD at PCC as well as to remove converter switching harmonics. Either a single inductor L or an inductance-capacitance LC filter can create a ripple filter. When compared to an LC filter combination, using a single L filter requires larger inductance values in order to meet the same voltage THD and current TDD specifications. Higher inductance values result in slower step responses to reactive power changes and higher regulation of voltage on the DC link capacitor from complete inductive mode to complete capacitive mode. In equation (4.2) gives the capacitance of the ripple filter to be used in this thesis.

$$\begin{aligned} X_C &= \frac{V_{DST}^2}{0.15 \times Q_D} = \frac{400^2}{0.15 \times 343120} = 3.1 \Omega \\ X_C &= \frac{1}{2\pi f C}, \\ C &= \frac{1}{2\pi f X_C} = \frac{1}{2 \times 3.14 \times 50 \times 3.1} = 870 \mu F \end{aligned} \quad (4.2)$$

The next available capacitor is 1000 μF and is selected to be used here with the resistance of 1Ω .

The ripple filter current is show is given by equation (4.3) as below.

$$\begin{aligned} I_{filter} &= 15\% \text{ of } I_{D \text{ peak}} \\ I_{D \text{ peak}} &= \sqrt{2} I_D = 593.96 A \\ I_{filter} &= 89.1 A \end{aligned} \quad (4.3)$$

The harmonics produced by the IGBT switches at PCC must therefore be filtered out using three 1000.6F single-phase input filter capacitors.

4.3.4. DC link Capacitor design

When selecting the DC link capacitor, there are two key factors to take into account. In order to prevent high harmonics in the D-STATCOM AC voltage output, it had to be large enough to supply the VSC with a suitably stable DC voltage and capable of providing the system with the necessary reactive power for improvement of the power factor. An excessive capacitor will cause the DC link controller to respond more slowly, while an undersized capacitor will cause the D-STATCOM AC voltage output to have high harmonics [8].

When a system is operating temporarily, the D-STATCOM instantly supplies energy to it. D-

STATCOM responds in between 200 and 350 s. DC capacitor (C_{dc}) of VSC D-STATCOM depends on the instantaneous energy that the D-STATCOM has during transients. The low of conservation of energy is used in the equation (4.4) to derive the quantity of dc link capacitor.

$$\text{Energy transfer} = \frac{1}{2} C_{dc} [V_{DC}^2 - V_{DC1}^2] = k_1 3V a I t \quad (4.4)$$

Where

V_{DC1} is the voltage to be considered minimum at the level of the DC bus, $V_{DC1} = 653.2V$

a is an overloading factor, $a = 1.2$

k_1 Represents the variation of energy during dynamics, $k_1 = 10\% = 0.1$

V is the converter phase output voltage, $V = 230.1V$

V_{DC} is the DC reference voltage of the DC bus, $V_{DC} = 700V$

T is the time by which the dc bus voltage is to be recovered, I is phase current, t is given by the product of ripple capacitor and its resistance, $t = 1000\mu F \times 1\Omega = 1000\mu s$.

Rearrangement of equation (4.4) gives the value of the DC link capacitor in equation (4.5)

$$C_{dc} = \frac{2 \times k_1 3V a I t}{V_{DC}^2 - V_{DC1}^2} \quad (4.5)$$

$$C_{dc} = \frac{2 \times 0.1 \times 3 \times 230.1 \times 1.2 \times 285.9 \times 1000 \times 10^{-6}}{700^2 - 653.2^2} = 747.59\mu F \text{ and it is selected as } 1000\mu F.$$

4.3.5 AC Inductor design

The choice of the ac inductance, L_{AC} of VSC depends on the dc bus voltage, switching frequency f_s , and ripple filter currents i_{crp-p} and V_{DC} . These variables play a major role in the calculation of AC inductance. Equation (4.6) gives expression for calculating AC inductance:

$$L_{AC} = \sqrt{3} \frac{m \times V_{DC}}{12 \times a \times f_s \times i_{ripple}} \quad (4.6)$$

Where m represents the modulation index and is equal to 1, f_s is the frequency of switching and is 20 kHz and is the overloading factor which is equal 1.2.

Consider ripple current at its 5%. $5\% i_{ripple} = 89.1 \times 0.05 = 4.45A$

V_{DC} is the DC reference voltage of the DC bus, $V_{DC} = 700V$

$$L_{AC} = \sqrt{3} \frac{1 \times 700}{12 \times 1.2 \times 20000 \times 4.45} = 0.94mH$$

$$X_{LAC} = 2\pi fl = 2 \times 3.14 \times 50 \times 0.94 \times 10^{-3}$$

$$X_{LAC} = 0.29 \Omega$$

4.3.6. Power and Control circuits of DSTATCOM connected to the circuit

The load of Gatare Tea Factory before and after connection of DSTATCOM with its control circuit was built and simulated using MATLAB/Simulink to assess the potential of DSTATCOM to improve the power factor. The Figure 4.1 shows the simplified circuit diagram of load connected to the system without connection of DSTATCOM and the same load connected in shunt with DSTATCOM is shown in Figure 4.2.

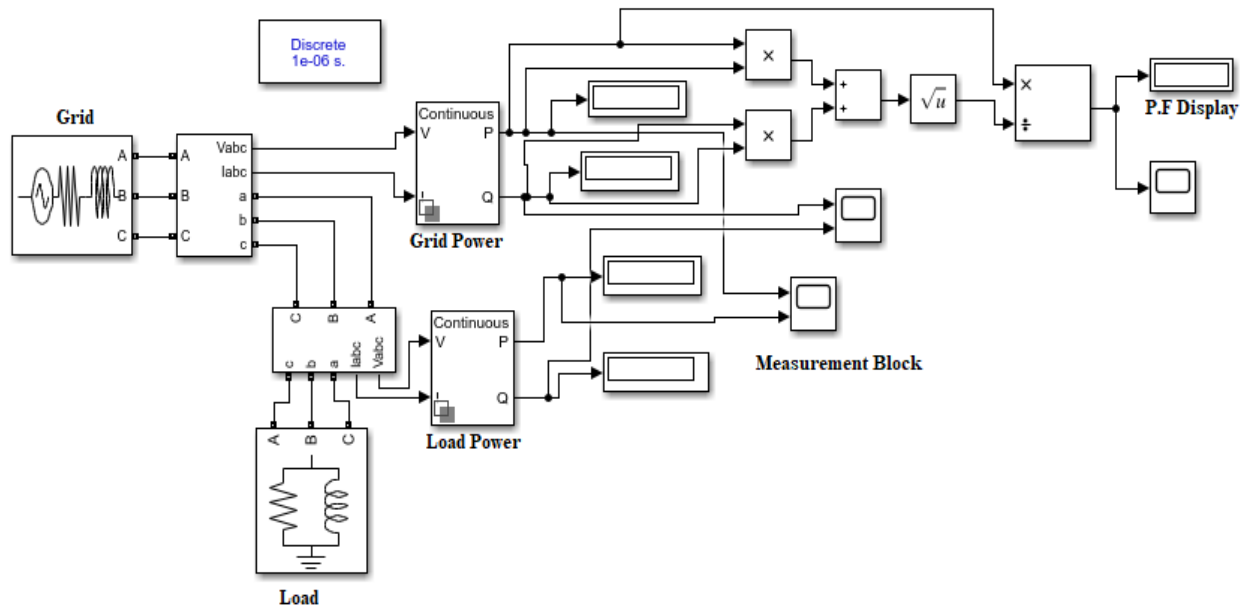


Figure 4.1. Gatare Tea Factory load before power factor improvement

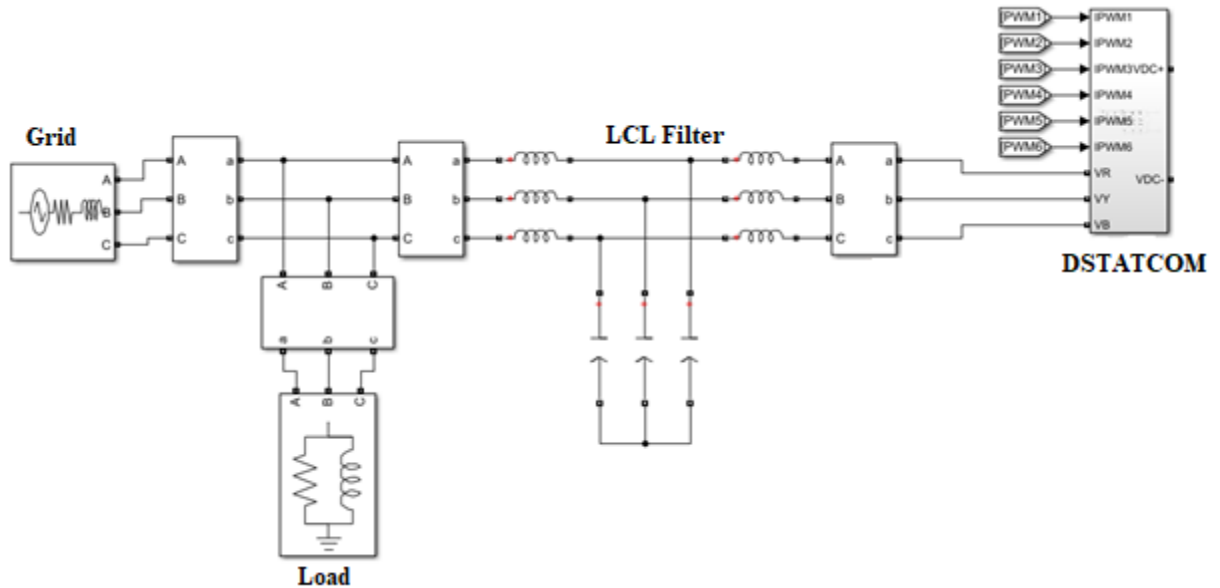


Figure 4.2. Circuit arrangement of Gatare Tea factory after connection of DSTATCOM
 For potential assessment of DSTATCOM to improve Power factor of Gatare Tea Factory, the measurement block to measure active and reactive power, current and voltage as well as the power factor of the system was realized in Simulink. This measurement block is shown on the Figure 4.3.

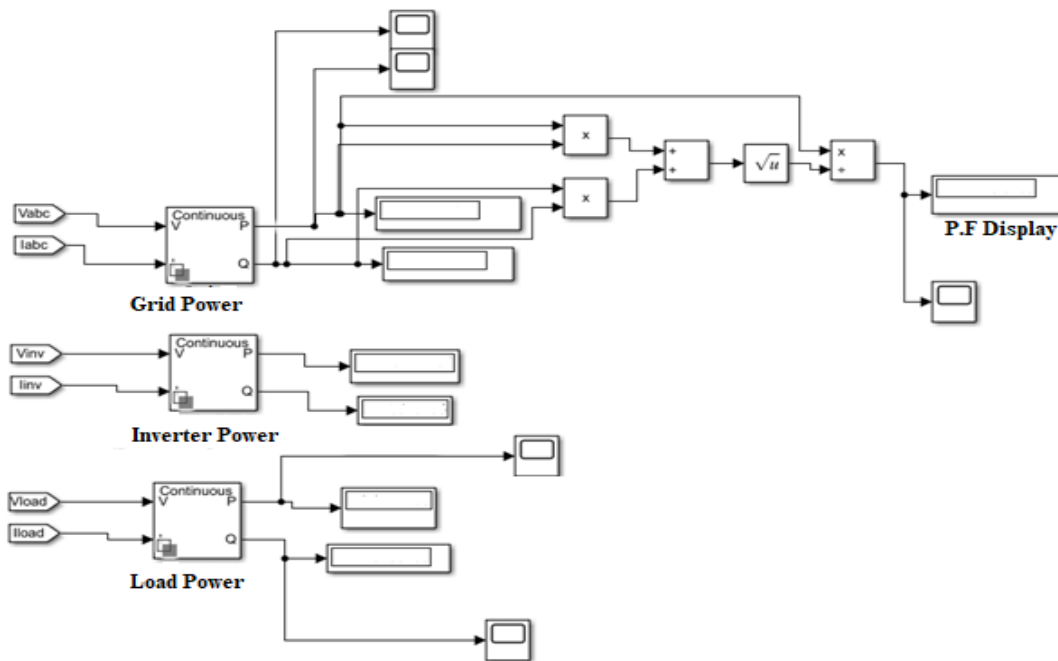


Figure 4.3. Measurements block of electrical parameters

This block shows the grid's active and reactive power as well as the power of the inverter and load. It also calculates the system's power factor by evaluating the ratio system's active to apparent power. The reactive power of the system is controlled by the block diagram shown in Figure 4.4.

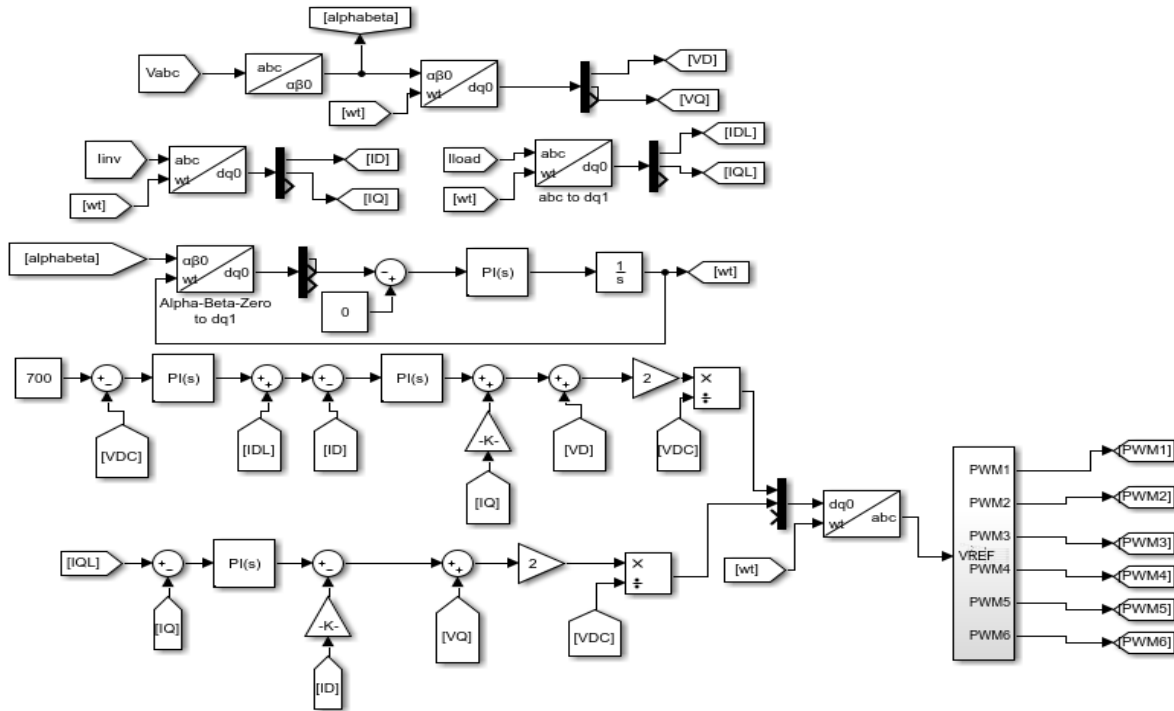


Figure 4.4. Measurements block of electrical parameters

The control mechanism is based on the dq0 transformation of quantities and PI controller. The dq0 transformation blocks transform the quantities from PCC (V_a , V_b and V_c) into dq quantities (V_D and V_Q), inverter currents into I_D and I_Q and load current into I_{DL} and I_{QL} for being easy controlled by PI. The Phase locked Loop (PLL) and Voltage and current control blocks control the DSTATCOM current in order to maintain the amplitude of PCC voltage at the reference value. The PWM control block controls the switching pulses for inverter. The input of the PWM is an error produced by comparison between the PCC voltage and reference voltage and which is processed by a PI controller and finally give pulses to the inverter according to the error produced[21]. Hence there is the reactive power exchange in the system. For the case of this thesis, is the reactive power which flows from the DSTATCOM to the PCC to reduce the reactive power form the Grid so to improve the power factor of the system.

4.4 Cost analysis of DSTATCOM

After power factor improvement, 264.53 kVAr are saved which results in \$947.7 saved every month equivalent to \$11372.4. Comparing the saved money every year with the cost of DSTATCOM (\$138.5/kVAr)[22] to improve the power factor at the factory, it is proved that the payback period of DSTATCOM is 3.5years and the rest is for the profit of the factory. It means that factory will be in the profit for other 15 -25 years as the life time of DSTATCOM is estimated to 20-30 years.

4.5 Modeling of DSTATCOM

4.5.1 Working Modes of DSTATCOM

The working principle of DSTATCOM is based on the value of its output voltage compared to the system voltage. The direction of DSTATCOM reactive power is dictated by the voltages comparison output. Due to fact that the voltages can be the same, greater or less than another, three modes of operation of DSTATCOM are explained as follows:

- When the amplitude of D-STATCOM output voltage is greater than that of the grid, the current flows through the converter toward network, in this condition, D-STATCOM supply reactive power.
- When the output voltage of converter is less than that of the Grid, the current flows from the grid to the converter, the DSTATCOM absorbs reactive power.
- When output voltage of the converter is same as that of the grid, there is no flow of current either form the gird nor from the converter. The converter (DSTATCOM) is the state of equilibrium. The reactive power exchange is zero.

In this thesis, the main objective is to inject reactive current in the system for power factor correction. Equation 4.7 and 4.8 describe the active and reactive power supplied by DSTATCOM in the network respectively.

$$P_{ST} = \frac{V_{PCC} V_{ST} \sin \delta}{X_{ST}} \quad (4.7)$$

$$Q_{ST} = \frac{V_{PCC}(V_{PCC} - V_{ST} \cos \delta)}{X_{ST}} \quad (4.8)$$

Where δ is an angle of shift between voltage at point of common coupling (V_{PCC}) and output voltage of DSTATCOM (V_{DST}), X_{DST} is the reactance of LC inductor in series with the

converter, P_{ST} is the dissipated power in DSTATCOM and Q_{ST} is the reactive power supplied by DSTATCOM to the point of common coupling. In the permanent operation, angle $\delta = 0$, active power ($P_{ST} = 0$) and there is only the flow of reactive power. Its expression is shown by equation (4.9).

$$Q_{ST} = \frac{V_{PCC}(V_{PCC} - V_{ST})}{X_{ST}} \quad (4.9)$$

The capacitor plugged into the D-STATCOM continuous bus, work as a source of continuous voltage source. In permanent operation, with DSTATCOM and inductor losses compensation and constant continuous bus, the voltage V_{DST} is shifted late to maintain voltage V_{PCC} . The dc bus voltage, V_{dc} is given by equation (4.10) and the dc bus current, i_{dc} is given by equation (4.11).

$$V_{dc} = \frac{1}{c} \int i_{dc} dt \quad (4.10)$$

And the continuous current is given by equation

$$i_{dc} = m(i_q \sin(\delta) + i_d \cos(\delta)) \quad (4.11)$$

δ is the shift phase angle between V_{DST} and V_{PCC} , m is the conversion ratio while i_q and i_d are the components of dc link current in the Park reference frame. The expressions of m and δ are given in equations (4.12) and (4.13) respectively.

$$m = \frac{\sqrt{V_{qST}^2 + V_{dST}^2}}{V_{dc}} \quad (4.12)$$

$$\delta = \tan^{-1}\left(\frac{V_{qST}}{V_{dST}}\right) \quad (4.13)$$

V_{qST} is the q component of DSTATCOM voltage in dq0 reference frame and

V_{dST} is the d component of DSTATCOM voltage in dq0 reference frame

4.5.2 Modeling of DSTATCOM based on DQ0 quantities

The instantaneous three phase voltages and currents must be transformed into the synchronously rotating reference direct-quadrature-zero (dq0) frame for being much easier computed and secondly to allow the independent control of active (d-axis) and reactive (q-axis) components of the currents. The relationship between V_{ST} , V_{PCC} and V_{qST} & V_{dST} is shown in the Figure 4.5 and

Figure 4.6 shows the single line diagram of DSTATCOM connected to the grid. Equation (4.14) shows the relationship between current and voltage in Park reference frame [21].

$$L_{sh} \frac{d}{dt} \begin{bmatrix} i_q \\ i_d \end{bmatrix} = \begin{bmatrix} -R_{sh} & -\omega_s \\ \omega_s & -R_{sh} \end{bmatrix} \begin{bmatrix} i_q \\ i_d \end{bmatrix} + \begin{bmatrix} V_{qPCC} & -V_{qST} \\ V_{dPCC} & -V_{dST} \end{bmatrix} \quad (4.14)$$

Where L_{sh} is the inductance of DSTATCOM coupling inductor.

R_{sh} is the resistance of DSTATCOM coupling inductor.

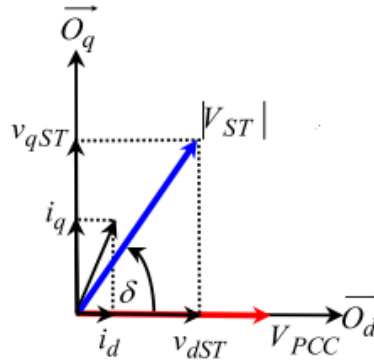


Figure 4.5. Vector diagram of VSC based DSTACOM currents and voltages.

In the Figure 4.5, the transformation relation between abc values and dq values is shown and is based on the δ which is an angle of shift between voltage at point of common coupling (V_{PCC}) and output voltage of STATCOM (V_{ST}).

The role of transforming three phase instantaneous voltages in rotating synchronous dq0 reference frame, is to make them easy to be processed by MATLAB/Simulink and to give the system operator independent control over the active (d-axis) and reactive (q-axis) components of the currents.

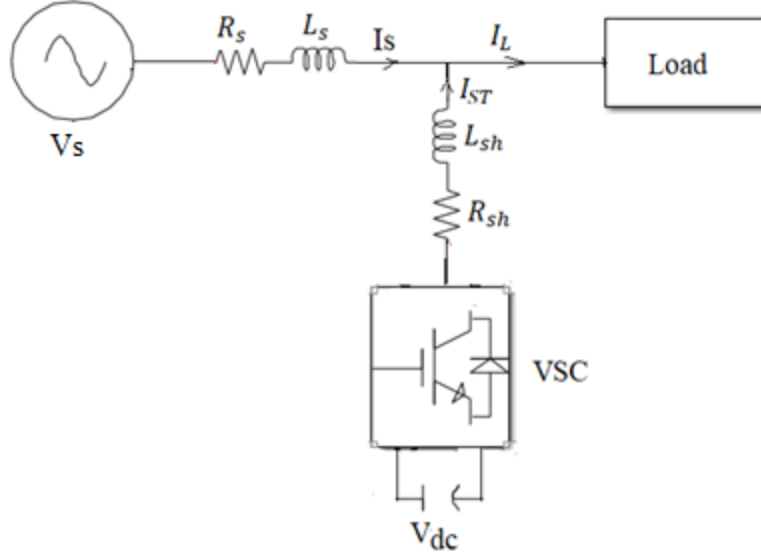


Figure 4.6. Single line diagram of DSTATCOM connected to the system

The transformation of quantities from a-b-c reference frame to dq0 reference frame and vice versa are given in equations (4.15) and (4.16) respectively.

$$V_{abc} = \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \text{ and } V_{dq0} = \begin{bmatrix} V_d \\ V_q \\ V_0 \end{bmatrix}$$

$$V_{abc} = T_{\theta}^{-1} V_{dq0} \quad (4.15)$$

$$V_{dq0} = T_{\theta} V_{abc} \quad (4.16)$$

When the three phase system is balanced, the component with 0 becomes zero and the dq0 becomes dq [23], which is the case in this report.

Where T_{θ} is the dq0 transformation factor and its expression is given by equation (2.17) [24].

$$T_{\theta} = \frac{2}{3} \begin{pmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix}$$

(4.17)

T_{θ}^{-1} is the inverse matrix of T_{θ} .

$$T_{\theta}^{-1} = \begin{pmatrix} \cos\theta & -\sin\theta & 1 \\ \cos\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta + \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) & 1 \end{pmatrix}$$

$\theta = wt$ where w is the frequency of the infinite bus of the system or the frequency of the generator[23]. θ is angle which determines the value of instantaneous voltage or current in sinusoidal waveform.

Equation (4.18) gives expressions of three phase voltages of the system in a-b-c reference frame. The transformation of V_{PCC} to dq0 reference frame is given by equation (4.19) while the transformation of DSTATCOM voltage, V_{ST} is given by equation (4.20).

$$\begin{aligned} V_a &= A\cos wt \\ V_b &= A\cos\left(wt - \frac{2\pi}{3}\right) \\ V_c &= A\cos\left(wt + \frac{2\pi}{3}\right) \end{aligned}$$

(4.18)

$$\begin{bmatrix} V_{dPCC} \\ V_{qPCC} \\ V_{0PCC} \end{bmatrix} = \begin{pmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} V_{aPCC} \\ V_{bPCC} \\ V_{cPCC} \end{pmatrix}$$

(4.19)

$$\begin{bmatrix} V_{dST} \\ V_{qST} \\ V_{0ST} \end{bmatrix} = \begin{pmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} V_{aST} \\ V_{bST} \\ V_{cST} \end{pmatrix}$$

(4.20)

$$\begin{bmatrix} i_d \\ i_q \\ i_0 \end{bmatrix} = \begin{pmatrix} \cos\theta & \cos\left(\theta - \frac{2\pi}{3}\right) & \cos\left(\theta + \frac{2\pi}{3}\right) \\ -\sin\theta & -\sin\left(\theta - \frac{2\pi}{3}\right) & -\sin\left(\theta + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \begin{pmatrix} i_a \\ i_b \\ i_c \end{pmatrix}$$

(4.21)

V_{dST} and V_{qST} are the components of DSTATCOM voltage in dq0 reference frame

V_{dPCC} and V_{qPCC} are the components of system voltage in dq0 reference frame

The expression shown in equation (4.21) shows the transformation of three phase current in a-b-c reference frame to dq0 reference frame currents. i_d , and i_q are the components of currents in dq0 reference frame and i_a, i_b, i_c are the components of currents in a-b-c reference frame. Currents and voltages required in the control of DSTATCOM, are transformed in the dq0 reference frame to be processed by PI controller as shown in the Figure 4.7.

Single phase active and reactive power of DSTATCOM in d-q reference frame are given by equations (4.22) and (4.23) respectively.

$$P_{3\theta} = v_a(t)i_a(t) + v_b(t)i_b(t) + v_c(t)i_c(t) = \frac{2}{3}[v_d(t)i_d(t) + v_q(t)i_q(t) + v_0(t)i_0(t)]$$

$$P(t) = \frac{1}{2}(v_d(t)i_d(t) + v_q(t)i_q(t)) \quad (4.22)$$

$$Q(t) = \frac{1}{2}(v_q(t)i_q(t) - v_d(t)i_d(t)) \quad (4.23)$$

The expressions above are multiplied by three to give three phase active and reactive powers of DSTATCOM and are shown in equations (4.24) and (4.25) respectively. The system is assumed to be balanced where three phases have equal powers.

$$P(t) = \frac{3}{2}(v_d(t)i_d(t) + v_q(t)i_q(t)) \quad (4.24)$$

$$Q(t) = \frac{3}{2}(v_q(t)i_q(t) - v_d(t)i_d(t)) \quad (4.25)$$

$P(t)$ represents the power dissipated in DSTATCOM while $Q(t)$ represents reactive power injected to PCC by DSTATCOM.

$$F_{Cl_i}(S) = \frac{K_{p_i}S + K_{i_i}}{S^2 + \left(\frac{R_{sh}}{L_{sh}} + K_{p_i}\right)S + K_{i_i}} \quad (4.27)$$

Where:

K_p is the proportional coefficient, K_i is the integral coefficient, K_{p_i} is the converter current proportional coefficient, K_{i_i} is the converter current integral coefficient, i_q is the q component of converter instantaneous current, i_q^* is the q component of the converter reference current, i_d is the d component of converter instantaneous current and i_d^* is the d component of the converter reference current.

$$K_{p_i} = 2\zeta - \frac{R_{sh}}{L_{sh}} \text{ and } K_{i_i} = \omega^2$$

ζ is the damping ratio of the system

ω is the undamped natural frequency of the control loop.

The DC bus voltage transfer function of PI controller in the open loop is given by equation (4.28) while equation (4.29) gives the transfer function of DC bus voltage on the closed loop.

$$F_{Op_dc}(S) = \frac{V_{dc}}{V_{dc}^*} = \left(K_{p_vdc} + \frac{K_{i_vdc}}{s} \right) \left(\frac{1}{C_s} \right) \quad (4.28)$$

$$F_{Cl_vdc}(S) = \frac{\frac{K_{p_vdc}S + K_{i_vdc}}{C}}{s^2 + \frac{K_{p_vdc}}{C}S + \frac{K_{i_vdc}}{C}} \quad (4.29)$$

$$K_{p_vdc} = 2\zeta - \frac{R_{sh}}{L_{sh}} \text{ and } K_{i_vdc} = \omega^2$$

Where: K_{p_vdc} and K_{i_vdc} are the proportional and integral coefficients of DC bus voltage respectively.

CHAPTER 5. SIMULATION AND RESULTS ANALYSIS

A 343.13kVA DSTATCOM was designed and simulated to improve the power factor of Gatare Tea Factory from 0.54 to above 0.96 and above. When the load operates without power factor improvement, it draws high amount of reactive power from the grid which results in the low power factor of the system. And after connection of DSTATCOM in shunt with the load, the reactive power taken by load from Grid was reduced which resulted in the increase of power factor (above 0.9). The table 5.1. Shows the change of power factor versus load power before and after power factor improvement and the compared with the recorded power factor the factory.

Table 5.1. Comparison of power factor versus load power before and after its improvement

| S/N | Load | | P.F recorded from the factory before its improvement | P.F from simulation before its Improvement | P.F from simulation after its Improvement |
|-----|------|------|--|--|---|
| | kW | kVAr | | | |
| 1 | 251 | 385 | 0.54 | 0.54 | 0.99 |
| 2 | 154 | 288 | 0.47 | 0.47 | 0.96 |
| 3 | 180 | 320 | 0.49 | 0.49 | 0.99 |
| 4 | 234 | 354 | 0.55 | 0.55 | 0.99 |
| 5 | 232 | 390 | 0.51 | 0.51 | 0.99 |
| 6 | 132 | 118 | 0.74 | 0.74 | 0.96 |
| 7 | 122 | 149 | 0.63 | 0.63 | 0.96 |
| 8 | 109 | 206 | 0.46 | 0.46 | 0.90 |
| 9 | 118 | 216 | 0.47 | 0.47 | 0.91 |
| 10 | 142 | 245 | 0.50 | 0.50 | 0.97 |

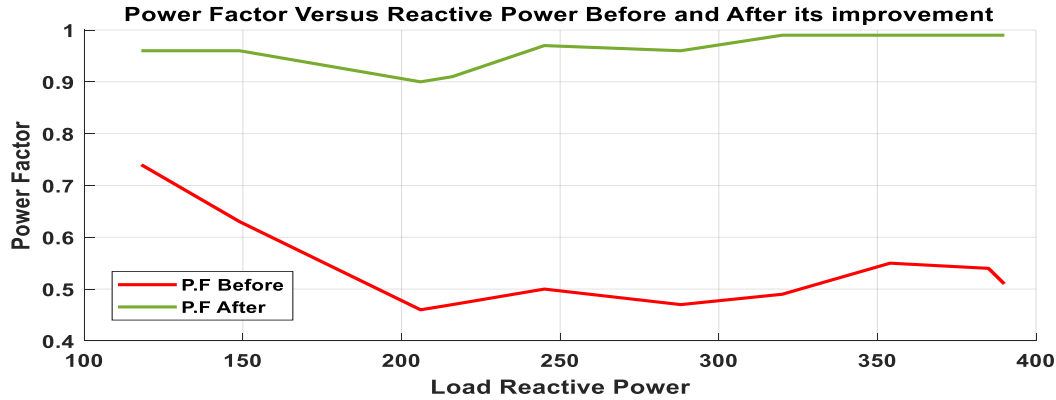


Figure 5.1. Power factor versus load reactive power before and after power factor improvement

From Table 5.1, it is shown that the power factor of the system without its improvement is below 0.74 and it is the same as the real power factor recorded from the factory. After connection of DSTATCOM in shunt to the load, the power factor of the system was raised to above 0.9 and the loads with the power approaching the one used in the design have the power factor greater than 0.96. The curve in green is the power factor from simulation and the curve in red is the power factor recorded from the factory and is the same as what from simulation before connection of DSTATCOM to the circuit.

5.1. Grid power Simulation Results Before and after Power Factor Improvement

The design of DSTATCOM in this thesis was based on 251kW and 385kVAr load. To assess the potential of DSTATCOM the simulation of load before and after connection of DSTATCOM to improve power factor was done based on this load. Before connection of DSTATCOM in the circuit, active power from the Grid was the same as that of the load and reactive power from the Grid was equal to that of load and both are shown in the Figure 5.2(a) and Figure 5.2(b) respectively.

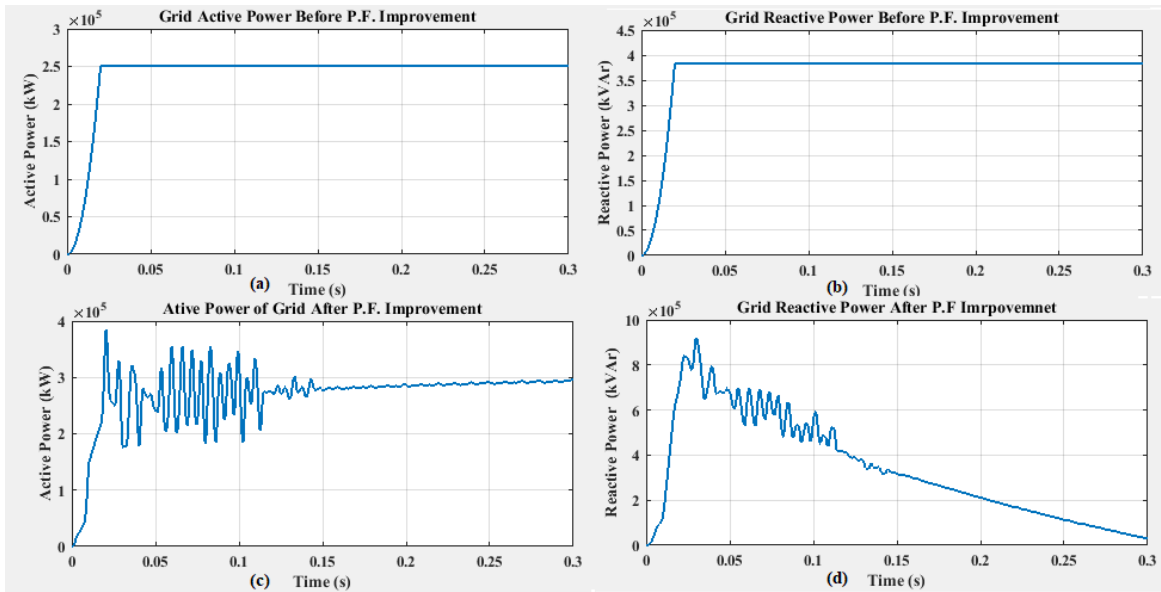


Figure 5.2. Active and Reactive Power from Grid before and After Power Factor Improvement

Active and reactive power from the grid after connection of DSTATCOM in the circuit are shown in the 5.2(c) and 5.2(b) respectively. Active power would be the same as before Connection of Inverter, but it is not the case as was increased due to switching power losses of inverter. The reactive power supplied by DSTATCOM in the system resulted in the crease of reactive power from the grid and the power factor increased to above 0.96.

5.2. Comparison of power factors before and After Connection of DSTATCOM

With the used load power of 251kW and 385kVAr, the simulation was done before and after connection of DSTATCOM. The results shows that the power factor of the factory before and after its improvement is 0.54 and 0.99 lagging respectively. The power factor before its improvement is shown on the Figure 5.3 and the power factor after its improvement is shown on Figure 5.4.

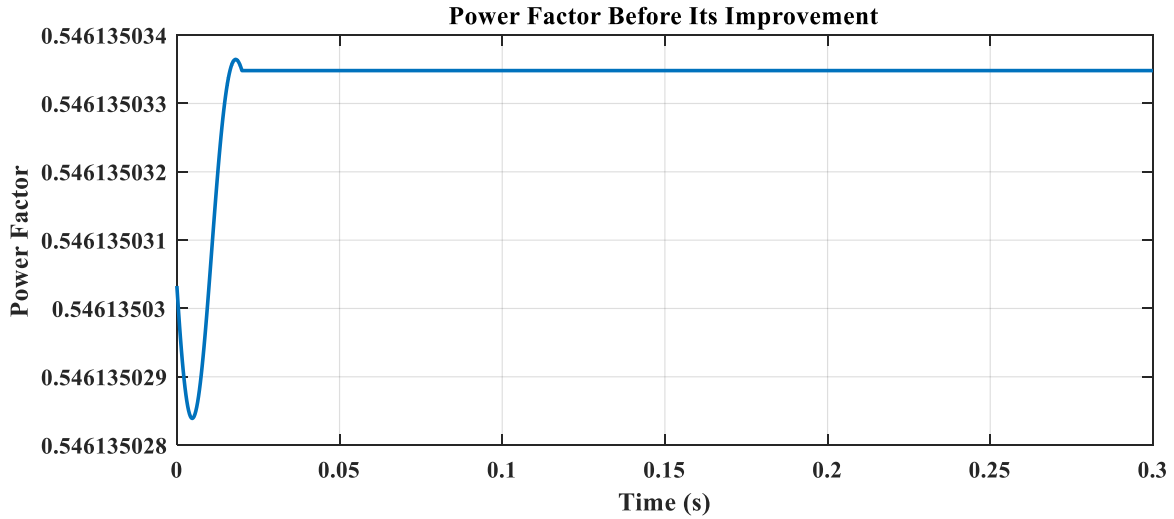


Figure 5.3. Factory Power Factor Before Its Improvement

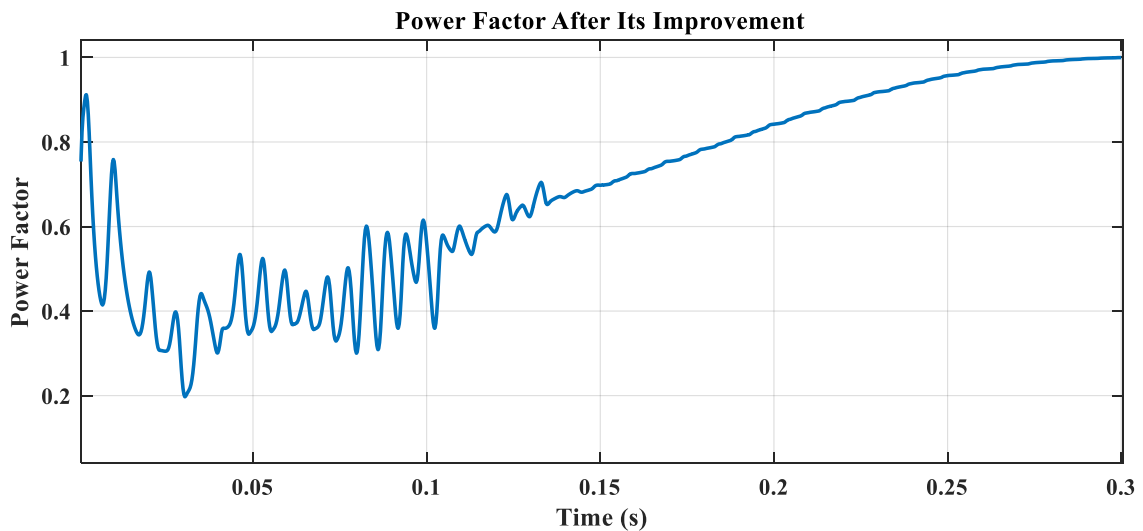


Figure 5.4. Factory Power Factor After Its Improvement

The Grid reactive power before power factor improvement is the same as that of the load and is shown in the Figure 5.2(b). The power factor of the system after its improvement was increased to 0.99, and is shown in Figure 5.4. That increment of power factor is due to the reactive power supplied by DSTATCOM in the circuit. The decreased reactive power of the grid is shown on the Figure 5.2(d).

5.3. Voltage and Current Simulation Results

After design of DSTATCOM the voltage and current were simulated to show the contribution of DSTATCOM in system current reduction. The current and voltage wave forms before and after power factor improvement are shown below.

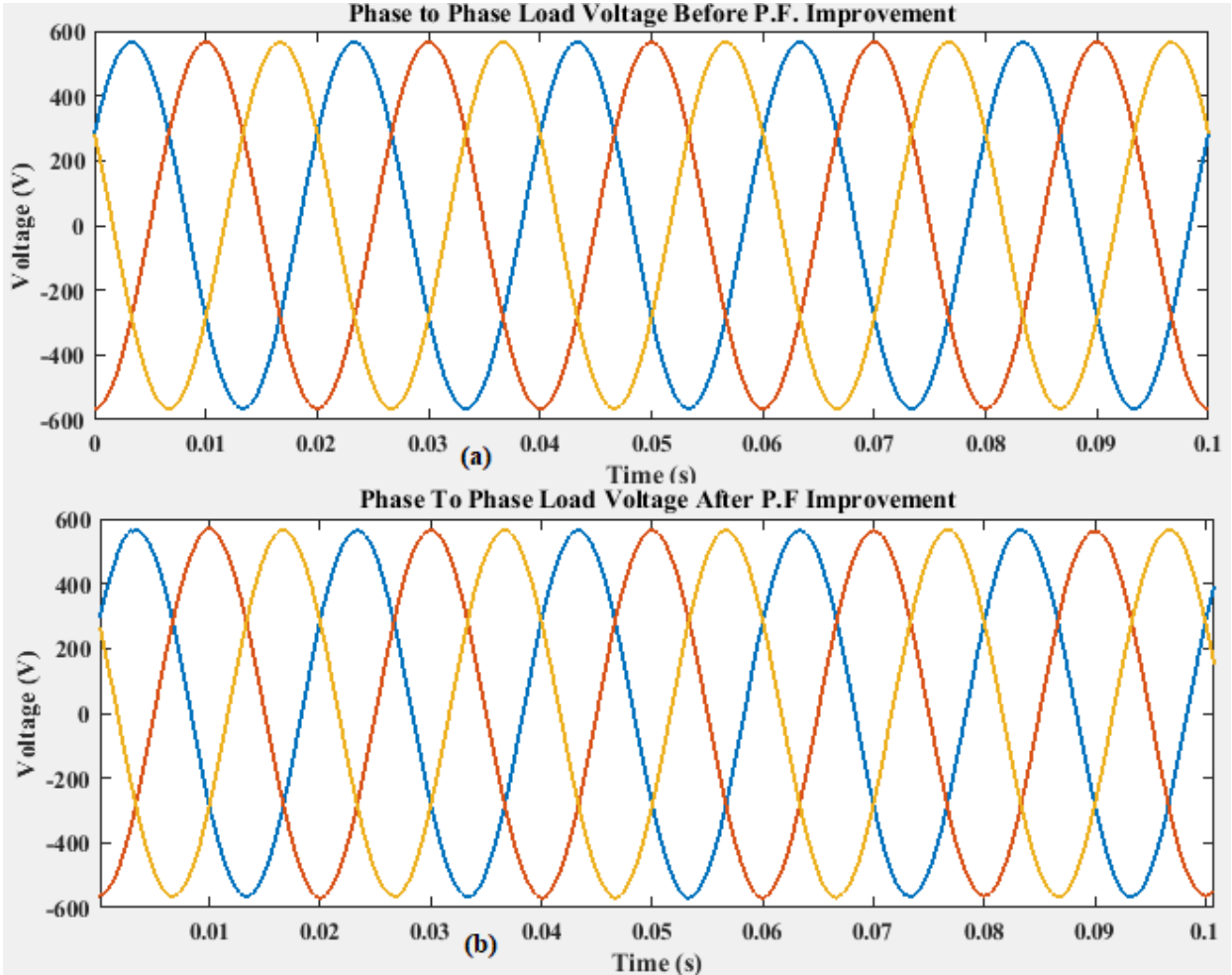


Figure 5.5. Load Voltage waveform before (a) and after (b) power factor Improvement

The waveform of load voltage before power factor improvement is shown in Figure 5.5(a) while the load voltage waveform after power factor improvement is shown in Figure 5.5(b). The waveforms are similar because there is no voltage drop as the source is an infinite bus bar.

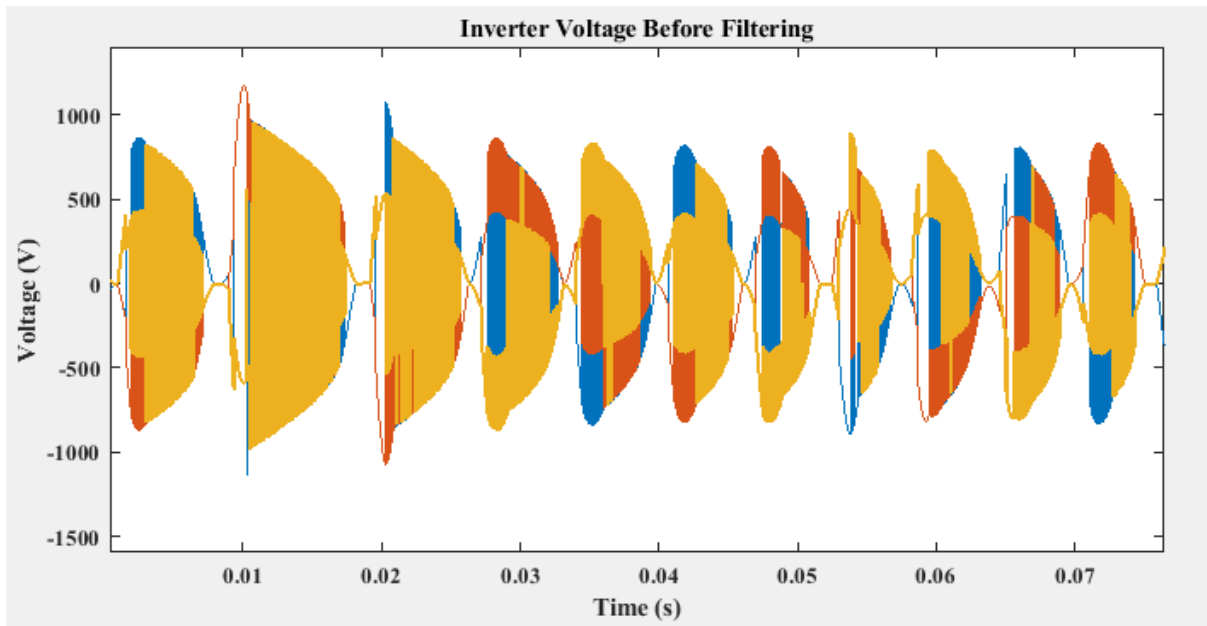


Figure 5.6. Inverter Voltage before filtering

The waveform of inverter voltage before filtering is shown in the Figure 5.6 and it is a three phase rectangular waveform as it is produced by 6IGBTs but two by two work simultaneously.

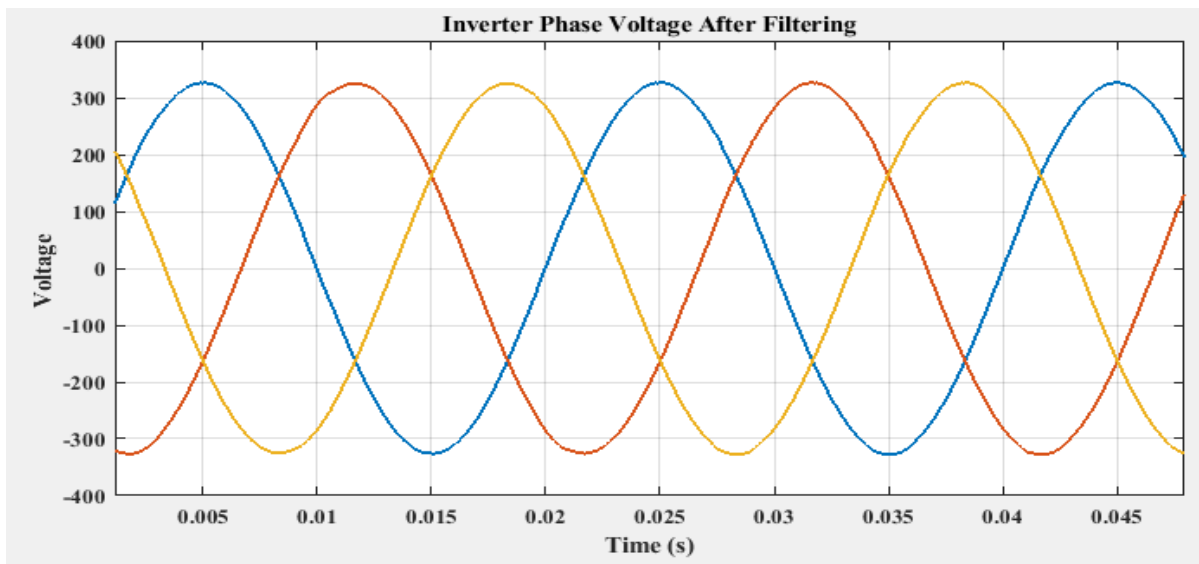


Figure 5.7. Output voltage of DSTATCOM after filtering

The voltage of inverter after being filtered by LCL filter, the voltage has a three phase waveform with is similar to that of the Grid to be synchronized at PCC with the same parameters as the control system of DSTATCOM maintain its output voltage to the reference voltage which is the desired voltage at PCC. Its wave form is shown in the Figure 5.8.

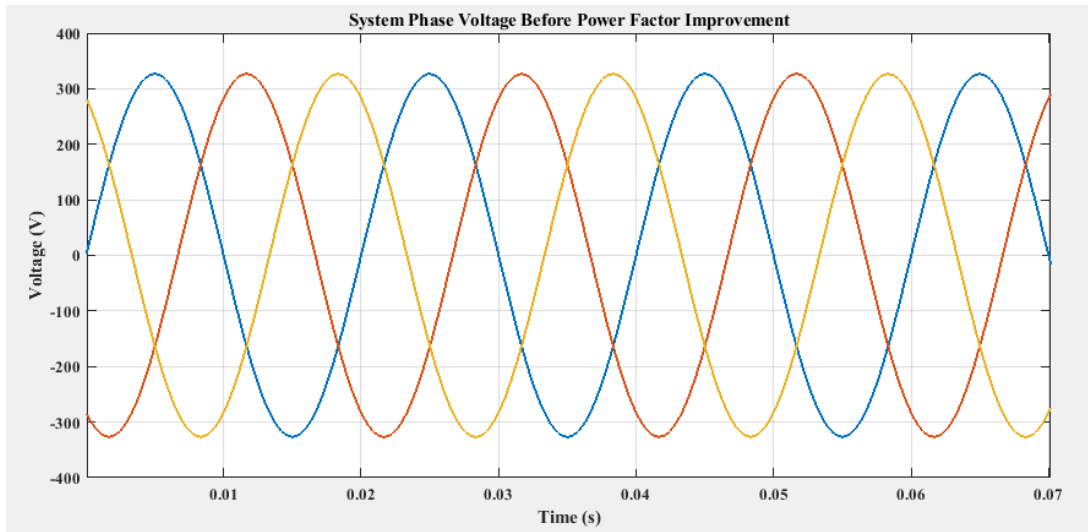


Figure 5.8. System Phase voltage before power factor Improvement

In Figure 5.9, the three phase system voltage is shown and its maximum value is about 330V which gives the RMS value of 234V and this is the same as what recorded at the factory during data collection.

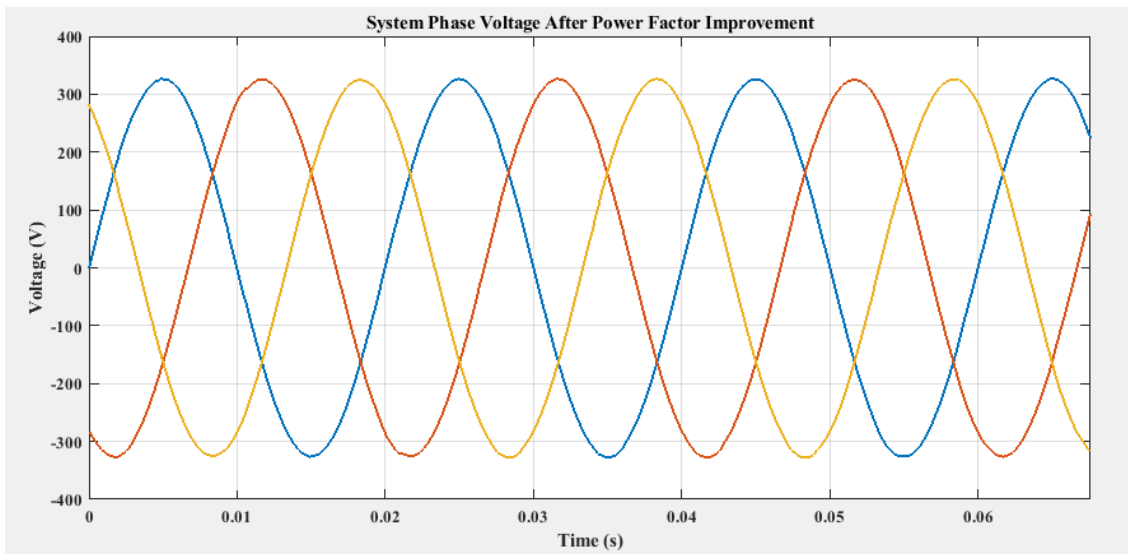


Figure 5.9. System Phase Voltage after Power factor Improvement

The system phase voltage after power factor improvement is shown in the Figure 5.9, and is similar as before, the reason behind is that the voltage drop caused by the load is not sensitive because the source is an infinite bus bar.

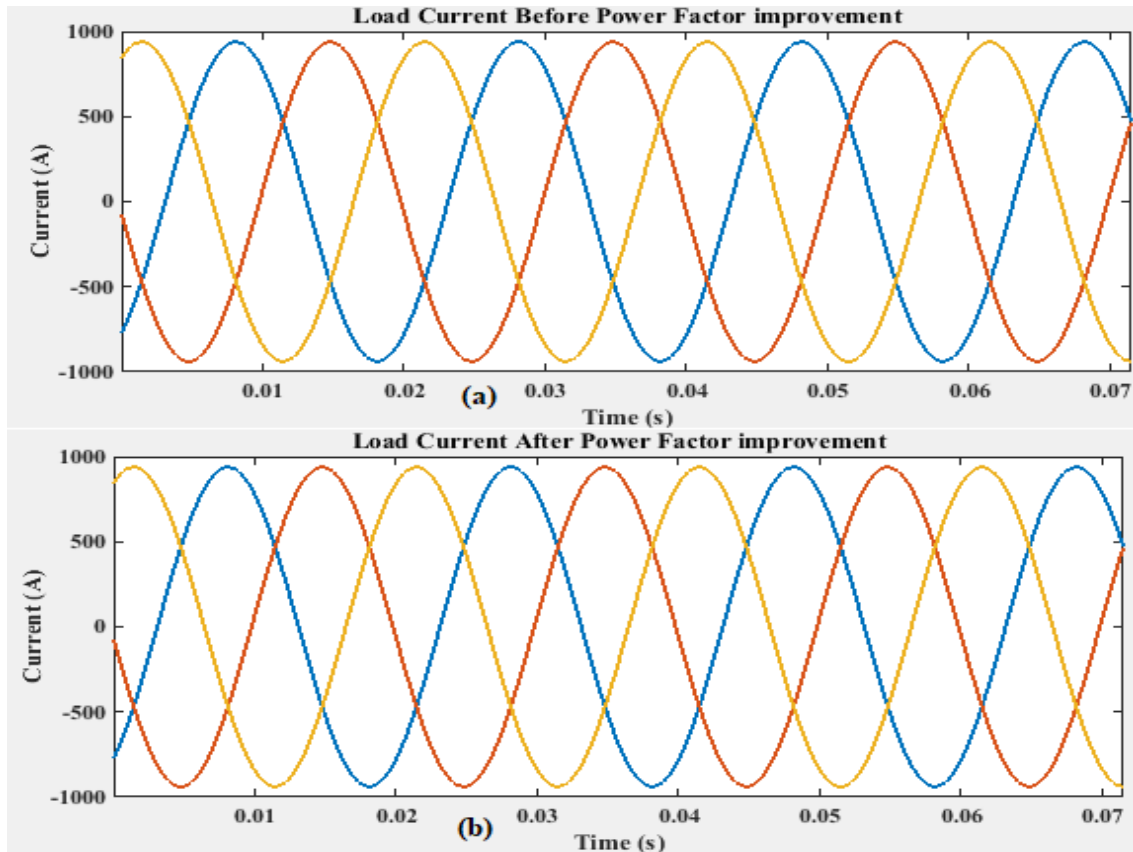


Figure 5.10. Load Current Before (a) and After (b) Power Factor Improvement

The load current are the same before and after the power factor improvement since the load remained the same; only the amount of reactive power from the grid was changed. The load current waveforms before and after power factor improvement are shown in Figure 5.10.

From the results obtained from the simulation, it is shown that the power factor of Gatere Tea Factory is improved from 0.54 to 0.96 and above when DSTATCOM is connected in the circuit parallel to the load.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1. Conclusions

This was about Design and modelling of DSTATCOM for power factor improvement at Gatare Tea Factory. For the completion of this work, different methods have been used; daily energy consumption, working power factor and working voltage of the factory. After collection of these data the design of DSTATCOM based on the factory maximum load power and targeted power factor. After the design and modelling of DSTATCOM the simulation before and after power factor correction of the system was done in M/Simulink and the results showed that the power factor was increased from 0.54 to 0.96 and above. The cost analysis of DSTATCOM showed that the device is economical as compared to the monthly payment of factory due low power factor, it was proved that the payback period is 3 years and six months and the rest years are for the factory profit as the lifetime of DSTATCOM is around 20 to 30 Years.

6.2. Recommendations

Based on the results found in his thesis, It recommended to Gatare Tea Factory to use DSTATCOM to improve their power factor it is reliable in this task, has low cost compered to its lifetime and do not occupy large area. The DSTATCOM cause harmonic currents in the system, hence it is recommended for next designers to consider this and design the current harmonic filter that can remove harmonics in DSTATCOM currents which can affect the system current.

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APPENDICES

A: MATLAB Codes

1. Codes used to draw the Graph(Variation of Power Factor Before and After Its Improvement)

```
x=[118 149 206 216 245 288 320 354 385 390];  
y=[0.74 0.63 0.46 0.47 0.5 0.47 0.49 0.55 0.54 0.51];  
z=[0.96 0.96 0.90 0.91 0.97 0.96 0.99 0.99 0.99 0.99];  
plot(x,y,'r-',x,z,'g-')  
xlabel('Load Reactive Power')  
ylabel('Power factor its Improvement')  
zlabel('Power factor after its Improvement')  
title ('Power factor versus Reactive Power before and after Power factor Improvement')
```

2. Codes used to log Figure from scope/Simulink to workspace

```
plot("figurename".time,"figurename".signals(1).values)
```

B: Energy consumption of Gatare Tea Factory

| Period | Hourly energy Consumption | | Apparent Power (kVA) | Power Factor |
|---------|---------------------------|-------------------------|----------------------|--------------|
| | Active Energy (kWh) | Reactive Energy (kVARh) | | |
| 23h-00h | 108 | 230 | 254.09 | 0.43 |
| 00h-01h | 108 | 190 | 218.55 | 0.49 |
| 01h-02h | 108 | 190 | 218.55 | 0.49 |
| 02h-03h | 108 | 190 | 218.55 | 0.49 |
| 03h-04h | 106 | 270 | 290.06 | 0.37 |
| 04h-05h | 142 | 243 | 281.45 | 0.50 |
| 05h-06h | 168 | 226 | 281.60 | 0.60 |
| 06h-07h | 234 | 354 | 424.35 | 0.55 |
| 07h-08h | 251 | 385 | 459.59 | 0.55 |
| 08h-09h | 186 | 261 | 320.49 | 0.58 |
| 09h-10h | 212 | 261 | 336.25 | 0.63 |
| 10h-11h | 156 | 273 | 314.43 | 0.50 |
| 11h-12h | 118 | 216 | 246.13 | 0.48 |
| 12h-13h | 109 | 206 | 233.06 | 0.47 |
| 14h-15h | 174 | 189 | 256.90 | 0.68 |
| 15h-16h | 136 | 186 | 230.42 | 0.59 |
| 16h-17h | 132 | 118 | 177.05 | 0.75 |
| 17h-18h | 122 | 149 | 192.57 | 0.63 |
| 18h-19h | 109 | 195 | 223.40 | 0.49 |
| 20h-21h | 180 | 320 | 367.15 | 0.49 |
| 22h-23h | 232 | 390 | 453.79 | 0.51 |