



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

School of Electrical and Computer Engineering

**ENERGY AUDIT AND POWER QUALITY IMPROVEMENT
IN DEBRE BERHAN BLANKET FACTORY**

A thesis Submitted to the Addis Ababa Institute of Technology, School of
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In partial fulfilment of the Requirement for the Degree of
**MASTERS OF SCIENCE IN ELECTRICAL ENGINEERING
(ELECTRICAL POWER ENGINEERING)**

By

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Advisor: Getachew Bekele (PhD)

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Addis Ababa, Ethiopia



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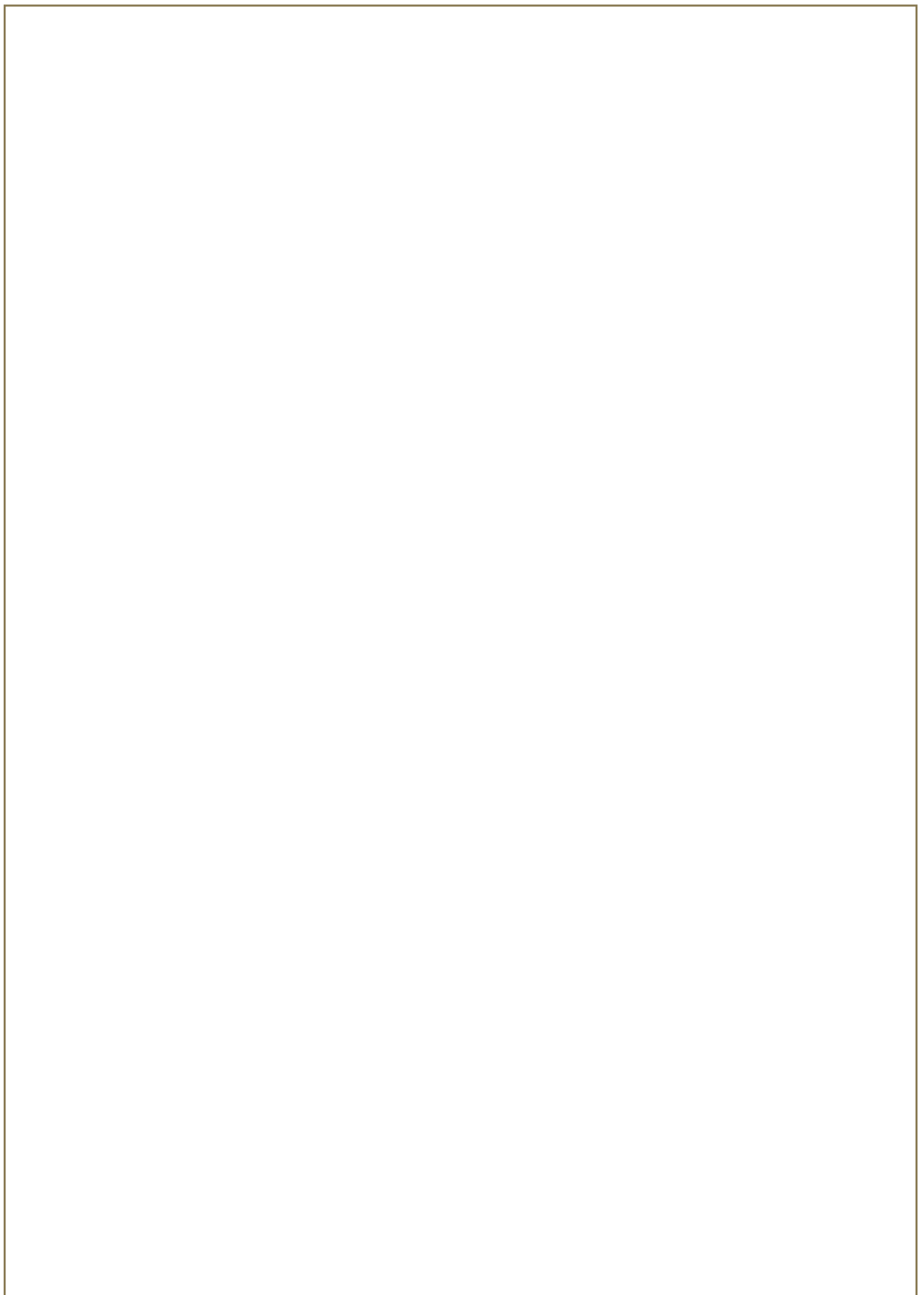
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DECLARATION

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or other universities, all sources of materials used for this thesis work have been fully acknowledged.

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Signature

DEDICATION

To my beloved brother

Amanuel Gidey

&

To my family.

AKNOWLEDGMENT

First, I take this opportunity to give glory to the almighty God, without whom the completion of this work would have been impossible.

Next, I would like to express my sincere gratitude to my advisor, Getachew Bekele (PhD), for his guidance, constructive comments, suggestions and supports for the successful completion of this thesis. He has also played an indispensable role as the primary source of inspiration on every step of the activities or proceedings of my study.

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ABSTRACT

Adequate and reliable supply of energy is essential to ensure maintainable development of any country. However, the use and conversion of primary energy results in energy waste, high cost energy and emission. In addition, developing countries, like Ethiopia, have low consciousness on energy conservation and faced to generate more energy rather than to use the existing energy efficiently. This thesis studies on energy audit and power quality related issues in Debre Berhan Blanket Factory.

A detailed assessment of energy consumption and loss has been analysed. Based on the losses, energy efficiency assessments on the major energy intensive equipment's like electric motors, air compressors, boilers, and lightings have been done.

It has been found from energy audit results that there exists a difference of 3.14 kWh/kg average electric energy intensity between the benchmarks and what exists at Debre Berhan Blanket Factory; the factory spends US \$ 17,475.55 per year on this account. Using Motor Master + International software it has been seen that some under loaded motors has been replaced with proper sized motors and energy efficient motors. This brings energy savings of 120,265.00 kWh per year and money savings of US \$ 8545.00 per year with some payback year ranging from 1.52 to 6.29 years. Also through improving, the lighting systems resulted in money savings of US \$ 2644.81 annually. Moreover, a similar analysis is taken for air compressor that result in energy saving of 72,536.76 kWh, and money saving of US \$ 1552.27 annually and, for a boiler, fuel oil saving of 2197.52 Lit and a money saving of US \$ 1,302.23 per year with almost zero or negligible pay back periods.

In addition, measurements and simulations have been made to assess power quality related problems of the factory. Moreover, a comparison of the measured values with standards is made which shows that the current harmonic pollution was found out of the standard limit. This thesis also presents the design of passive filters to reduce the current harmonics produced by non-linear loads in the factory. MATLAB/Simulink software has been used for the simulation purpose with and without installation of filters. As a result, all the harmonic distortion levels the 3rd, 5th, and the 7th are reduced from 3.18% to 0.15%, 15.84% to 0.06%, and 16.28% to 0.03% respectively. Moreover, the current total harmonic distortion THD_I reduces from 22.94% to 0.16% values.

Keywords: Energy Audit, Energy Assessment, Power Quality, Harmonic Filter, MATLAB Simulation

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NOMENCLATURE

ALR	Actual Lamp Required
ANSI	American Nation Standards Institute
CB	Circuit Breaker
D	Diameter
DBBF	Debre Berhan Blanket Factory
DEA	Detailed Energy Audit
Dep.t	Department
ECO	Energy Conservation Opportunity
ED	Energy Difference
EEA	Ethiopian Energy Authority
EEU	Ethiopian Electric Utility
Eff.	Efficiency
ER	Energy Required
ES	Energy Saved
EU	Energy Utilization
FAD	Free Air Delivery
FFT	Fast Fourier Transform
FL	Fluorescent Lamp
GC	Gregorian calendar
h	Harmonic
HEM	High Efficiency Motors
hp	Horse Power
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineering
IGBT	Insulated Gate Bipolar Transistor
IUF	Current Unbalanced Factor
LBB	Load Bus Bar
LFO	Light Fuel Oil
LV	Low Voltage
MDBMM	Maximum Deviation between Measured value and Mean

NEMA	National Electrical Manufacturers Association of USA
NL	Number of Lamps
OH	Operating Hours
PCC	Point of Common Coupling
PEA	Preliminary Energy Audit
PF	Power Factor
P_{lt}	Long-term Flicker
ppm	Parts per million
P_{st}	Short-term Flicker
P_u	per unit
r	Radius
RA	Room Area
RMS	Root Mean Square
RPM	Revolution per Minute
SPC	Specific Power Consumption
SPP	Simple Payback Period
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
THD_I	Total Harmonic Distortion of Current
THD_V	Total Harmonic Distortion of Voltage
T_{ILu}	Total Illuminations Produced
T_L	Loading Time
T_{Lu}	Total Lumens Out put
T_{UL}	Un-loading Time
TP	Total Power
UPS	Uninterrupted Power Supply
US DOE	United States Department of Energy
VAR	Volt Ampere Reactive
VSD	Variable Speed Drives
VUF	Voltage Unbalance Factor
WWT	Waste Water Treatment

CHAPTER -1-

INTRODUCTION

1.1 Background

Textile Industry is one of the most important industries in the world. The industry agonises from inadequate development planning, which is atypical problem with most of the textile industries. A typical textile industry structure contains sub-sections, which are occupied by a number of different units working independently. There might be some hidden defects left in the structure that leads to unnecessary energy use.

The industrial sector in general books around 40% of the commercial energy worldwide [1]. The electrical and thermal energies are widely used in several equipment's like in water pumps, boilers compressors etc. However, there are many problems in the industry sector in using their energy resourcefully. They are not well informed on the concept of energy conservation. Due to this, they loss lots of money on energy bills, causes problems on the environment, industries will not be competitive, etc. [1].

This documentation summarizes energy conservation opportunities identified during an energy audit conducted and power quality improvement at Debre Berhan Blanket Factory. Data collected during the audit uses to estimate energy savings that can be achieved by implementation of the measures recommended. By using a systematic approach through which data concerning the energy utilization performance of the plant will be collected. The initial step consists of the conduct of a visual inspection and collection of readily available energy-related data. This preliminary energy audit (PEA) permits identification of major energy-consuming systems that can be evaluated using portable instrumentation during the detailed energy audit (DEA).

Each major energy-consuming system will be tested as part of a detailed energy audit to determine its relative energy efficiency and to determine energy cost reduction opportunities. An important part of the energy audit process is the interviewing of plant personnel to establish procedures, schedules, and operating details. During the detailed energy audit, personnel from the different departments have been interviewed.

Today manufacturers face an increasingly economical global business environment; they seek opportunities to reduce production costs without negatively affecting product yield or quality. For public and private companies alike, rising energy prices are driving up costs and decreasing value added at the plant. Successful, cost-effective investment into energy-efficiency technologies and practices meets the challenge of maintaining the output of a high quality product despite reduced production costs. This is especially important in the current age, as energy-efficient technologies often include additional benefits, such as increasing the productivity of the company or reducing the materials consumption [2].

1.2 Plant Description

The factory is located in Debre Berhan city around 150 km North of Addis Ababa and is engaged in the production of mainly a blanket. In addition, a finished product such as bed-cover, acrylic yarn, mattress and pillow. A brief process description follows.

Raw materials, in the form of salvage, wool, and acrylic fiber are formed into thread through sorting, pulling, cutting, ramming, dyeing, squeezing, drying, blending, carding and spinning, yarning, warping, weaving and finishing operations. Accomplishment of some sizing process depends on the requirements of the final product.

At the first step, the wool and acrylic fiber is sorted and then go to the pulling and cutting process as a result of this a pulled material is gained. Moreover, this pulled material is then goes to the ramming machine. Then according to the required color it goes to the dyeing process and because of this, it produces a colorful or a dyed wool, dyed staff. Then it goes to a drying process that eliminates some moistures. After this, it goes in to the pulling and sucker machines and the output goes through pipes and stored in to a temporary store. After this, it goes in to the carding and spinning machines and the material changed in to a yarn.

In the weaving department, the yarn changes into rolls of cloth. From the weaving department, the cloth passes on to the mending department in which unwanted part of the blanket is cut-off. Finally, the hard blanket goes through the raising machine, becomes a soft blanket, and then goes to the finishing department. The actual processes employed to finish the blanket depend on the final product requirement. The plant is capable of performing a number of wet and dry operations.

The plant consists of many buildings, which includes the processing departments, boiler room, chilled water plant, and administrative offices and a separate building houses an employee dining room. The plant was built in 1964 G.C. Most of the equipment in the facility installed during the construction of the facility. It employs around 800 people.

1.2.1 Operating Schedules

The operation of the factory is broken into a number of process and service areas. While the operation of the factory as a whole is 16 hours per day, 6 days per week (6:00 a.m. - 10:00p.m Monday through Saturday), individual operating schedules for the process and service departments are shown in the Table 1-1.

Normal shift times are 6:00a.m to 2:00 p.m., 2:00 p.m. to 10:00p.m., and are of 8 hours duration. The boiler plant operates at least 1 hour before normal first shift start up time to allow availability of steam chilled water at the start of the production day. The factory operates an average of 50 weeks per year.

Table 1-1: Operating Schedules of the Factory

Department	Hours per Day	Days per Week
Material preparation	8	6
Dying and drying	8	6
Carding and spinning	16	6
Warp preparation	16	6
Weaving	16	6
Mending	16	6
Raising and shearing	16	6
Finishing	16	6
Boiler	8-16	6
Air compressor	8-16	6
Pump station	16	6
Water supply	16	6
Lighting	8	6
Mechanical workshop	8	6

1.2.2 Production Data

The factory is engaged in the production of finished blanket, bed cover, acrylic yarn, and mattress and pillow products for home. Salvage, wool, and acrylic fiber materials are the main input raw materials. The Table 1-2 presents production statistics for the various plant departments.

Table 1-2: Production Data of the Factory

Department	Year (G.C)	Production	Units
Spinning	2017	235,791.30	kg
Weaving	2017	550,100.52	kg
Finishing	2017	1,708,498.90	kg

1.2.3 Energy Consumption and Costs

Electricity is purchased from Ethiopian electric utility (EEU). The cost for electricity is US \$ 0.0264 per kWh, inclusive of all adjustments. In addition, there is also a demand charge of US \$ 13.74 (Average) and a service charge of US \$ 2.4562 per month. A power factor penalty is included in the tariff for industrial users with power factor of less than 0.85. Since DBBF maintains power factor of 0.89 which is above 0.85. Thus, no penalty due to power factor. Both the Furness oil and diesel oil are purchased from Kenya. The cost of Furness oil is in range between US \$ 0.6046 - 0.7054 per liter. Table 1-3 shows the energy consumption by fuel type for the year 2016 G.C.

Table 1-3: Energy Consumption and Costs of the Year 2016 G.C

Energy	Year (G.C)	Units	Consumption	Annual Cost (US \$)	Percent of Total Cost (%)
Electricity	2016	kWh	1,752,276.91	46,267.35	52.30%
Furness oil	2016	Lit	67,357.10	40,731.06	46.05%
Diesel oil	2016	Lit	2250	1,442.96	1.65%
Total				88,441.37	100%

1.3 Energy Audit

An energy audit is an enquiry of all surfaces of organization's historical and current energy use with the objective of identifying and quantifying areas of energy wastage within the organization's activities. It establishes a starting position for any improvements in energy use. It is an important commercial tool to save energy and to improve financial state of an organization. Almost all the large scaled and many small scaled organizations i.e. industries as well as non-industrial sectors are guiding energy audit to save energy and to minimize the electricity cost. Energy audits support industrial companies or facilities in understanding how they use energy and help to identify the areas where waste occurs and where opportunities for improvement exist [3]. The objectives of an energy audit can vary from one plant to another. However, an energy audit is usually directed to understand how energy is used within the plant and to find opportunities for enhancement and energy saving. Sometimes, energy audits are conducted to evaluate the efficiency of an energy efficiency project or program [3].

1.3.1 Types of Energy Audit

The type of industrial energy audit accompanied depends on the function, size, and type of the industry, the deepness to which the audit is needed, and the potential and magnitude of energy savings and cost reduction desired. Based on these criteria, an industrial energy audit can be classified into two types: a preliminary energy audit (walk-through audit) and a detailed energy audit (diagnostic audit) [4].

a) Preliminary Audit: In a preliminary energy audit, readily available data are mostly used for a simple analysis of energy use and performance of the plant. This type of audit does not involve a lot of measurement and data gathering. These audits take a comparatively short time and the results are overall, providing common chances for energy efficiency. The economic analysis is typically limited to calculation of the simple payback period, or the time required paying back the initial capital asset through realized energy savings [4].

b) Detailed Audit: For detailed (or diagnostic) energy audits, more in depth data and information are necessary. Measurements and a data inventory are usually accompanied and different energy systems (pump, fan, compressed air, steam, process heating, etc.) are evaluated in detail. Hence, the time required for this type of audit is longer than that of preliminary audits. The results of these audits are more all-inclusive and useful since they give a more precise picture of the energy performance of the plant and more explicit recommendation for enhancements [4].

1.4 Problem Statement

The aim of energy efficiency is to decrease the amount of energy required to provide products and services. Enhancements in energy efficiency are mostly achieved by adopting a more efficient technology or production process or by request of commonly accepted methods to reduce energy losses.

Energy in DBBF in the form of electricity is a common power source for machinery, cooling and temperature control systems, lighting, office equipment, compound etc. It is detected that the unproductive use of the energy in the factory causes wastage and losses of the useful electrical energy. Some of the common reasons for the inefficient use of energies are:

- Lack of responsiveness and consciousness on energy efficiency management program
- Poor and incorrect design of electrical installation.
- Absence of proper replacement, regular maintenance and control of industrial apparatus
- Absence of spare parts and accessories.
- Due to the non-linear devices in the factory, such as derives which are the reason for harmonic currents injected into power system and declining the quality of power and hence rise the loss.

This thesis, thus tries to make a detailed analysis of the above-mentioned problems, identify their causes and effects and try to recommend possible solutions.

1.5 Objectives

1.5.1 General Objectives

The general objective of this thesis is to analyse the present use and management of electrical energy as well as to identify the power quality problems in the factory and recommend proper measures to improve the energy usage and power quality.

1.5.2 Specific Objectives

The specific objectives are:

- To study the working conditions and collect relevant data from Debre Berhan blanket factory.
- To analyse the data and determine energy conservation opportunities for the major energy consuming equipment.

- Determine the potential of energy savings in different energy consuming equipment through energy auditing.
- Analyse the major causes of energy losses at the factory.
- Study and analyse the motors performance.
- Study and investigation of the lighting systems.
- Measure and analyse the air compressor and boiler performance parameters.
- Measure the power quality parameters, assess the power quality related problems in the factory, and suggest the appropriate solution.

1.6 Scope of the Study

Energy is one of the largest controllable costs in most manufacturing and processing industries and there is significant scope for reducing energy depletion and hence cost. DBBF had no explicit study of the energy consumption of its textile manufacturing processes. Thus, the scope in first place is allocated to the study of the energy use in the textile manufacturing processes. The study incorporates reading relevant literature, collecting (measuring) and analysing data from the factory for energy consumption, monitoring, accounting and management in the factory. The analysis focus on identification of the major energy using processes and the amount of energy that is lost.

1.7 Methodology

- Site visit
- Data collection

The required data for this thesis are collected from different sources. The necessary data are:

- ✓ The electrical energy consumptions of the factory for at least three years.
- ✓ The fuel consumption for the last three years.
- ✓ Specification, working conditions and maintenance measures of the equipment's in the utility plants.
- ✓ History of the production cost of the factory, energy bill, lighting data.
- ✓ Measurements such as 3-phase voltage, 3-phase current, power factor, active power, reactive power, etc. In addition, the performances of the major energy intensive equipment's like motors, boilers, compressors, and lightings are assessed.

- Conducting introductory meetings, audit interview, walk through tour with relevant managers by establishing work relation with industry management.
- Recognising energy conservation occasions by:
 - ✓ Performing technical evaluation
 - ✓ Calculating payback periods
- Data Analysis

All the above data are then analysed quantitatively and qualitatively. Depending on the assessed data, opportunities to reduce energy losses are identified. From the analysed data, conclusion and recommendation have been forwarded.
- Software tools
 - ✓ Motor master + International software. It supports motor and motor systems improvement planning through identifying the most efficient action for a given repair or motor purchase decision. In addition, it is used to identify inefficient or oversized inventory motors and compute the energy and demand savings associated with selection and replacement energy-efficient model.
 - ✓ MATLAB Simulink Software.

1.8 Outline of Thesis

This thesis is organized into the following five chapters:

Chapter-One: Gives an overview of the thesis and lists the contents of the chapters in the thesis. Besides that, the general idea of the research and briefly introducing the important aspects of the research.

Chapter-Two: Discusses the relevant literature review of the research including all the theory. In addition, research studies relevant to this thesis.

Chapter-Three: It discusses all the factory manufacturing process, data collection, and measurements taken.

Chapter-Four: According to the the collected data and the measurements taken in the factory, this chapter tries to summarise and identify the causes of major energy losses and their energy saving opportunities in plant factory. In addition, it tries to put all the summarized results, analysis and discussion of the thesis theoretically and simulation based outputs.

Chapter- Five: Finally, it presents conclusions and recommendations.

CHAPTER -2-

LITERATURE REVIEW AND THEORETICAL BACKGROUND

2.1 Energy Efficiency

Energy efficiency improvements for the factory refers to a decrease in the energy usage for a given energy service such as production, heating, lighting. This reduction in the energy consumption is not necessarily related to technical changes, since it can also result from a better organization and management or improved economic efficiency in the area. Energy efficiency is first a matter of individual behaviour and rationale of energy consumers. Avoiding needless consumption of energy or choosing the most suitable equipment to reduce the cost of the energy add to decrease individual energy consumption without decreasing individual benefit and production. It is clear that it also pays to increase the overall energy efficiency of the national economy [5].

There are diverse opportunities to improve energy efficiency in a plant while keeping or enhancing productivity. Improving energy efficiency at a plant should be approached from numerous directions. First, the plant uses energy for different equipment's, which need consistent maintenance, good operation, and replacement, when necessary. Thus, a critical element of plant energy management includes the efficient control of crosscutting equipment that powers the production processes of a plant. A second and similarly essential area is the proper and efficient procedure of the processes. Process optimization and confirming that the most productive technologies are in place are keys to understand energy saving in a plant's operation [2].

2.2 Lighting System

For diverse types of lamps, there will be different levels of luminous intensity and illumination, which are essential in several working areas. Table 2-1 and Table 2-2 show the luminous intensity and lifetime of various lamps and illuminations necessary in various working station respectively. In addition, Table 2-1 and Table 2-2 are standard tables, which are needed to estimate whether the current installation system is appropriate, or not.

Table 2-1: Luminous Intensity and Lifetime of Various Lamps [6]

No.	Lamp Type	Output Power (Watt)	Luminous Intensity (Efficiency) (Lumen / Watt)	Service Life (hrs)
1.	Incandescent lamp	3-1000	10-15	1,000-2,000
2.	Halogen lamp	5-500	15-25	2,000-4,000
3.	Fluorescent tube	4-60	50-100	7,500 -24,000
5.	Compact Fluorescent (CFL)	5-40	50-80	10,000-20,000
6.	Metal Halide	30-2000	50-115	6,000-20,000
7.	HP Mercury vapour	40-1000	25-55	16,000-24,000
8.	High Pressure Sodium	35-1000	40-140	16,000-24,000
9.	Low Pressure Sodium	35-180	100-185	14,000-18,000
10.	Light Emitting Diode (LED)	1-400	>100 (continuous increase)	20,000-50,000

Table 2-2: Illuminations Required in Various Working Station [7]

No.	Working Area	Average Illuminance Required (Lux)
1.	Office	500
2.	Canteens	150
3.	Boilers and Pump house	20-100
4.	Spinning	150-450
5.	Knitting	300-750
6.	Weaving	200-700
7.	Grey close inspection	700-1000
8.	Final inspection	700-1000
9.	Work shops	200-750
10.	Clock rooms, Entrance, Corridors, Stairs	100

Various terms and definitions are used to quantify light, light source, etc. These are luminous flux, luminous intensity, illumination, luminance, etc. and their corresponding mathematical expressions are given in Table 2-3.

Table 2-3: Important Formulas for Lighting Assessment

Important Formula	Key
$TP = LR \times NL \quad (2.1)$	<p>TP = Total power ratings (Watts) of the lamps installed in the department. LR = Lamp Rating (Watt). NL = Number of lamps installed.</p>
$TL_u = NL \times L_o \quad (2.2)$	<p>TL_u = Total lumens output of lamps installed in the department (Lumen). L_o = is the luminous output of each fluorescent lamp, which is 85 Lumens/Watt, obtained Table 2-1 for fluorescent lamps.</p>
$IL_u = \frac{TL_u}{RA} \quad (2.3)$	<p>IL_u = The illumination produced by the installed lamps expressed in Lux (1Lux = 1Lumens/m²). RA = Room area of each department (m²).</p>
$ALR = \left(\frac{IL_u R}{IL_u} \right) \times NL \quad (2.4)$	<p>ALR = The actual lamps required for proper illumination, which uses to analyze energy wastes due to improper illumination. $IL_u R$ = is the illumination required in each area. (E.g., for office, $IL_u R$ is 500 Lux from Table 2-2 and this figure is compared with the actual Lux produced in each office.) The actual fluorescent lamp required (ALR) are calculated for each department and compared with number of lamps (NL) currently installed.</p>
$EU = NL \times LR \quad (2.5)$	<p>EU = Energy utilization for the lighting systems (kWh)</p>
$ER = ALR \times LR \quad (2.6)$	<p>ER = Energy required after a proper illumination (kWh)</p>
$ED = EU - ER \quad (2.7)$	<p>ED = Energy difference (kWh). It compares the EU, of the currently installed lamps, with the ER, after proper illumination. OH = Operating hours</p>

2.3 Electric Motor

When considering energy-efficiency improvements to a facility's motor systems, a systems tactic must be used in order to achieve optimal savings and performance. In the following, essential mathematical formulas, bearing in mind with respect to energy use and energy saving opportunities, for a motor system are presented.

2.3.1 Motor Efficiency

The efficiency of a motor can be well defined as the ratio of mechanical power output to its electrical power input. It is expressed as:

$$\eta = \frac{0.746 \times h_p \times Load}{p_i} \quad (2.8)$$

Where,

η = Efficiency as operated in %

h_p = Name plate rated horsepower

Load = Output power as a % of rated power

p_i = Three phase power in kW

An electric motor's function is to convert electrical energy to mechanical energy to accomplish useful work. In the procedure of converting electrical energy to mechanical energy to serve a certain load, motor losses their energy as shown in the Figure 2-1. Losses can differ from approximately 2% to 20% [8].

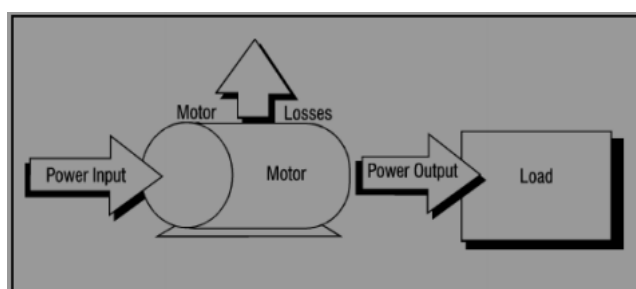


Figure 2-1: Illustration of Motor Energy Losses [9]

The efficiency of a motor is determined by intrinsic losses that can be reduced only by changes in motor design. Intrinsic losses are of two types: fixed losses - independent of motor load, and variable losses - dependent on load. Fixed losses involve of magnetic core losses, friction and winding losses. Magnetic core losses, sometimes called iron losses, consist of eddy current and hysteresis losses in the stator. They differ with the core material,

geometry and with input voltage. Friction and winding losses are caused by friction in the bearings of the motor and aerodynamic losses related with the ventilation fan and other rotating parts. Variable losses comprise of resistance losses in the stator and in the rotor and miscellaneous stray losses.

The primary factors affecting motor efficiency are:

- The size of the motor: Larger motor rate capacity tend to be more efficient.
- Speed: High-speed motors tend to be more efficient.
- Kind of enclosure: Open enclosures tend to be more efficient.
- Design classification: Lower slip motors tend to be more efficient.
- Size of the air gap stuck between the rotor and the stator: Large air gaps tend to exploit efficiency at the expense of power factor, while small air gaps slightly compromise efficiency while significantly improving power factor.
- Rewinding: It may diminish its efficiency.
- Motor load: In general motors operating below 75% of full load relatively reduces their efficiency and with operating below 50% very inefficient.
- Age: New motors are more efficient.
- Temperature totally enclosed fan-cooled (TEFC) motors are more efficient than screen protected drip-proof (SPDP) motors.

2.3.2 Motor Loading

Loading or load factor is defined as the ratio of the average load over a given period to the maximum demand, peak load, occurring in that period. In other words, the load factor is the ratio of energy consumed in a given period of hours to the peak load, which has happened during that particular period or is the amount of work the motor does compared with its maximum rated power output. Load factor means how professionally we use energy. It is the measure of the use of electrical energy during a given period to the maximum energy, which would have been consumed in that period. For example, a motor rated at 80kW driving a 60kW load is said to be 75% loaded. Modern motors work most efficiently above 50% loading with a peak between 75% and 90% load. Note that the rating plate on a motor announces its output power at the shaft, so that the real electrical input energy drawn will be the output power at the shaft and the power lost due to the motor inefficiency [10].

Since the efficiency of a motor is hard to assess under normal operating conditions, the motor load can be measured as an indicator of the motor's efficiency. As loading increases, the power

factor and the motor efficiency increase to an optimum value at around full load. Most electric motors are designed to run at 50% to 100% of rated load. Maximum efficiency is usually near 75% of rated load [11]. Thus, an 80 hp motor has an acceptable load range of 40 to 80 hp, peak efficiency is at 60 hp. A motor's efficiency tends to reduction dramatically below about 50% load. However, as Figure 2-2 shows, the range of good efficiency differs with individual motors and tends to extend over a wider range for larger motors.

A motor is considered under loaded when it is in the range where efficiency drops meaningfully with reducing load. Overloaded motors can overheat and lose efficiency. Many motors are designed with a service factor that allows irregular overloading. Service factor is a multiplier that indicates how much a motor can be overloaded under ideal ambient conditions. For example, a 20 hp motor with a 1.15 service factor can handle a 21.5 hp load for short periods without suffering important damage. Although many motors have service factors of 1.15, running the motor continuously above rated load reduces efficiency and motor life. The US DOE fact sheet provides tables with typical motor efficiency values [11].

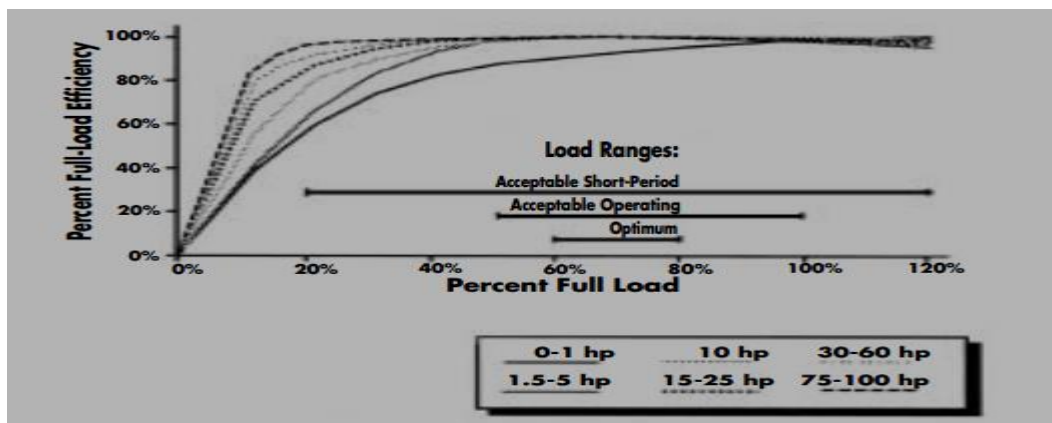


Figure 2-2: Motor Part Load Efficiency as a Function of % Full Load [Taken from a fact sheet, US Department of Energy] [11]

Motor Load Estimation Techniques

To relate the operating costs of an existing standard motor with an appropriately sized energy efficient replacement, it is required to determine operating hours, efficiency enhancement values, and load. Rated motor load defines the capacity of the motor to do work. Power and energy measurements are used to regulate loads on equipment, energy consumption, running costs, and to prove suitable system sizing and operation. To compare operating costs of an existing motor and a more efficient replacement unit needs to decide operating parameters of the motor, efficiency improvement values, and load. A motor load survey is carried out to

measure the operating load of different motors across the factory. The results are used to identify motors that are undersized, causing motor burn out, or oversized, resulting in ineffectiveness. To calculate the motor load, it should be compare the power draw, obtained through wattmeter or voltage, amperage, and power factor measurements, with the nameplate rating of the motor.

Part-load is a term used to define the actual load worked by the motor as compared to the rated full-load capability of the motor. Motor part-loads may be expected through using input power, amperage, or speed measurements. Determining whether the motors are correctly loaded or not, it helps to make knowledgeable decisions about when to replace motors and which replacements to choose. Let us briefly discusses several load estimation techniques as follow [11]:

1. Input Power Measurements Method:

When direct-read power measurements are available, use them to estimate motor part-load. With measured parameters taken from hand-held instruments, Equation 2.9 can be used to calculate the three-phase input power to the loaded motor. Then the motor's part-load can be computed by comparing the measured input power under load to the power essential when the motor operates at rated capacity. The relationship is shown in Equation 2.11 [11].

Measuring the motor's actual power delivers a convenient and accurate way to decide the load. In this case, the motor's measured kW (or V, PF and I) is required.

Measurements Required:

$$P_{input\ measured} = P_{im} = \text{Measured motor load, kW (from the instrument)}$$

OR

I = Measured RMS motor current, average of 3-phases

V = Measured average RMS line-to-line voltage

PF = Measured power factor

Inputs Required:

hp = Motor's rated power output, hp (or kW)

η_{fl} = Motor's full load rated efficiency

Formula:

With measured parameters taken, use Equation 2.9 to calculate the three-phase input power to the loaded motor.

$$P_{im} = \frac{\sqrt{3} \times V \times I \times PF}{1000} [kW] \quad (2.9)$$

$$P_{ir} = \frac{hp \times 0.746}{\eta_{fl}} [kW] \quad (2.10)$$

Where,

P_{ir} = Motor's power input at rated full load [kW]

Therefore,

$$Load = \frac{P_{im}}{P_{ir}} \times 100\% \quad (2.11)$$

Where,

$Load$ = Output power as a % of rated power

With Equation 2.10, the exact efficiency (η_{fl}) is almost never known, but there are several ways to reach at a rational estimate. One way is to refer to motor manufacturer's literature or motor nameplate data.

2. Voltage Compensated Current Ratio Method:

This method assumes that the percentage of load is closely proportional to the percentage of the ratio of measured current to full load current. The amperage draw of a motor varies almost linearly with respect to load, down to approximately 50 - 60% load. Below this load range, magnetizing current desires and other ineffectiveness cause increasing non-linearity. Therefore, if the nameplate full-load current is known and the actual current is measured, one can estimate the motor load. As with rated speed in the slip calculations, the rated full load current is based on operation at the rated voltage. If the actual operating voltage is different from the rated voltage, the full-load current must be corrected [11].

Measurements required:

I = Measured RMS motor current, average of 3-phases

V = Measured average RMS voltage, mean line-to-line of 3-phases

Input required:

I_r = Name plate rated current at full load

V_r = Name plate rated voltage at full load

Formula:

The equation that relates motor load to measured current values is shown in Equation 2.12.

$$Load = \frac{I}{I_r} \times \frac{V}{V_r} \times 100\% \quad (2.12)$$

Where,

$Load$ = Output power as a % of rated power

3. Slip Method:

Slip is the variance between synchronous and shaft speed. A motor's speed and slip is comparative to its load. The amount of slip present is proportional to the load imposed upon the motor by the driven apparatus [11].

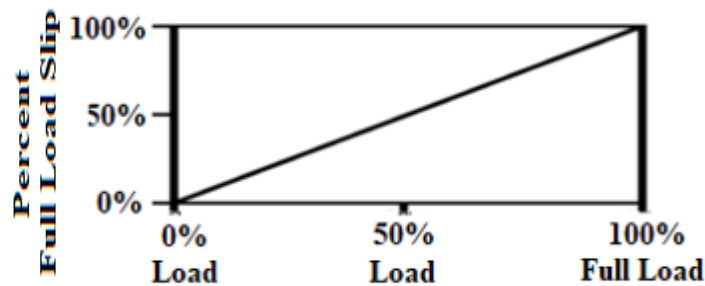


Figure 2-3: Percent Motor Slip as Function of Motor Load [Taken from a fact sheet, US Department of Energy] [11]

The synchronous speed of an induction motor is usually accessible from motor nameplate rating or can be calculated. It depends on the frequency of power supply and on the number of poles for which the motor is wound.

Measurements required:

S = Measured motor speed, RPM

Inputs required:

S_s = Motor's synchronous speed (RPM)

S_r = Motor's nameplate full load speed (RPM)

P = Number of poles

f = Frequency in Hz

Formula:

The motor load can be expected with slip measurements as shown in Equation 2.13.

$$Load = \frac{Slip}{S_s - S_r} \times 100\% \quad (2.13)$$

Where,

Load = Output power as a % of rated power

$$Slip = S_s - S \quad (2.14)$$

$$S_s = \frac{120 \times f}{P} \quad (2.15)$$

Energy Efficiency Opportunities in Electric Motors

When planning to increase the efficiency of the motor system in an industry, a system method including pumps, compressors, and fans must be used in order to achieve optimum savings and performance. Consideration with respect to energy use and energy saving chances for a motor system are discussed as follow.

a) Replacing Under Load Motors with Proper Sized Motors

Possibly the utmost common practice contributing to less motor efficiency is that of under loading. Under loading effects in lower efficiency, power factor and higher than required first cost for the motor and associated control equipment.

Under loading rises motor losses and reduces motor efficiency and the power factor. Under-loading is the most common reason of inefficiencies for numerous causes:

- ✓ Apparatus producers tend to use a big safety factor when choosing the motor.
- ✓ Equipment is often under-utilized. For example, machine tool apparatus producers offer for a motor rated for the full capacity load of the equipment. In reality, the user may rarely want this full capacity, causing in under-loaded operation most of the time.
- ✓ Large motors are designated to allow the output to be retained at the preferred level even when input voltages are unusually low.
- ✓ Large motor is chosen for applications demanding a high starting torque but where a smaller motor that is designed for; high torque would have been more appropriate.

Motor size should be carefully chosen based on a cautious evaluation of the load. However, when substituting an oversized motor with a smaller motor, it is also significant to consider the potential efficiency achievement. Larger motors namely have essentially higher rated efficiencies than smaller motors. Therefore, the replacement of motors operating at 60 – 70% of capacity or higher is generally not recommended. If the plant's motor functions under 50% of full rated load, it considers to replace large, partially loaded motors with lesser, full loaded motors either from company index or new energy efficient motor.

On the other hand, there are no firm rules governing motor selection and the savings potential desires to be estimated on a case-by-case foundation [12].

b) Replace Standard Motors with Energy Efficient Motors

High efficiency motors have been designed specially to rise operating efficiency compared to standard motors. Design enhancements emphasis on decreasing intrinsic motor losses and contain the use of lower-loss silicon steel, a longer core, thicker wires, thinner laminations, smaller air gap between stator and rotor, copper instead of aluminium bars in the rotor, superior bearings and a smaller fan, etc. Energy efficient motors cover a wide range of ratings and the full load. Efficiencies are 3% to 7% higher compared with standard motors as shown in Figure 2-4, for a typical three-phase induction motor.

Due to the changes in improving performance, the costs of energy efficient motors are greater than standard motors. The greater cost will often be paid back quickly through reduced operational costs, particularly in new applications or end-of-life motor replacements. However, replacing existing motors that have not reached the end of their useful life with energy efficient motors may not always be financially feasible, and therefore it is recommended to only replace these with energy efficiency motors when they fail [9].

Though high efficiency motors typically cost 30% more than standard motors, the reduced electricity usage can offset the higher capital costs in a short period. An industrial motor can use electricity worth about four times its capital cost yearly. Shifting to high efficiency models produces larger efficiency enhancements and percentage cost savings in the small motor sizes, but greater absolute cost savings in the large. Larger motors are often rewound, not substituted, when they failure. Rewinding is at first less expensive than purchasing a new motor, but eventually costs more because of degraded efficiency. The efficiency of a rewind motor is typically about 2% points below that of a new standard motor [13].

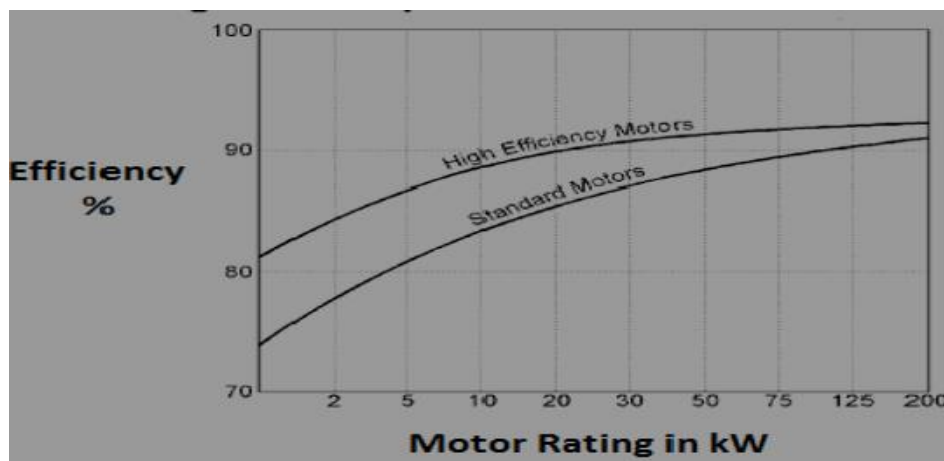


Figure 2-4: Typical Efficiencies of Standard and Energy Efficient Motors (Taken from Bureau of Energy Efficiency Publications)

Motor Master + international (IMSSA) Software

The International Motor Selection and Analysis (IMSSA), helps motor controlling functions at commercial and institutional services, water supply and wastewater handling systems, irrigation areas, and medium-sized and large industrial services. Motor Master + international software can support in appropriate motor selection and helps for motor systems enhancement scheduling, through recognising the cost effectiveness, operating cost due to the continual operation of an existing standard efficiency motor to make decision on buying new premium efficiency, rewinding or replacing of the existing motor. This software aids on motor selection and analysis of the saving potential as the outcome of comparison of the existing motor with efficient motor.

U.S department of energy's best practices program provides the software for the purpose of [14]:

- ✓ Estimating the performance of the existing motor with the appropriate energy efficient motors.
- ✓ In judgments concerning replacement of oversized and under loaded motors.
- ✓ Demand attention to a life-cycle cost approach to motor replacement judgements.
- ✓ Support motor users in choosing the appropriate motor for an application.
- ✓ Increase consciousness of electric motor system efficiencies.

Motor Master + international software uses field data measurements of a motor as input parameters for the existing motor in a factory. In addition, field data measurements and the purchase price for the energy efficient motors column taken from the Motor Master + international software catalogue. Table 2-4 shows, the input and output field data

measurements for analysis saving potential of electric motor using Motor Master + international software. These values are chosen in such a way to increase the loadings of the existing operation. The output parameters that can get from the software are energy, demand savings and a simple back period. In this part the saving potential of electrical energy and cost of energy are found by evaluating of the electric motors and looking for alternative options to increase the efficiency of the existing motors.

Table 2-4: Input and Output Field Data Measurements of Motor Master Software

Existing Motor Input Data	Energy Efficient Motor Input Data (Software catalogue)	Output parameters
Power Rating (kW)	Power Rating (kW)	Energy Saving (kWh)
Loading (%)	Loading (%)	Demand Saving (kW)
Efficiency (%)	Efficiency (%)	Simple pay-back period (yrs.)
Name Plate Speed (RPM)	Name Plate Speed (RPM)	-
Voltage Rating (V)	Voltage Rating (V)	-
-	Purchase Price (US \$)	-

c) Improving Motor Maintenance

The purposes of motor maintenance are to increase motor life span and to forecast a motor failure. Motor maintenance procedures can be categorized as either preventive or predictive. The aim of preventative measures is to prevent unexpected downtime of motors, include electrical consideration, voltage unbalance minimization, load consideration, and motor ventilation, alignment, and lubrication. The aim of predictive motor maintenance is to detect on going motor temperature, vibration, and other operational facts to recognise when it becomes essential to repair or substitute a motor before failure occurs. The savings related with an on-going motor maintenance program are important, and could range from 2% to 30% of total motor system energy use [31].

2.4 Air Compressor

▪ Free Air Delivery (FAD) Test For Air Compressors

FAD test for compressors can be carried out in two ways:

1. Pump-up Method
2. Suction Velocity Method

The second method takes suction side and hence does not need process intervention. Although the pump up method is better for its precise results, the suction velocity method is employed in this thesis. The suction velocity method takes in intake air velocity and suction area in a given time to yield amount of compressed air in cubic feet per minute, cfm or m³/hour.

The recommended procedures and essential formulas for the FAD test of air compressor are summarized as the follow [36].

Average Velocity, V_{av} :

$$V_{av} = \left(\frac{V_1 + V_2 + V_3 + \dots + V_n}{n} \right) \quad (2.16)$$

Where,

V_n = n numbers of velocity measurements

Area of the Air Inlet Tube (A):

$$Area (A) = \pi r^2 \text{ (Assuming a circle tube)} \quad (2.17)$$

The Actual Inlet Air Flow (Q_{actual}) :

$$Q_{actual} = V_{av} \times A \quad (2.18)$$

Note that the rated inlet air flow , Q_{rate} , can be determined from the name plate of the air compressor.

Average Input Power (Loading Power), P_{av} :

$$P_{av} = \left(\frac{P_1 + P_2 + P_3 + \dots + P_n}{n} \right) \quad (2.19)$$

Where,

P_n = n numbers of input power measurements

Actual Specific Power Consumption (SPC_{actual}) Per cfm (SPC/cfm):

$$SPC_{actual} = \frac{P_{av}}{Q_{actual}} \quad (2.20)$$

Average Loading Time (T_{Lav}):

$$T_{Lav} = \left(\frac{T_{L1} + T_{L2} + \dots + T_{Ln}}{n} \right) \quad (2.21)$$

Where,

T_{Ln} = n numbers of measured loading time in second

Average Un-Loading Time (T_{ULav}):

$$T_{ULav} = \left(\frac{T_{UL1} + T_{UL2} + \dots + T_{ULn}}{n} \right) \quad (2.22)$$

Where,

T_{ULn} = n numbers of measured un-loading time in second

Percent of Leakage During Loading Time (Leak, Load):

$$\% \text{ Leak, Load} = \frac{T_{Lav}}{T_{Lav} + T_{ULav}} \quad (2.23)$$

Percent of Leakage During Un-Loading Time (Leak, Un-Load):

$$\% \text{ Leak, Un - Load} = \frac{T_{ULav}}{T_{Lav} + T_{ULav}} \quad (2.24)$$

The Leak Quantity During Loading Time (LQ_{Load}):

$$LQ_{Load} = Q_{actual} \times \% \text{ Leak, Load} \quad (2.25)$$

Amount of Leakage in kW (Power Loss due to Leakage = ΔkW_1 , during Loading):

$$\text{Leak (kW)} = \Delta kW_1 = SPC_{actual} \times LQ_{Load} \quad (2.26)$$

Design SPC:

$$\text{Design SPC} = \frac{P_{nameplate}}{Q_{nameplate}} \quad (2.27)$$

Change in SPC (ΔSPC):

$$\Delta SPC = (SPC)_{Actual} - (SPC)_{Design} \quad (2.28)$$

Power Loss due to SPC deviation (ΔkW_2):

$$\Delta kW_2 = \Delta SPC \times Q_{actual} \quad (2.29)$$

Total Power Loss:

$$\text{Total Power Loss} = \Delta kW_1 + \Delta kW_2 \quad (2.30)$$

Efficiency (η) of the Air Compressor:

$$\eta = 1 - \frac{\text{Total Loss}}{P_{av,input}} \quad (2.31)$$

Annual Energy (E_{LA}) and Money Loss (M_{LA}):

$$E_{LA} = \text{Total Power Loss} \times \frac{\text{No.of Working days}}{\text{year}} \times \frac{\text{No.of Working hours}}{\text{day}} \quad (2.32)$$

$$M_{LA} = \text{Energy Loss}_{Annual} \times \frac{US \$}{kWh} \quad (2.33)$$

2.5 Boiler

Performance of the boiler decreases with time, due to poor combustion, heat transfer fouling and poor operation and maintenance. Deterioration of fuel quality and water quality also leads to poor performance of boiler. Efficiency testing supports us to find out how far the boiler efficiency drifts away from the best efficiency. Any observed unusual deviations could be examined to pinpoint the problem area for essential corrective action. Hence, it is crucial to find out the current level of efficiency for performance evaluation, which is a pre requisite for energy conservation action in industry [33].

Boiler Efficiency Evaluation

Boiler efficiency (η) can be calculated in one of the two ways, direct or indirect method. The direct method uses only a few and readily available parameters to yield the efficiency of a boiler with rational precision [33].

1. Direct Method:

$$\eta = \frac{Q(H_g - H_f)}{q \times GCV} \times 100 \quad (2.34)$$

Where,

Q = Quantity of steam generated per hour [ton/hr]

H_g = Enthalpy of saturated Steam [kCal/kg]

H_f = Enthalpy of feed water in [kCal/kg]

q = Quantity of fuel used per hour

GCV = Gross calorific value of fuel

2. Indirect Method:

The efficiency can be measured easily by measuring all the losses happening in the boilers. The drawbacks of the direct method can be overwhelmed by this method, which calculates the numerous heat losses related with boiler. The efficiency can be arrived at, by subtracting the heat loss fractions from 100. An essential benefit of this method is that the errors in measurement do not make major change in efficiency.

The indirect method computes the efficiency taking into account several losses such as:

- Heat loss due to dry flue gas (LDFG)
- Heat loss due to H₂ in fuel (LH₂F)
- Heat loss due to moisture in fuel (LMF)
- Heat loss due to moisture in air (LMA)
- Heat loss due to incomplete combustion (LIC)
- Surface radiation and convection (LRC)

Taking these losses into account the boiler efficiency becomes:

$$\eta = 100 - (LDFG + LH_2F + LMF + LMA + LIC + LRC) \quad (2.35)$$

2.6 Power Quality

The word power quality refers to the characteristics of the voltage and current at a given time and location on a power system. It is the measure, analysis, and enhancement of bus voltage, commonly a load bus voltage, to preserve that voltage to be a sinusoid at rated voltage and frequency. The nature of equipment being used by the end user affects power quality at the end-user level.

Power quality problem can be well defined as any power problem expressed in voltage, current, or frequency variations that result in let-down or misused operation of utility or end user equipment.

Variations in Voltage:

Voltage variation is a consistent change in voltage that occur when devices or equipment demanding a higher load is used. This power problem can have a substantial consequence on the lifetime of electrical devices. There are two forms of variations in the voltages [34]:

1. Short-Duration Voltage Variation

Short duration voltage deviations are commonly produced by errors or faults in the power system. It actually depends on what type of fault is produced in the power system under what circumstance, which may lead to voltage drops, voltage rise and even disturbances in certain circumstances. When such faults occur, protective devices are used in order to avoid the fault. However, the effect of voltage during such faulty conditions is of short-duration deviation. The short duration voltage deviations are more divided into three different groups i.e. interruptions, sags and swell.

Interruption: When there are declines in the voltage or current supply interruptions occur. Interruptions may happen due to several causes; some of them being faults in the power system, failures in the apparatus and occurs when the supply voltage or load current declines to less than 0.1 pu for a period of time not beyond 1 min. The interruptions are measured by their period, as the voltage magnitude is always below 10% of nominal. Utility protective devices and the specific occasion that is triggering the fault decide the duration of an interruption because of a fault on the utility system. The period of an interruption due to device failures or loose connections can be asymmetrical. The interval of the interruption will be determined by the reclosing ability of the protective device.

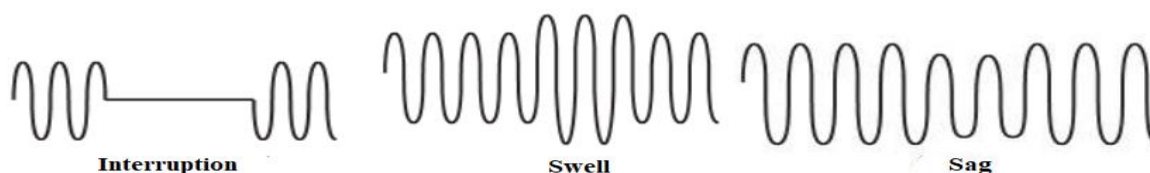


Figure 2-5: Short Duration Voltage Variations [34]

Sags (Dips): It is a short period voltage deviation. When there is a reduction between 0.1 and 0.9 per unit in RMS, voltage sagging occur. There are several means to find the magnitude of sagging from the RMS voltages. Most of the times lowermost value achieved during the event are assumed. Sagging usually has fixed RMS value during the deep part of the sag. Thus, lowest value is a suitable estimated value terminology used to define the magnitude of voltage sag is often unclear. The suggested usage is “a sag to 20%,” which means that the line voltage is reduced down to 20% of the normal value, not reduced by 20%. Using the preposition “of” (as in “a sag of 20%,” or implied in “a 20% sag”) is deprecated. This choice is reliable with IEC practice, and with most disturbance analysers that also report remaining voltage. Voltage sags are commonly related with system faults but can also be triggered by switching of heavyweight

loads or starting of large motors. Typical fault clearing times varies from 3 to 30 cycles, depending on the fault current amount and the kind of overcurrent detection and interruption. Heavy load changes or motor starting can as well cause voltage sags. An induction motor will draw six to ten times its full load current during starting. This lagging current causes a voltage drop across the impedance of the system.

Swells: It is a rise in RMS voltage or current at the power frequency for periods from 0.5 cycles to 1 min. typical scales are between 1.1 and 1.8 per unit. Swell magnitude is moreover defined by its remaining voltage, in this case, at all times greater than 1.0. As with sags, swells are commonly related with system fault situations, but they are much less common than voltage sags. A swell can happen because of a single line-to-ground fault on the system causing in a momentary voltage increase on the unfaulty phases. Swells can as well be produced by switching off a huge load or switching on a large capacitor bank. Swells are categorised by their magnitude, RMS value, and duration. The severity of a voltage swell throughout a fault condition is a function of the fault place, system impedance, and grounding.

2. Long Duration Voltage Variations

Long duration voltage deviations are consist of over voltages plus under voltage conditions. These under voltage and over voltage conditions are triggered by variations in the power system and not essentially because of the faults in the system. The long duration voltage deviations imply the steady state condition of the RMS voltage of the power system. The long duration voltage variations are further grouped into three different types i.e. interruptions, over-voltage and under-voltage.

Over-Voltage: Over voltages can be the outcome of load switching (e.g., switching off a large load), or deviations in the reactive compensation on the system (e.g., switching on a capacitor bank). Poor voltage regulation abilities or controls result in over voltages. Improper tap settings on transformers can also effect in system over voltages. Related to the under voltage condition, over voltage is a rise in the RMS ac voltage to greater than 110% of the power system for some extent of time.

Under-Voltage: There are several causes for the under voltage situations in the power system. When there is a reduction in the RMS ac voltage to less than 90% of a power system for some amount of time then under voltage circumstance occurs. Load switching on or switching off a capacitor bank can furthermore reason for under voltage condition. Besides, when a power system is over loaded it may effect into under voltage condition.

Sustained Interruptions: It is the decline to zero of the supply voltage for a period in excess of 1 min. Voltage interruptions longer than 1 min are often long-lasting in nature and need manual involvement for reestablishment. Continued interruptions are specific power system phenomena and are not related to the usage of the term outage.

3. Voltage Imbalance

Voltage imbalance or voltage unbalance is the ratio of the negative or zero sequence components to the positive sequence component. The negative or zero sequence voltages in a power system are commonly outcome from unbalanced loads triggering negative or zero sequence currents to flow. Imbalance can be assessed as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three phase voltages or currents, expressed in percent.

For example, with phase-to-phase voltage readings of 230V, 232V, and 225V, the average is 229V. The maximum deviation from the average among the three readings is 4V. The percent imbalance is $100 * 4V / 229V = 1.7\%$. The primary source of voltage imbalance less than 2% is unbalanced single-phase loads on a three-phase circuit. Voltage imbalance can also be the outcome of capacitor bank abnormalities, such as a blown fuse on one phase of a three-phase bank. Severe voltage imbalance, greater than 5%, can result from single-phasing conditions.

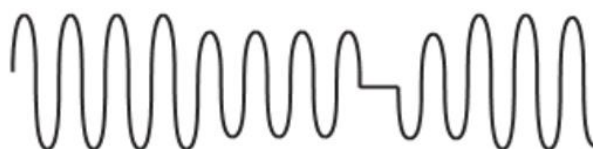


Figure 2-6: Imbalance Waveform [34]

4. Power Frequency Variations

The power system frequency is directly associated to the rotational speed of the generators on the system. At any instant, the frequency rest on the balance between the load and the capacity of the available generation. When this dynamic balance changes, small changes in frequency happen. The size of the frequency shift and its duration depends on the load characteristics and the response of the generation system to load changes. Frequency deviations that go outside of conventional limits for normal steady state operation of the power system are usually triggered by faults on the bulk power transmission system, a large block of load being disconnected or a large source of generation going off-line.

5. Harmonics

Harmonics are non-sinusoidal voltages or currents having frequencies that are integer multiples of the frequency at which the supply system is designed to operate, termed the fundamental frequency; usually 50 Hz or 60 Hz. Harmonics combine with the fundamental voltage or current, and yield waveform distortion. Harmonic distortion occurs due to the non-linear characteristics of devices and loads on the power system. Harmonics are one of the main concerns in a power system. Harmonics are sources of distortion in current and voltage waveforms ensuing into deterioration of the power system. The first step for harmonic analysis is the harmonics from non-linear loads. Non-linear loads as the cause of harmonics are considered. The application of sinusoidal voltage does not result in a sinusoidal flow applied sinusoidal voltage for non-linear devices. The non-linear loads draw a current that may be discontinuous. Harmonic current, by using harmonic filters to protect the electrical equipment from damage due to harmonic voltage distortion, can be isolated. Furthermore, it can advance the power factor. The risky and harmful effects of harmonic distortion can be evident in many diverse ways such as electronics mistiming, increased heating effect in electrical equipment, capacitor overloads.

There can be two kinds of filters used in order to decrease the harmonic distortion i.e. the active filters and the passive filters. Active harmonic filters are electronic devices that remove the unwanted harmonics on the network by inserting negative harmonics into the network. The active filters are usually available for low voltage networks. The active filters comprise of active components such as IGBT-transistors and eradicate several and different harmonic frequencies. The signal forms can be single-phase AC, three-phases AC. In contrast, passive harmonic filters comprise of passive components such as resistors, inductors and capacitors. Unlike the active filters, which used only for low voltages, the passive filters are commonly used and are available for different voltage levels.

2.6.1 Power Quality Standards

Institute of Electrical and Electronics Engineers (IEEE) has come out with standards and guiding principle regarding harmonics. One of the standards, IEEE Standard 519-1992, offers comprehensive recommended guidelines on investigation, assessment and measurement of harmonics in power system. The standard encompasses steady state limits on current harmonic and harmonic voltages at all system voltage levels. The boundary or limit was set for a steady

state operation and for worst-case scenario [13]. The IEEE power quality standards of different power quality problems are given through Tables 2-5 through Table 2-7.

Table 2-5: Current Distortion Limit for General Distribution Systems (120V- 69kV) [13]

Maximum Harmonic Current Distortion in Percent of I_L						
$\frac{I_{SC}}{I_L}$	$h < 11$	$11 \leq h < 17$	$17 \leq h < 23$	$23 \leq h < 35$	$h < 35$	$TDD(\%)$
≤ 20	4.0	2.0	1.5	0.6	0.3	5.0
$20 < 50$	7.0	3.5	2.5	1.0	0.5	8.0
$50 < 100$	10.0	4.5	4.0	1.5	0.7	12.0
$100 < 1000$	12.0	5.5	5.0	2.0	1.0	15.0
> 1000	15.0	7.0	6.0	2.5	1.4	20.0

h = Odd harmonic order. I_{SC} = Maximum short-circuit at the common point of coupling (PCC)
 I_L = Maximum demand load current (fundamental frequency component) at PCC, TDD = Total Demand Distortion, Even harmonic are limited to 25% of the odd harmonic limits above.

Table 2-6: Voltage Distortion Limits

Bus Voltage at PCC	Individual Voltage Distortion (%)	Total Voltage Distortion, THD_V (%)
69kV and below	3.0	5.0
69.001kV through 16kV	1.5	2.5
161.001kV and above	1.0	1.5

Table 2-7: The IEEE Power Quality Standards of Different Power Quality Problems

Problem Classification	Standard
Voltage-Sag	0.1-0.9 Pu
Voltage-Swell	1.1-1.8 Pu
Under voltage	0.8-0.9 Pu
Overvoltage	1.1-1.2 Pu
Voltage Unbalance	< 3%
Dc Offset	0-0.1%
Harmonics (THD_V)	< 5%
Harmonics (THD_I)	< 10%
Power Factor	0.85 -1
Power Frequency Variation	$50 \pm 0.5\%$
Current unbalance	< 10%

2.6.2 Voltage and Current Unbalance Factor

The voltage and current unbalance factors of the factory distribution systems are determined based on the line-to-line measurement. According to the NEMA (National Electrical Manufacturers Association of USA) standard voltage or current unbalance is well defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percentage, which is given by the following Equation 2.36.

% Voltage Unbalance (% V_{un}):

$$\%V_{un} = \frac{\text{Maximum deviation from mean of } (V_{12}, V_{23}, V_{31})}{\text{Mean of } (V_{12}, V_{23}, V_{31})} * 100\% \quad (2.36)$$

2.6.3 Power Frequency Variation

The electric power network is designed to function at a definite value of frequency, 50 Hz. If there is any imbalance in the supply and demand, the frequency deviations will produced. The failure of a generator or sudden switching of loads causes large variations in the frequency.

The allowable value of power frequency deviations based on the IEEE standard for normal operation is ± 0.5 (49.5 Hz to 50.5 Hz at 50 Hz nominal frequency).

2.6.4 Power Flicker

Voltage fluctuations can be a reason for light intensity fluctuations perceived by our brains. This effect, popularly known as flicker, can cause substantial physical discomfort. More specifically, flicker is the impression of instability of visual sensation convinced by a light stimulus whose luminance or spectral distribution properly fluctuates with time [14].

From the instantaneous flicker values, the following indices characterizing the intensity of flicker annoyance, the short-term flicker severity and the long-term flicker severity. The short-term flicker severity (P_{st}) is measured over a period of ten minutes. The long-term flicker severity (P_{lt}) calculated from a sequence of 12 P_{st} values over a two-hour interval, according to the Equation 2.37:

$$P_{lt} = \sqrt[3]{\frac{\sum_{i=1}^{12} P_{sti}^3}{12}} \quad (2.37)$$

In IEC 61000-3-7-1996, states the boundary or limit for the short- term flicker and the long-term flicker as a result the limits are $P_{st} = 1.0$ and $P_{lt} = 0.8$ [14]. P_{sti} is a short- term flicker severity and measured over the interval of 10 minutes.

2.6.5 Harmonics

The foremost industry standard used for harmonics in power systems is IEEE Std 519-1992. This standard was established through the IEEE Industry Applications Society and the IEEE Power Engineering Society. Through the combined work of these two societies, IEEE Std 519-1992 advises limits on the harmonic currents that a user can make back into the utility power system and also identifies the quality of the voltage that the utility should supply the user.

- **Sources and Effects of Harmonic Currents in Industries**

Harmonic current productions come from all kinds of non-linear loads. Non-linear loads are loads, which draw non-sinusoidal current even when the supply voltage is perfectly sinusoidal. Non-linear loads comprise saturated magnetic circuits, such as those in power system transformers and rotating machines, arc-furnaces, fluorescent lighting and of course power electronic loads. Power electronic loads definitely are the major harmonic providers relative to the amount of energy they draw [15].

Current distortions results from non-linear loads have a major adverse influence on both power system apparatuses and customer devices. These special effects may result into long-lasting harm of the devices. The effects of harmonics in the industry varies from fake or false actions and trips of fuses and circuit breakers, overheating of transformers because of the rise in copper and core losses. The destructive effects of harmonics on transformers frequently unobserved until an actual failure occurs and increased heating in motors caused by extra copper losses and iron losses in the stator winding, rotor circuit and rotor laminations.

- **Total Demand Distortion (TDD)**

Harmonic distortion is utmost significant when checked at the PCC, commonly the customer's metering point, over a period that can show maximum customer demand, typically 15 to 30 minutes as advised in IEEE-519 standard. Weak sources with a large demand current in relation to their rated current will tend to indicate greater waveform distortion. Contrary, rigid sources characterized for working at small demand currents will show reduced waveform distortion. The total demand distortion is based on the demand current, I_L over the monitoring period [16].

$$TDD(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} (I_h)^2}}{I_L} \times 100 \quad (2.38)$$

Where,

I_h = Individual harmonic current

I_L = Maximum fundamental load current.

▪ Harmonic Mitigation using Harmonic Filters

Idyllically, an electricity supply should regularly show a perfectly sinusoidal voltage signal at each customer area. However, it is stiff to reserve such necessary conditions. The variation of the voltage and current waveforms from sinusoidal is defined in terms of the waveform distortion, frequently articulated as harmonic distortion [16].

A number of harmonic-mitigation methods have been suggested and applied in recent years. In this case, filters are designed for the distortions that goes above harmonic boundaries or limits set by the IEEE Standard 519-1992. There are two classes of filters used for filtering the harmonic distortions: passive filters and active filters [16].

a) Passive Filters

Passive filters comprise inductance, capacitance, and resistance elements configured and tuned to regulate harmonics. They are frequently used and are relatively low-cost associated with other methods for removing harmonic distortion. They are engaged either to shunt the harmonic currents off the line or to block their flow between parts of the system by tuning the elements to produce a resonance at a selected frequency [15].

The most common type of passive filter is single-tuned notch filter, shown in Figure 2-7 (a), which is the most inexpensive and commonly used. In the single-tuned filter circuit, a capacitor and inductor are series connected. This filter is also known as low pass filter. The filter is single-tuned to present low impedance to a specific harmonic current. It is in shunt connection with the power system there by diverting the harmonic currents from their normal flow path on the line into the filter. Notch filter can offer power factor correction besides to harmonic suppression [15]. The first order high pass filter, in the Figure 2-7, not normally used, as it needs a large capacitor and has extreme loss at fundamental frequency. The second order high-pass filter offers the best filtering performance, but has higher fundamental frequency losses as compared with the third order. The third order high-pass filter's key benefit over second order is a significant decrease in fundamental frequency loss, owing to increased impedance at that

frequency triggered by the presence of the capacitor C_2 . In addition, the rating of C_2 is minor compared with C_1 .

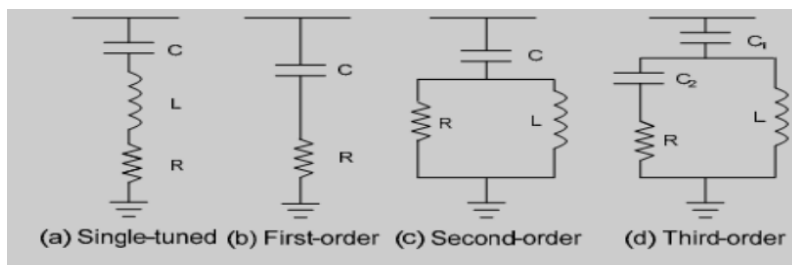


Figure 2-7: Common Passive Filter Configurations [16]

a) Active Filters

Active filters are relatively new categories of devices for removing harmonics. They are based on sophisticated power electronics and are much more expensive than passive filters. They are designed to inject harmonic currents to counterbalance the present harmonic components as they show up in the distribution system [15]. Nevertheless, they have a separate benefit that they do not resonate with the system. They can address more than one harmonic at a time and combat other power quality problems such as flicker. They are mainly valuable for large, distorting loads from relatively weak points on the power system. Most of the time active filters are used in very hard conditions where passive filters cannot function effectively.

In this thesis, passive filters are designed as actual solution for power system harmonic mitigation because passive filters are relatively cheap as compared to active filters.

▪ Single-Tuned Harmonic Filters and their Design

This section shows a procedure for designing harmonic filters for industrial applications. Passive filters all the time provide reactive compensation to a degree dictated by the volt-ampere size and voltage of the capacitor bank used, they could in fact be designed for the dual purpose of providing the filtering action and compensating power factor to the desired level. These passive filters presents very low impedance, with respect to line impedance, at the tuning frequency, through which all current of that specific frequency will be diverted. Despite its reactive power compensation advantage, a single-tuned shunt filter can only eradicate a single current harmonic component. Therefore, for a wide range generated harmonics a single tuned filter is to be designed for each current harmonic to be suppressed, individually.

This means multiple single-tuned filters are designed to eliminate multiple harmonics, as illustrated in Figure 2-8 [17].

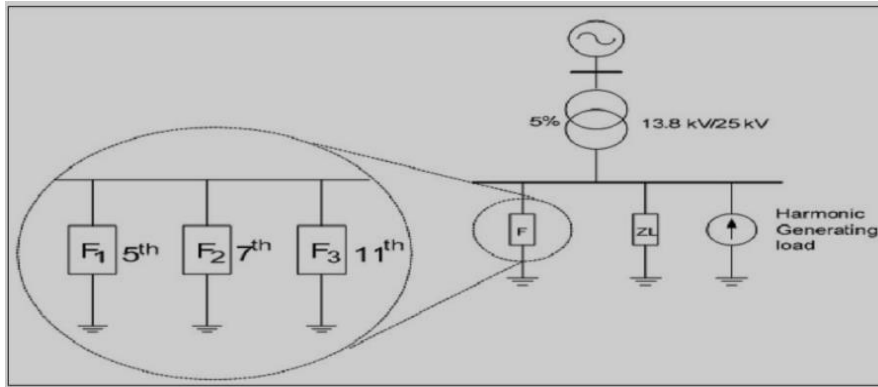


Figure 2-8: Three-branch Single Tuned Filters [17]

This section presents design procedures and equations of single-tuned filters. The main components of a harmonic filter are the capacitors (C), reactor (L), and a damping resistance (R) if necessary. The series-connected resistance decides the sharpness of the filtering action. However, it is usually ignored because the value of R usually results in a significant increase in losses within the filter. Therefore, the value of R comprises only of the internal resistance of the inductor.

The process of designing a filter is a compromise among numerous factors: low maintenance, economy and reliability. The design of the simplest filter that does the required job is what will be sought in the majority of cases.

The recommended ways for the design and validation of single-tuned harmonic filters are summarized as the following [16].

1. Select capacitor bank necessary to increase the power factor from the present low level to a higher level, near one.

The capacitive reactance required to compensate the needed VAR to increase the power factor from PF_1 (associated with θ_1) to PF_2 (associated with θ_2) is given by:

$$Q_{com} = P(\tan \theta_2 - \tan \theta_1) \tag{2.39}$$

Where, P the active power and Q_{com} is the reactive power required for compensation. The capacitance for a single filter can be set to [18].

$$Q_f = Q_{com} \tag{2.40}$$

For a multiple parallel single-tuned filter system, the capacitance corresponding to the h_{th} harmonics can be distributed as follow [18].

$$Q_{fh} = Q_{com} \times \frac{I_h}{I_2 + I_3 + \dots}, h = 2,3, \dots \tag{2.41}$$

Where, I_h is the h_{th} harmonic current and Q_{fh} is the capacity of the h_{th} harmonic filter. In addition, the filter capacity Q_{fh} contains the capacity of capacitance (Q_C) and capacity of inductor (Q_L),

$$Q_C = \frac{h^2}{h^2 - 1} \times Q_{fh} \quad (2.42)$$

$$Q_L = Q_C - Q_{fh} \quad (2.43)$$

$$Q_L = \frac{1}{h^2} \times Q_C \quad (2.44)$$

2. Choose reactor that, in series with capacitor, tunes filter to desired harmonic frequency.

The use of an inductor in series with a capacitor effects in a voltage rise at the capacitor terminals given by:

$$V_C = \left(\frac{h^2}{h^2 - 1} \right) \times V_{sys} \quad (2.45)$$

Where,

h = tuned impedance harmonic order of the frequency

V_{sys} = system line-to-line voltage, kV

V_C = capacitor line-to-line voltage, kV

The capacitive reactance required is obtained with the following relation:

$$X_{c1} = \frac{V_C^2}{Q_C} \quad (2.46)$$

At harmonic frequency h , this reactance is:

$$X_{ch} = \frac{X_{c1}}{h} \quad (2.47)$$

In addition, the inductive reactance at frequency of order h is given by:

$$X_{Lh} = hX_{L1} \quad (2.48)$$

At the resonant frequency, the capacitive and reactive impedances are equal. The following Equation 2.49 relates X_L and X_C as follow:

$$X_L = \frac{X_c}{h^2} \quad (2.49)$$

3. Decide whether capacitor-operating parameters fall within IEEE-18 maximum recommended limits. This may need a number of iterations until desired reduction of harmonic level is reached.

a. Capacitor Voltage: The RMS and peak voltage of the capacitor must not exceed 110% and 120%, respectively, of the rated voltage. They can be determined as follows:

$$V_{cpeak} = \sqrt{2}(V_{c1} + V_{ch}) \quad (2.50)$$

$$V_{crms} = \sqrt{(V_{c1}^2 + V_{ch}^2)} \quad (2.51)$$

Where voltage through the capacitor at fundamental frequency is given by:

$$V_{c1} = X_{c1}I_{c1} \quad (2.52)$$

V_{ch} is found in terms of I_{ch} , which must be determined from measurements or from a typical harmonic spectrum of the corresponding non-linear load.

$$V_{ch} = X_{ch}I_{ch} \quad (2.53)$$

I_{c1} is the current through the capacitor and it is calculated in terms of the maximum phase - to-neutral voltage, which in turn is specified 5% above the rated value, to account for voltage regulation practices:

$$I_{c1} = (1.05) \frac{V_{L-N}}{(X_{c1} - X_{L1})} = (1.05) \left[\frac{\left(\frac{V_{L-L}}{\sqrt{3}}\right)}{(X_{c1} - X_{L1})} \right] \quad (2.54)$$

b. Current through the capacitor bank: The RMS current through the capacitor bank must be within 135% of the rated capacitor current, to meet with IEEE-18. Its value is determined from the fundamental current and from the harmonic currents under consideration:

$$I_{crms} = \sqrt{(I_{c1}^2 + I_{ch}^2)} \quad (2.55)$$

c. Determine the capacitor bank duty and verify that it is within recommended IEEE-18 limits.

$$kVAR = \frac{V_{crms}I_{crms}}{1000} \quad (2.56)$$

Where, V_{crms} is the voltage through the capacitor calculated in Equation 2.51 and I_{crms} is the current through the capacitor of Equation 2.55. This value must be within 135%. Table 2-8, summarises the maximum recommended values.

Table 2-8: Maximum Recommended Limits for Continuous Operation of Shunt Capacitors under Contingency Conditions [IEEE-18] [16]

VAR	135%
RMS voltage	110%
Rated voltage, including harmonics	120%
RMS current	135%

If IEEE-18 is not met, the process may need more than one iteration to resize the capacitor bank. For designing proper tuned filter, the IEEE-18 filter design practice for limiting harmonic and improving reactive compensation, depicted in Appendix-E, is going to be used for this thesis.

2.7 Literature Review

This study requires a vast knowledge of the issues regarding energy auditing and efficiency improvement in industries, power qualities in the industrial systems, and harmonic modelling and simulation techniques, standard limits and requirements, and results from previous studies by other researchers. All these information are necessary to address, understand and complete the research. The following sections contain brief knowledge of energy audit, power quality and reviews on thesis and previous works relevant to this research.

Jatin Gupta [3], provides information on energy-efficient technologies and production measures applicable to the textile industry. The work also includes analysis of an audit conducted on motors of different horsepower in a textile plant and contains energy saving and cost information available. For some measures, this article also provides variety of savings and payback periods found in under varying conditions. The thesis report analysis is done only on rewind induction motors for its efficiency improvement.

T. Gutowski, J. Dahmus, A. Thiriez [20], carried out some of the earliest comprehensive investing, documenting the performance measures identified in literature that relates to energy consumption which are power, energy consumed and energy consumed in processing unit

volume of material (referred to as specific energy consumption, SEC), for a wide range of manufacturing processes.

Dhayaneswaran.Y, Ashokkumar.L [21], this thesis focuses towards energy consumption at load end by improving the efficiency of the motor. In this thesis, influence of motors and process of optimisation in textile mill on energy conservation was discussed with practical data. After conducting energy audit, total energy saving per month in the textile is 56,053 kWh. Considering unit cost of Rs. 4.50, total amount Rs. 252,239 has been saved during a month.

David Yih-Liang Chan, Kuang-Han Yang, Chung-Hsuan Hsu, Min-Hsien Chien, Gui Bing Hong [22], this study conducted on-site energy audits of 314 firms in Taiwan during 2000-2004, and identified potential electricity saving, fuel oil saving, steam coal saving, and natural gas saving. Because of this study, a huge potential energy was saved, representing a reduction in the carbon dioxide emissions. Thus, it is good to take substantial measures and established an energy audit group to assist energy users in enhancing energy efficiency, reducing CO₂ emission and promoting energy savings by all industrial sectors.

Rockwell Automation (2012) [23], according to this thesis, it would be difficult for companies today to be unaware of energy use in their facilities, i.e. consumption of water, air, gas, electricity, and steam. Energy consumes an increasingly larger share of operating costs, and extracting, producing, or making anything from beverages and chemicals to machinery and raw materials-demands energy for myriad processes: prototyping, refining, processing, mixing, heat-treating, blending, stamping, painting, assembling, etc.

Ali Hasanbeigi et.al [24], this thesis aims to contribute to the understanding of energy use in the textile industry by presenting the energy use of textile plants in five major sub-sectors in Iran, i.e. spinning, weaving, wet-processing, worsted fabric manufacturing, and carpet manufacturing. The energy intensity of each plant was calculated and compared against other plants within the same sub-sector. The results presented the range of energy intensities for plants in each subsector. It also showed that energy saving/management efforts should be focused on motor driven systems in spinning plants, whereas in other textile sub-sectors thermal energy is the dominant type of energy used and should be focused on. For conducting a fair and proper comparison or benchmarking studies, factors that meaningfully influence the energy intensity across plants within each textile sub-sector are explained. Finally, lists of energy efficiency enhancement actions observed during the study are presented.

A.E. Atabani, R. Saidur, and S. Mekhilef [25], this thesis describes a comprehensive literature review about industrial energy saving by management, technologies and policies. Latest

literatures in terms of thesis (MS and PhD), journal articles, conference proceedings, web materials, reports, and books, handbooks on industrial energy management, policies and energy savings strategies have been compiled. Energy saving technologies, such as use of high efficiency motors (HEM), variable speed drives (VSD), economizers, leak prevention and reducing pressure drop. Based on these energy saving technologies results, it has been found that in the industrial sectors, a sizeable amount of electric energy, emissions and utility bill can be saved using these technologies. Payback periods for diverse energy savings measures have been recognised and found to be economically viable in most cases.

Harjit Singh Birdi, (2006) [26], this thesis designates a technique to automate the classification and analysis of the power quality events using relay recorded data. The technique uses voltage duration and magnitude (as specified in the IEEE Std. 1159 - 1995, IEEE Recommended Practice for Monitoring Electric Power Quality) of three phases to detect and classify the events. It presents the classified results in a user-friendly graphical form. Also, uses Fast Fourier Transformation (FFT) to estimate the fundamental frequency and harmonic components in power systems.

Alexandre Nassif, (2009) [17], presents an evaluation of the relative severity of the harmonic currents from power electronic-based home appliances and the effect of the discrepancy of the harmonic current phase angles. An exploration is carried out on the common filter topologies, and the most cost-effective topologies for mitigating harmonics are recognised. As many of the larger harmonic loads also generate inter-harmonics, inter-harmonics has become prevalent in today's medium-voltage distribution system. Mitigation cannot be carried out until the inter-harmonic source location is known. A method for inter-harmonic source determination is proposed and then verified through simulation and field measurement studies.

Sharmistha Bhattacharyya et.al [27], presented the influence and relations of mixed LV linear and non-linear loads on the level of harmonic distortion. The thesis used software called Dig SILENT Power Factory to simulate the LV customer installation. It measures various household devices and the harmonic spectrums of the connected devices obtained from measurement were fed into the software to perform harmonic simulations. Additionally, a case study was carried out to estimate the total current harmonic distortion level at a customer's installation when the grid voltage is polluted with a specific order of harmonics. The analysis of this thesis shows that the use of non-linear loads in the household activities has important impact on the networks harmonic current pollution level. The collective effects of various non-linear LV devices (home appliances, etc.) attenuate the total harmonic current distortion in the

network mainly because of phase cancellation and diversity effects. In this study, it was found that the total current harmonic distortion level at the customer's installation is around 14% when the customer has mixed loads.

Prakash sundaram, Shimi S.L., Dr.S.Chatterji [28], they published a thesis entitled "Reduction in Harmonics in Marble Industry" on an industry found in India. After measuring the harmonic components of current, they found that the 5th harmonic content was beyond the IEEE limits, then design the harmonic filter. After installation of harmonic filter at Arihant Marble Industry, measurement were done again and found that 5th harmonic content was below IEEE limits. They are found shunt harmonic filters are efficient way of mitigating harmonics.

Zubair Ahmed Memon, Mohammad Aslam Uquaili , and Mukhtiar Ali Unar [29], with the growth of modern industrial technology a great number of non-linear loads are used in power system, which causes harmonic distortion in the power system. At the same time the power quality and safe operation becomes inferior. Therefore, mitigation of harmonics is very essential under the situation. This thesis presents the design of two passive filters to decrease the current harmonics produced by non-linear loads in industrial power system. MATLAB Simulink software has been used for the simulation purpose. The results have been obtained with and without installation of filters and then it is observed that after installation of filters harmonics of the current are reduced and power factor is enhanced.

CHAPTER -3-

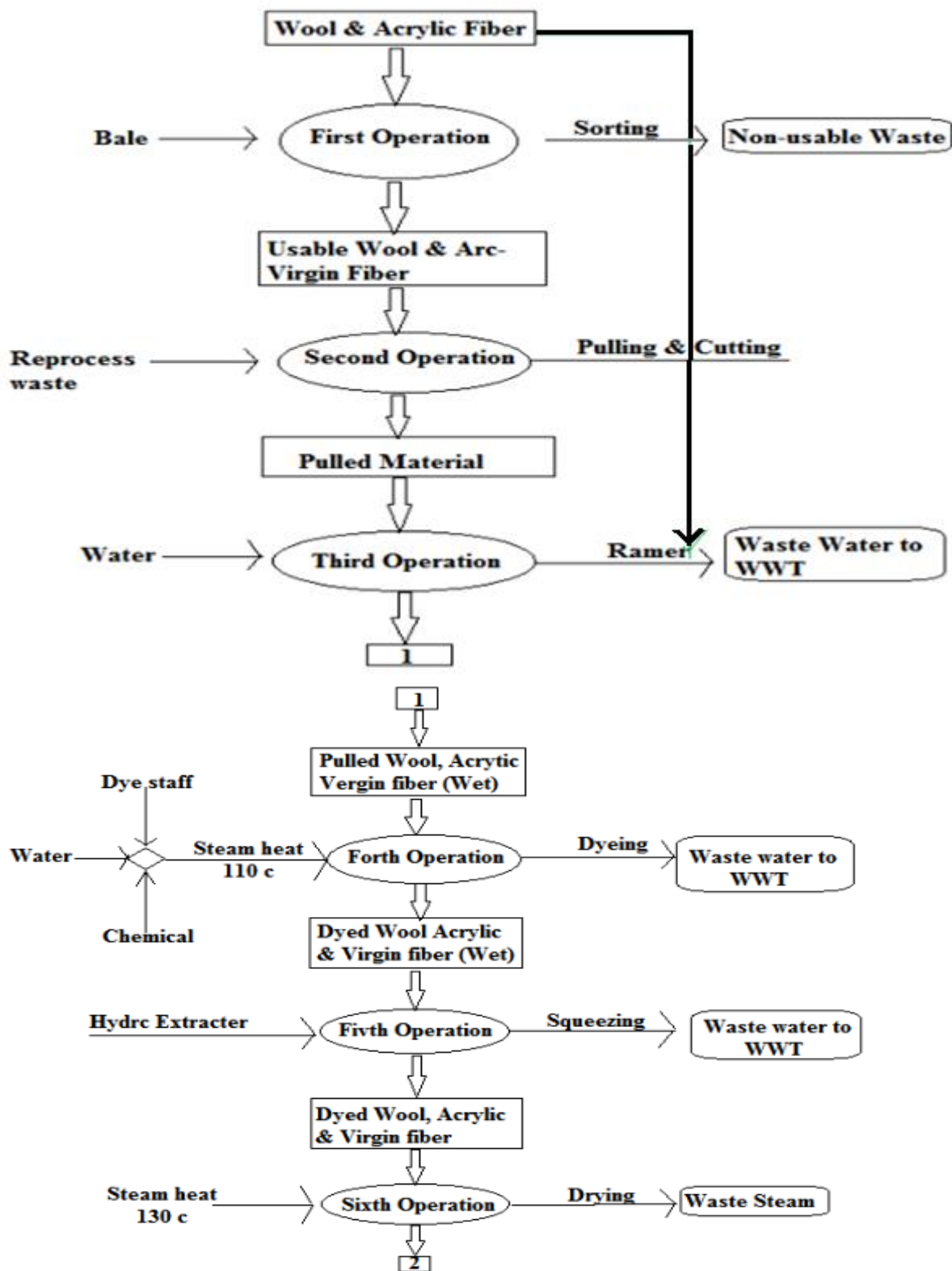
FACTORY PRODUCTION PROCESS AND DATA COLLECTION

3.1 Production Process of the Factory

The factory is engaged in the production of mainly a blanket. In addition, a finished product such as bed cover acrylic yarn, mattress and pillow. A brief process description follows. Raw materials, in the form of salvage, wool, and acrylic fiber changes their form into thread like through sorting, pulling, cutting, ramming, dyeing, squeezing, drying, blending, carding and spinning, yarning, warping, weaving and finishing operations. The essential sizing depends on the requirements of the final product.

At the first step, the wool and acrylic fiber is sorted and then go to the pulling and cutting process as a result of this a pulled material is gained. Moreover, this pulled material pass through ramming machine. Then according to the required color it goes to the dyeing process and because of this, it produces a colorful or a dyed wool, dyed staff. Then it goes to a drying process and it eliminates some moistures. After this, it goes in to the pulling and sucker machines and the output goes through pipes and stored in to a temporary store. After this, it goes in to the carding and spinning machines and these process changes materials in to a yarn.

In the weaving department, the yarn is woven into rolls of cloth. From the weaving department, the cloth passes on to the mending department in which unwanted part of the blanket is cut-off. Finally, the hard blanket goes through the raising machine, becomes a soft blanket, and then goes to the finishing department. The actual processes employed to finish the blanket depend on the final product requirement. The plant is capable of performing a number of wet and dry operations.



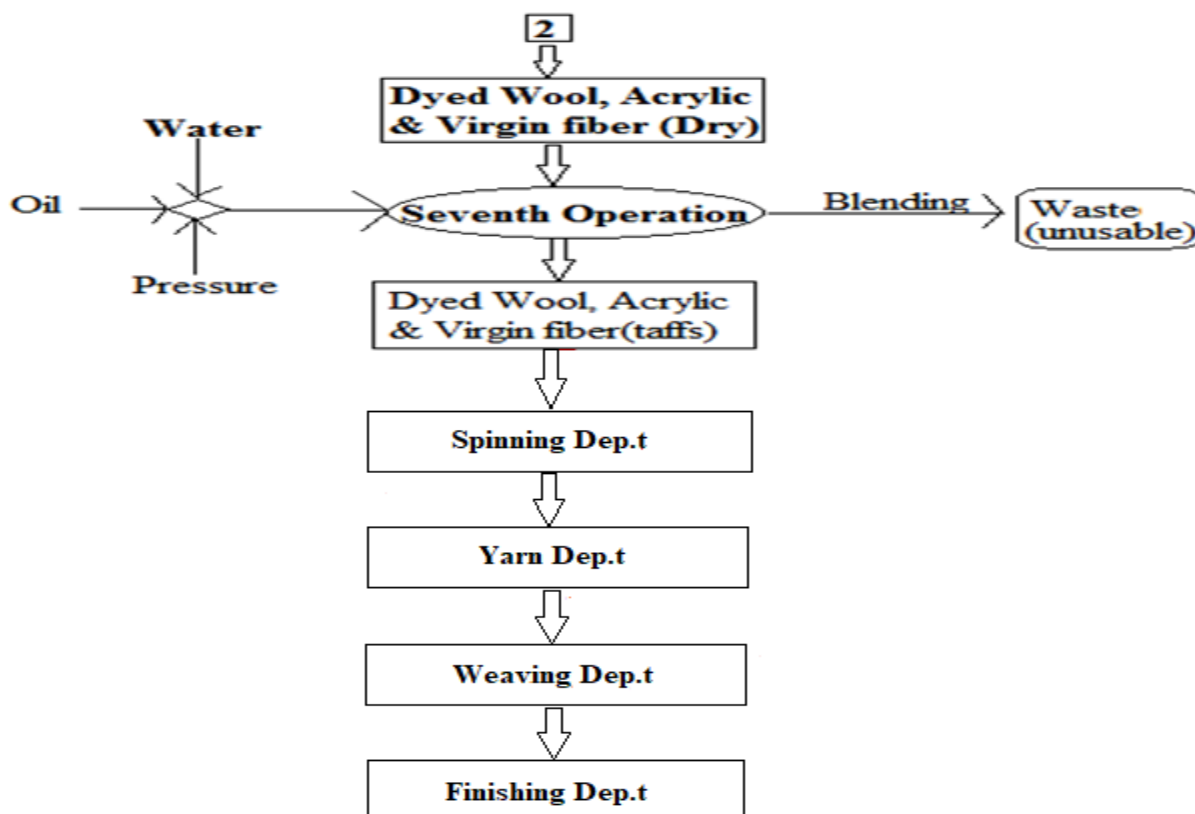


Figure 3-1: Production Process of the Factory

3.2 Major Energy Utilization Systems and Areas

Several major systems and processes in the factory consume energy. The following are the main energy sources used by the factory.

Electricity: DBBF uses an electricity as a main source of energy, which is supplied from EEU or from diesel generator when the electricity is off. In addition, this is a common energy source for running all DBBF machines and lightning. It is used primarily for motive power, compressed air, and lightning. The main use of electricity is for the motors and drives associated with process equipment in the pre-spinning, spinning, weaving, and finishing departments.

Furnace oil: It is consumed by a steam boiler plant to produce steam for process use and for generation of chilled water in a steam absorption chilled water plant.

Diesel oil: It is used primarily to power an emergency diesel-electric generator. The generator is water-cooled. In addition, used only when normal electric utility service is off.

Steam: Steam is one type of thermal energy and produced by combustion results of fuel and air at the required temperature. Combustion is carryout by mixing fuel and air at elevated temperatures. In addition, in the factory, steam energy is using as the main source of washing, size and de-sizing of yarns and fabrics respectively and for drying the processed fabrics.

Water: Water is the key source for producing steam, combining with steam it uses for washing grey fabrics, for preparing solutions of dye stuffs and chemicals, for AC of the factory and drinking and sanitation of the employees etc.

Compressed Air: This is one form of energy, and used for converting the potential energy in air to mechanical energy of all valves and other parts. For this reason, it can regulate every machine's air consumption through valves according to the settings in it.

3.2.1 Electrical Systems

Electrical power enters to the DBBF plant from a substation nearby with 15kV high voltage line. This 15kV high voltage-incoming line is connected to the factory's transformer with a capacity of 1250kVA. The incoming 15kV is step-down to 400/220 volts for distribution. Plant power factor is in range between 0.82-0.89 with a total of 12-capacitor banks of automatic switching capacitors. The total capacity of the factory is around 800kW. The utility-supplier provides a kWh-meter, located on the incoming power panel.

In addition to the utility supply, the factory plant maintains a diesel-electric generator with a total capacity of 500kW. It is cooled by a cooling tower placed outside of the plant. The generator is used only during periods when utility electric service is not available. Supplemental electric meters, located on the distribution panels, meter electricity production by the diesel generator. Motors and drives are the primary users of electricity in the factory. Figure 3-2 shows the simplified single line diagram of the electrical system in DBBF.

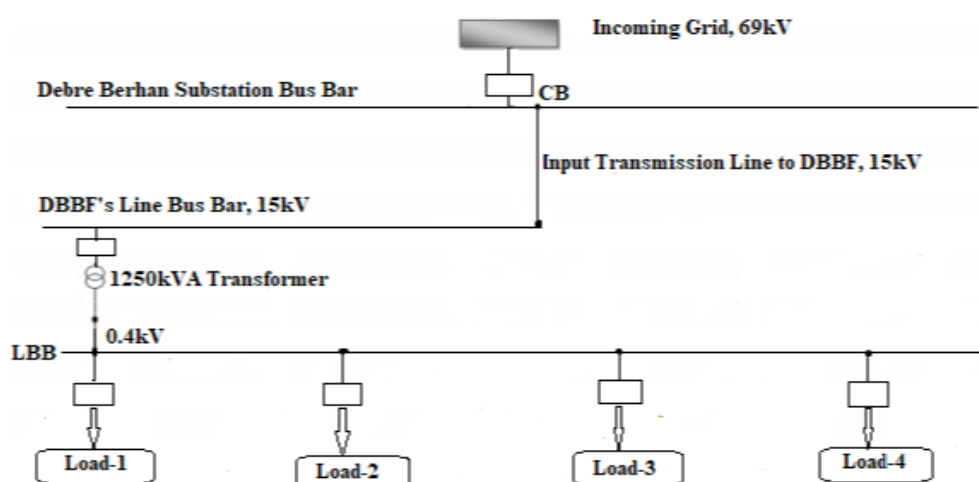


Figure 3-2: Simplified Single Line Diagram of the Power System in DBBF

The load-1 represents all the loads in spinning, and weaving departments. Load-2 represents all the loads in material preparation, dyeing, yarn, and finishing departments. Load-3 represents

all the loads in boiler, air compressor, water pump and workshop. Load-4 represents all the loads in offices and lightings of the factory.

3.2.2 Lighting System

Lighting in the plant is delivered primarily by 8-foot fluorescent tubes mounted two per fixture. These tubes are of standard wattage. Many T-12 tubes FL provide lighting in the different departments of the factory. Some fluorescent tubes provide office area lighting.

A lighting survey of the plant indicated that most areas are under-light, compared with published recommended illumination levels for textile plants. This has apparently caused no problems in the performance of processing operations. The main cause for low light levels in some areas of DBBF is primarily due to burn out without replacement. However, that ballasts serving these fixtures should be disconnected to increase energy savings.

3.2.3 Compressed Air Systems

Two compressors generates a compressed air. Compressor-1 and 2 are with a rating of 22 hp and 45 hp respectively with flow rate of 6.076 m³/min and 3.54 m³/min respectively. In addition, they provide a compressed air at 7.8 Bar. There were air leaks identified during the site survey. These leaks should be repaired. Because of the difficulty in locating compressed air leaks at times when the plant is operating, a program be instituted to check for leaks during weekend periods when the plant does not normally operate.

3.2.4 Steam Distribution and Condensate Return Systems

Steam circulation starts from the boiler house via three steam distribution lines. Two of these supply the chiller plant, while the third supplies the dyeing and finishing areas. Steam distribution is at boiler pressure to the point of use.

Condensate is returned to a cistern located outside of the boiler house. An additional cistern for collection of condensate from the finishing department is located outside of the finishing department. This condensate also contains cooling water that is discharged directly into the condensate lines. The steam and condensate system is in a generally good state of repair with few leaks observed. However, the distribution and return systems are poorly insulated with long runs of uninsulated pipework observed throughout the plant.

The cooling water that is discharged into the condensate return system is chemically treated water. While it is a good idea to reuse this water as boiler feed, the manner in which this is currently accomplished leaves much to be desired. The cooling water is discharged to the condensate return system at a much lower temperature than the condensate, causing an overall

reduction in condensate return temperature. The cooling water should be isolated from the condensate return and collected in a isolated tank to be used as boiler make-up water as required. In addition, hot condensate was found to be discharged to drain in several areas in the plant; this clean condensate should be returned to the boiler.

3.2.5 Boiler Plant

There is a fire tube boiler, manufactured by Milano, Italy. The design capacity of the boiler is rated $4000 \frac{kg}{hr}$ and a design pressure of 12 Bar. In normal operation, the boiler is on-line at any one time. In a normal workweek, the boilers are fired at Monday and operate through the working hours. The boiler shut down for the weekend at Sunday.

The boiler is close-fitted with a single pressure jet burner, which fires furnace oil utilizing air atomization. The burner is of the spill and return variety, with the return oil sent back to the fuel oil storage tank. Since this oil has already been heated prior to passage to the burner, it is recommended that the fuel oil system be improved to return the hot oil to the oil feed line before it enters the heat exchanger. Fuel oil is obtained from Kenya. In addition, the fuel oil is stored in two fuel oil tanks located outside of the boiler house. The tanks and fuel oil delivery lines are steam heated to assist transport of oil to the boilers.

The boiler plant is generally in a good condition, with a high level of maintenance evident. The operation of the boilers is generally good, considering that a high degree of manual control is employed. The boiler operator often sets air-fuel ratio manually after observation of the boiler stack for smoke.

Make-up water is delivered to the boiler in two ways. Part of the make-up water comes right from a water treatment plant placed outside of the boiler house. The balance of the make-up water is obtained in the finishing department. In this area, treated water is used for process cooling, and it is discharged directly to the condensate return system. While this conserves treated water, the temperature throughout the condensate return system lowers since this discharge cooling water is not very hot. However, this cooling water should be isolated from the condensate return system and stored in a separate tank for use as make-up water as needed. As the temperature of the condensate, returned water is too low, less than 65°C , and at such a low temperature, oxygen never eliminated from the feed water, and boiler injury due to corrosion may occur.

It is recommended that the feed water tank be insulated or, as an alternative, that the feed water tank be replaced by a deaerator.

To reduce the boiler total dissolved solids (TDS) levels, it is essential blowing down the boilers more repeatedly and for longer periods than normally practiced until the blowdown is maintained in the optimum or standard total dissolved solids range. The boiler house staff carry out water quality tests on a daily basis.

3.2.6 Spinning and Weaving Departments

The spinning and weaving departments use electric energy to yield raw textiles from raw material fibbers. In the spinning department, the fibbers are shaped to threads by a number of mechanical operations. Then, in the weaving department, these threads transformed into the textile matrix, by mechanical means.

3.2.7 Dyeing and Finishing Departments

The dyeing and finishing departments process the raw textiles in to the finished goods for distribution. A number of processing operations are available, the sequence of which hinge on the desires of the final product. The finishing department can process the raw textiles in a number of preparatory steps such as singeing, shearing, pressing, and washing. Dyeing is accomplished in jiggers or jet dyeing vessels. Then, mechanical and thermal processes accomplish drying. At the last, fabric printing is done.

3.3 Data Collections

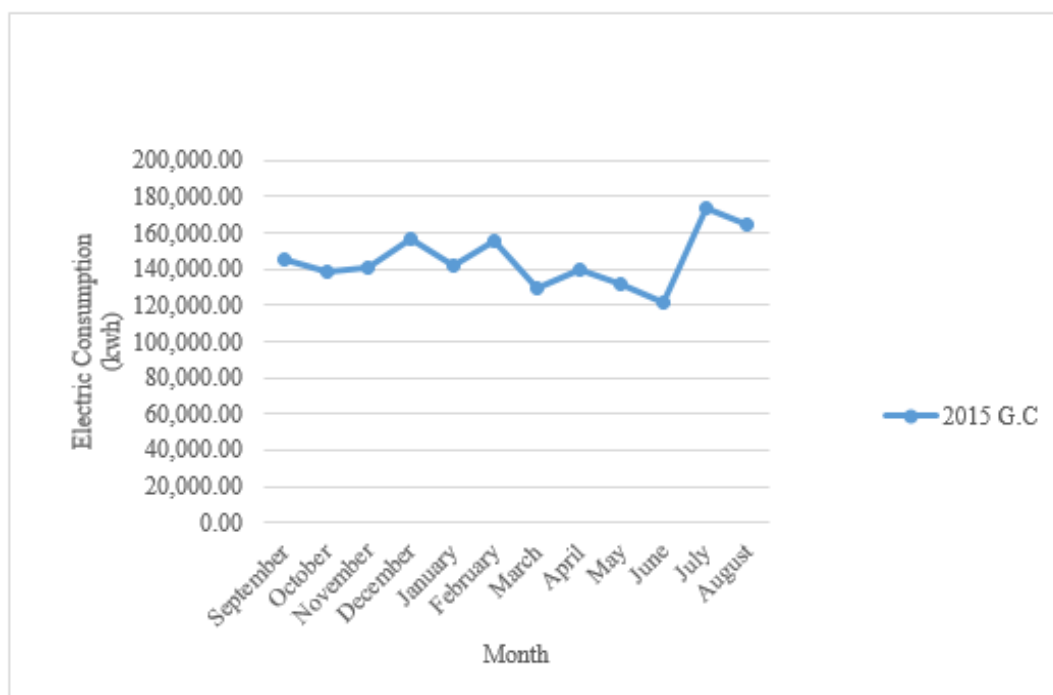
In this thesis work, on energy auditing and efficiency improvement at the factory, the data collection has been done through different methods such as personal interviews, direct observation of the factory, by taking measurements, telephone communication, and the available documents of the factory.

3.3.1 Factory Production and Energy Consumption Data

Table 3-1 provides the factory's three years of yarn production, energy consumption data and the specific energy consumption.

Table 3-1: Review of Factory Production and Energy Consumption at DBBF

No.	Items	Unit	Year(G.C)		
			2015/16	2016/17	2017/18
1.	Blanket Production	kg	1,477,781.77	1,312,121.73	1,708,498.90
2.	Electric Consumption	kWh	1,738,276.90	1,752,276.91	1,843,339.00
3.	Fuel Consumption	Lit	62,674.10	67,357.10	37,252.05
4.	Specific Electric Consumption	kWh/kg	1.17	1.33	1.07
5.	Specific Fuel Consumption	Lit/kg	0.04	0.05	0.02



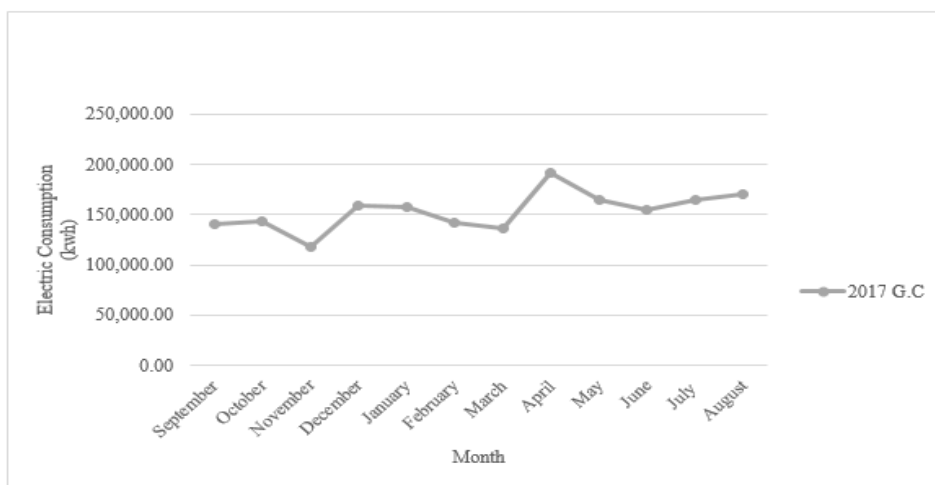
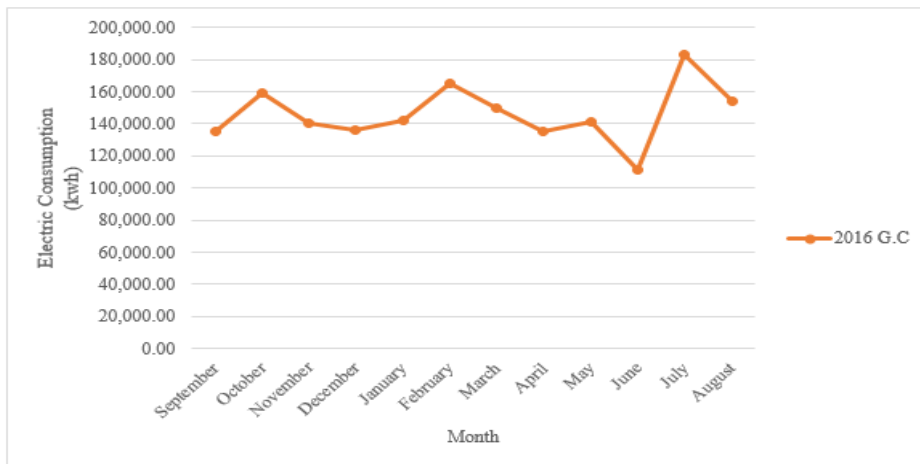
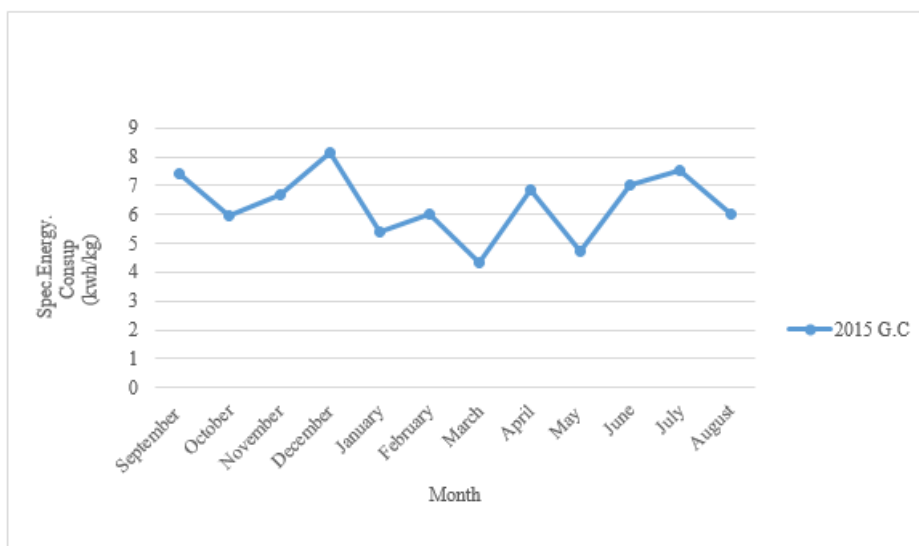


Figure 3-3: The Annual Electric Energy Consumption of DBBF



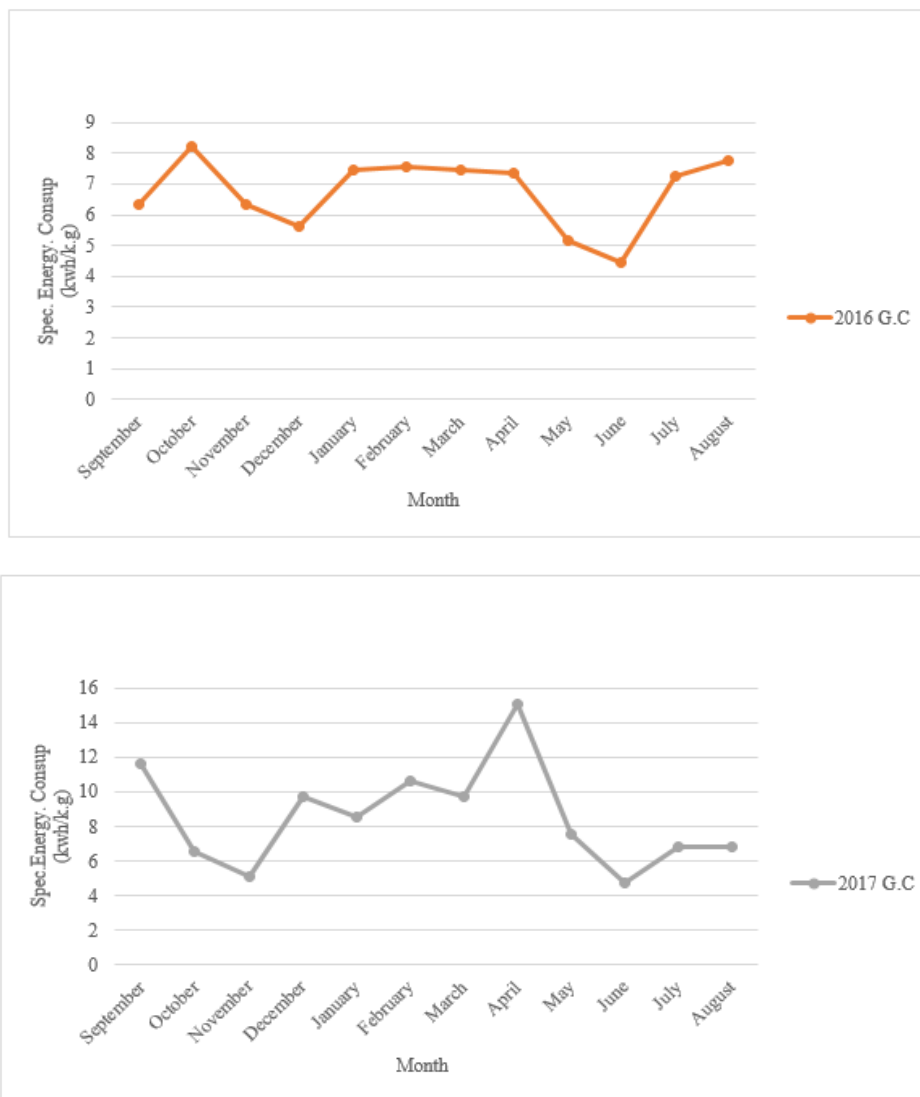


Figure 3-4: The Annual Specific Electric Energy Consumption of DBBF

3.3.2 Factory Energy Cost Data

Energy costs, of three years, for electric energy and furnace oil are shown in Table 3-2 as follow.

Table 3-2: Energy Costs at DBBF for Both Electric and Furnace oil

Items	Unit	Year (G.C)		
		2015/16	2016/2017	2017/18
Electric Energy	US \$	46,008.99	42,154.26	38,521.68
Furnace Oil	US \$	37,897.28	37,110.18	18,936.03
Total	US \$	83,906.27	79,264.44	57,457.72

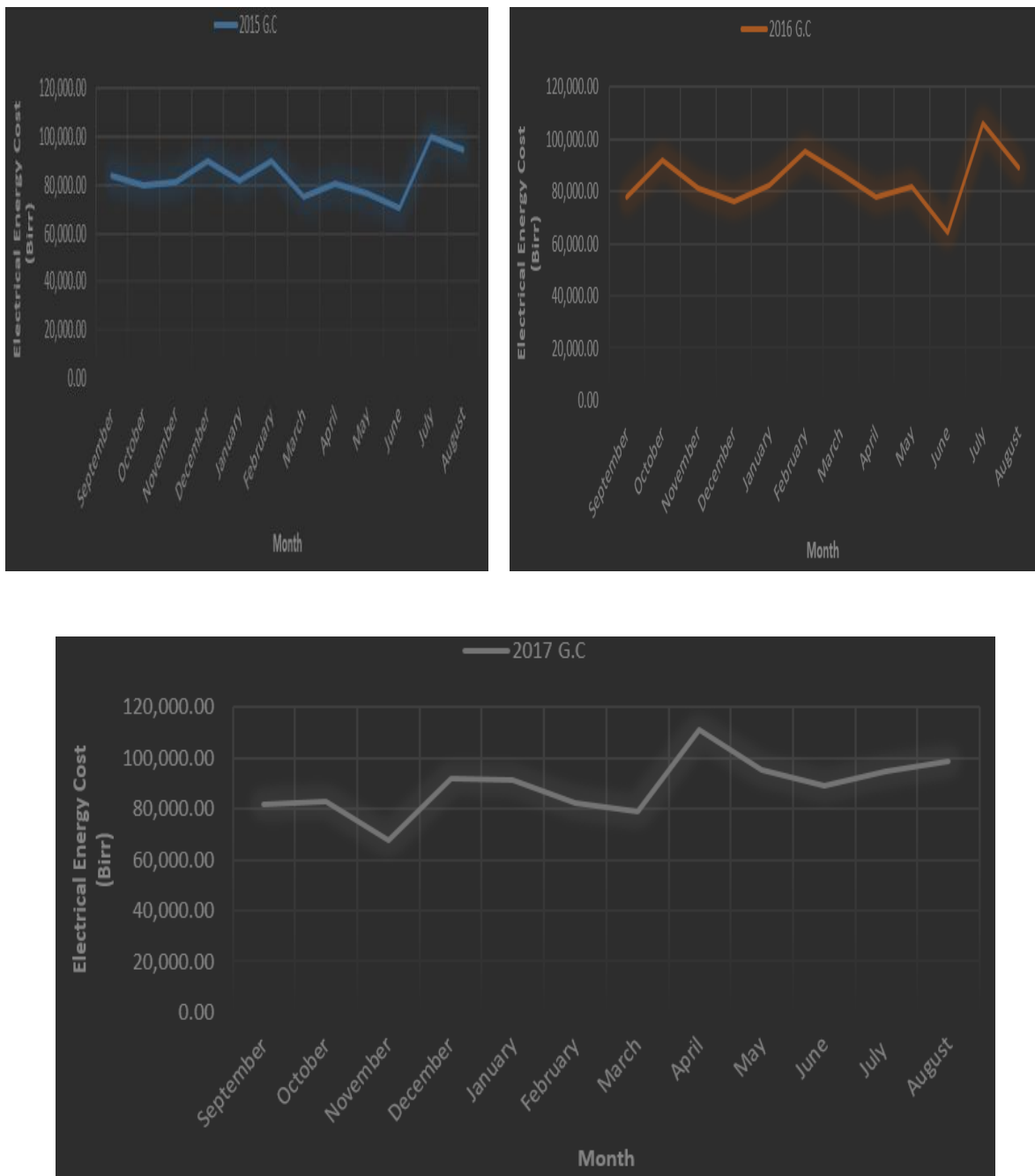


Figure 3-5: The Annual Electrical Energy Cost of DBBF

3.3.3 Factory Lighting Data

Various terms and meanings are used to quantify light, light source. In addition, their corresponding mathematical expressions are given in Table 2-3. According to the important formulas on Table 2-3, all the necessary lighting data are summarised in Table 3-3. In addition, Table 3-4 shows the number of non-functional ballasts that still consumes an electrical energy.

Table 3-3: Lighting Data of the Factory's Department

No.	Department	NL	TP (Watt)	TLu, (Lumen)	RA, (m ²)	TILu (Lux)	ALR	OH	EU(kWh)	ER(kWh)	ED(Wh/day)
1.	Guard	2	72	6,120	25	244.8	1	12	0.864	0.432	0.43
2.	Labor Union Bakery	10	360	30,600	90	340	7	8	2.88	2.02	0.86
3.	Carpentry Shop	30	1080	91,800	100	918	17	8	8.64	4.89	3.75
4.	Mechanical Work Shop	40	1,440	122,400	100	1,224	32	8	11.52	9.23	2.29
5.	Office & Residence	132	4,752	403,920	804	502.38	131	8	38.02	37.73	0.29
6.	Compound	40	1,440	122,400	-	-	-	12	17.28	-	-
7.	Material preparation	32	1,152	97,920	90	1,088	29	8	9.22	8.35	0.87
8.	Dying & Drying Area	66	3960	336,600	200	1,683	40	16	63.36	38.40	24.96
9.	Carding & Spinning	200	12,000	1,020,000	1200	850	188	16	192	180.48	11.52
10.	Warp Preparation Area	80	4,800	408,000	500	816	74	16	76	71.04	4.96
11.	Weaving Area	250	15,000	1,275,000	1400	910.71	206	16	240	197.76	42.24
12.	Raising & Shearing Area	40	2400	204,000	300	680	44	16	38.40	42.24	-3.84
13.	Finishing Area	38	1368	116,280	200	581.4	33	16	21.89	19.01	2.88
14.	Boiler	8	288	24,480	100	244.8	5	8	2.30	1.44	0.86
15.	Air Compressor	4	144	12,240	36	340	2	16	2.30	1.15	1.15
16.	Yarn Store	20	720	61,200	150	408	8	16	11.52	4.61	6.91
17.	Store	36	1296	110,160	300	367.2	14	8	10.37	4.03	6.34
Total		1,028	52,270				831		741.964	622.812	106.47

Table 3-4: Non-functional Ballasts to Remove

No.	Area or Location	Number of Ballast	Annual hours of Use
1.	Spinning Department	72	4960
2.	Weaving Department	46	4960
3.	Carding Room	18	4960
4.	Boiler House	10	2480
5.	Yarn Store	16	2480
6.	Raising Room	24	4960

3.3.4 Factory Motor Data

Table 3-5 shows the nameplate data, measured data and calculated parameters of the motor in the factory in each departments of the factory. To determine motor loading, input power measurements method is used in this thesis. Because kW readings take into account the change in power factor and amperage that occur as the motor loading changes, as it is described in Equation 2.9 through Equation 2.11.

Table 3-5: Summary of Measured Electric Motor Data of DBBF

No.	Machine Description	Motor Name Plate Data			Motor Measured Data			Motor Calculated Data		
		Rated Power (kW)	Rated Efficiency (%)	Speed (RPM)	Voltage (V)	Current (A)	Power factor (Cos θ)	Actual Power Output (kW)	Actual Power input (kW)	Loading (%)
1.	Material Preparation									
1.1	Blanket Cutter	3	75	1500	385.5	3.5	0.82	1.43	1.91	47.7
1.2	Pulling Machine	90	87.2	1500	389.2	88.4	0.89	46.24	53.03	48.6
1.3	Blending OMMI	75	81	1450	379.5	80	0.86	41.76	45.22	48.8
1.4	Oil Pump	2	75	1400	383.8	2	0.80	0.79	1.06	39.8
1.5	Horizontal Bell Press	5.5	75	1475	391.7	5.5	0.87	2.43	3.24	44.2
2.	Dying and Drying Area									
2.1	Dyeing Machine	4.2	79	1465	365	5	0.89	2.21	2.81	52.9
2.2	Dyeing Machine	4.3	75	1430	385	5.2	0.72	1.86	2.49	46.5

2.3	Dyeing Machine	45	90.1	1420	368	82	0.86	40.49	44.94	89.9
2.4	Centrifugal drying	7.5	75	1470	390.3	7	0.89	3.15	4.21	41.3
2.5	Drying	38.2	89.2	1500	375	53	0.85	26.09	29.26	68.3
2.6	Scouring Machine	5.5	80	1500	375.6	5.6	0.84	2.44	3.06	44.5
2.7	Pump	2.2	80	1475	391	2	0.91	0.98	1.23	44.7
2.8	Mixer	0.35	78.1	1430	388.1	0.4	0.85	0.2	0.22	51.8
2.9	Feeding Motor	4	85	1460	378	5	0.8	2.2	2.61	53.3
2.10	Dyeing Lifting	11	75.5	1470	374.5	7.2	0.89	3.2	4.15	28.3
2.11	Dyeing Pressing	0.37	75.5	980	367	0.5	0.89	0.21	0.28	59.5
2.12	Rammer Machine	14.2	83.5	1480	373.9	20	0.85	9.13	11.00	64.3
3.	Carding and Spinning									
3.1	Spinning Begage-1	73.3	90.7	1460	384	102	0.85	51.8	57.66	70.8
3.2	Card Beffama-1	128	92.6	1500	392	190	0.84	99.6	108.2	77.8
3.3	Card Beffama-2	35	88.3	1450	395	47	0.84	23.76	27.01	67.9
3.4	Spinning Begage-2	57	92.0	1450	394	66	0.85	52.44	38.28	61.7
3.5	Spinning Single Side	30.5	86	1470	388.6	40	0.84	19.44	22.61	63.7
3.6	Spinning Double S.	165.5	93.1	1550	390	200	0.84	105.4	113.48	63.7
4.	Warp Preparation Area									
4.1	Winding Machine	4.4	75.5	1445	370	5.1	0.84	2.19	2.74	46.7
4.2	Warp Machine	0.37	75	980	387	0.5	0.73	0.18	0.24	48.9
4.3	Warp Machine	0.75	75.8	1400	370.7	0.8	0.73	0.28	0.37	37.2
4.4	Warp Machine	0.9	78	1470	390	1.0	0.8	0.42	0.54	46.9
4.5	Warp Machine	2	80	1330	380	2.1	0.81	0.88	1.11	44.4
4.6	Warp Machine	0.37	76.3	1420	381	0.5	0.85	0.21	0.28	58.3

4.7	Cone Winding	14.4	81.6	1400	389	18	0.84	8.30	10.18	57.7
4.8	Warp Beam	5.2	78.3	1430	365	6	0.8	2.36	3.03	45.6
4.9	Warp Beam Lifter	0.4	70.3	987	386	0.6	0.81	0.22	0.32	57.1
4.10	Warp Beam	4.8	80	2000	380	6.5	0.73	2.49	3.12	52.00
5.	Weaving									
5.1	Jacked Loom	7.5	78	1500	390	7.6	0.8	3.19	4.10	42.6
5.2	Rapier Loom	189	92.1	1480	385	265	0.85	138.33	150.2	73.1
5.3	Nuovo Loom	30	80.3	1500	378.9	41.5	0.84	18.3	22.8	61.1
6.	Mending Area									
6.1	Blanket Cutter	2.2	75.3	1440	392	2	0.77	0.78	1.04	35.6
7.	Blanket Raising & Shearing									
7.1	Textima	19.2	85.8	1460	390	23	0.85	11.22	13.20	58.4
7.2	Raising Machine Lamperti	30.5	80	1450	379	29	0.83	16.50	15.80	41.4
7.3	Raising Machine Lamperti	50	90.2	1430	383	62	-	31.52	34.95	63.05
8.	Last-Touch Finishing									
8.1	Juki Sewing Machine	18.5	78.5	1445	370	20	0.8	8.21	10.25	43.2
8.2	Blanket Metering	3.7	78.6	1430	390	4	0.85	1.79	2.29	48.3
8.3	Sewing	3.25	80.3	2800	385	4.2	0.90	2.52	2.02	62.3
8.4	Sewing Machine Blanket	3.25	80	2860	391	4.5	0.81	1.96	2.46	60.5
9.	Carpentry Shop	20	85.6	1470	379	25	0.81	11.37	13.29	56.8
10.	Mechanical Work-shop	54.5	90.7	3000	392	56	0.85	29.30	32.31	53.7
11.	Pump Station	41	86	1500	375	50	0.89	24.85	28.91	60.6
12.	Air Compressor	44	80.3	1480	370	45	0.81	28.74	23.07	42.1
13.	Suction Cleaner	5.5	78.5	1430	390	6	0.8	2.52	3.24	45.9

3.3.5 Factory Air Compressor Data

Compressed air is required throughout the plant for various purposes such as cleaning, packing, operation of pneumatic valves. During the audit measurement, data was taken on both compressors at operational time. Table 3-6 shows the compressors design specifications.

Table 3-6: Design Specifications of Available Compressors

No.	Name of Air Compressor	Type	Design Parameters	Quantity
1.	Air Compressor No-1	Screw	Power = 22 kW	1
			Design Pressure = 7.8 Bar	
			Flow Rate = 6.076 m ³ /min	
2.	Air Compressor No-2	Screw	Power = 45 kW	1
			Design Pressure = 7.8 Bar	
			Flow Rate = 3.54 m ³ /min	

▪ Measured Electrical Energy Consumption of the Air Compressors

During operation, the electrical energy consumption of compressors was measured in real time. The average recorded data is presented in Table 3-7 as follows.

Table 3-7: Real Time Electrical Consumption Data of the Compressors

No.	Description	Compressors	
		Compressor No-1	Compressor No-2
1.	Rating (kW)	22	45
2.	Actual Power (kW)	16.64	26.89
		Measured Actual total power = 16.64+26.89 = 43.53 Kw	

▪ Measured Parameters of Air Compressor for FAD Test

Measurements of the inlet air velocity using an anemometer and other useful measurements are taken while the air compressors are in operation. Table 3-8 shows the recorded values of these measurements.

Table 3-8: Measured Parameters of the Air Compressors

Measurements	Compressor No-1	Compressor No-2
	Measured Air Velocity (m/s)	Measured Air Velocity (m/s)
V ₁	14.9	13.3
V ₂	13.6	15
V ₃	15	16.5
V ₄	13.2	-
Measurements	Measured Input Power (kW)	Measured Input Power (kW)
P ₁	18.31	27.12
P ₂	16.10	28.80
P ₃	15.52	24.75
Measurements	Measured Loading Time (sec)	Measured Loading Time (sec)
T _{L1}	21.13	24.58
T _{L2}	22.05	23.93
Measurements	Measured Un-Loading Time (sec)	Measured Un-Loading Time (sec)
T _{UL1}	29.31	33.25
T _{UL2}	29.82	32.83
Measurements	Measured Value	Measured Value
Loading Pressure (Bar)	6.6	6.8
Unloading Pressure (Bar)	7.8	7.8
Inlet air tube diameter (cm)	9.3	8.7
Air flow rate (FAD)	3.85 m^3/min or 137.5 cfm	3.54 m^3/min or 126.43 cfm

(Note that: $1cfm = 0.028 \frac{m^3}{min}$)

There is also an observed air leakage at the Compressor No-2 during the measurements of air compressors in the factory as shown in Figure 3-6.



Figure 3-6: Place of Air Leakage Occurred at Air Compressor No-2

3.3.6 Factory Boiler Data

The factory has two light fuel oil boilers, one is operating at a time and the other is standby, to supply steam to various sections. The design specifications of the operating boiler are given in Table 3-9.

Table 3-9: Design Specifications of Boilers

Particulars	Unit	Boiler
Made in	-	Milano, Italy
Capacity	kg/hr	4000
Design pressure	Bar	12
Steam temperature	°C	175-180
Steam pressure	Bar	6-8
Fuel	Lit	Furnace oil

▪ Measured Boiler Parameters

During the detail audit, the performance of one of the two boilers has been measured. The flue gas temperature, CO, O₂ & CO₂ percentage has been measured using a device called Combustion analyser at the boilers outlet. The recorded parameters are shown in Table 3-10.

Table 3-10: Measured or Monitored Boiler's Parameter

Parameters	Unit	Boiler No-1
Feed water temperature	°C	107
Maximum steam pressure	Bar	8
Steam temperature (as per steam table)	°C	180
Boiler side temperature	°C	70 – 81
Heating surface area of boiler	m ²	105
Flue gas Parameters		
Flue gas temperature	°C	209
% O ₂ in flue gas	%	9.1
% CO ₂ in flue gas	%	11.4
CO ppm	Ppm	5

The boiler steam lines have been observed that some steam lines have not been insulated. The steam line just at the out let of the boiler is not insulated and the condensate line at the header inlet not insulated. Some of the non-insulated steam lines and steam leaks observed in the steam distribution system are shown in Figure 3-7 and Figure 3-8.

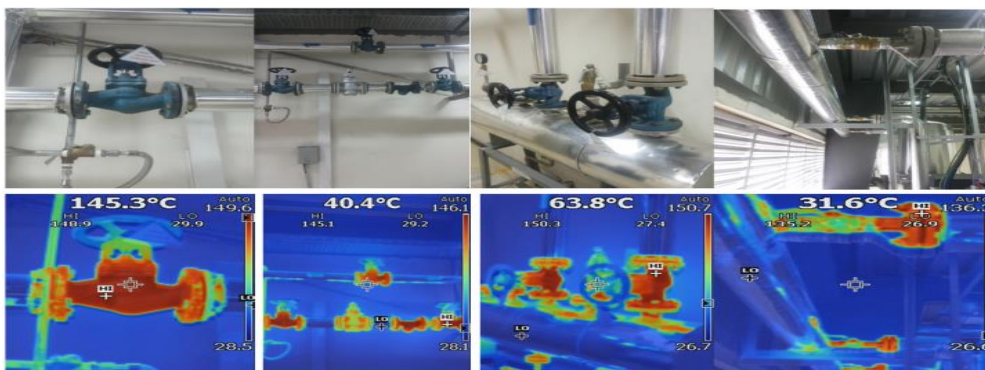


Figure 3-7: Non-insulated Steam Lines at DBBF

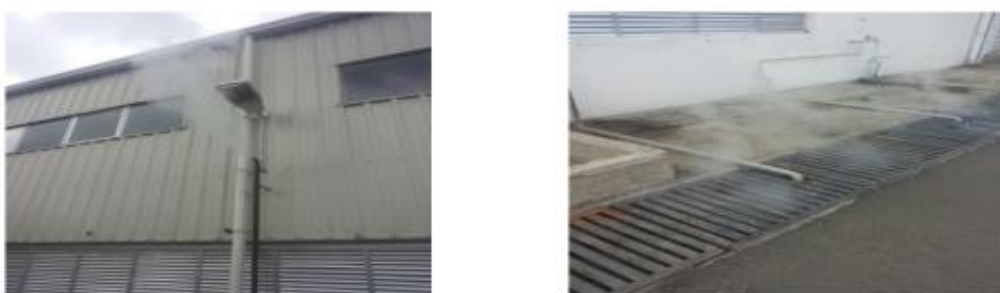


Figure 3-8: Some of the Steam Leaks in the Steam Distribution System

3.3.7 Factory Power Quality Data

Power quality measurements (such as voltage unbalance factor, current unbalance factor, power frequency variation, short and long-term flicker, total harmonic distortion for voltage and current, harmonic spectrum etc...) are taken with the help of Fluke power quality and energy analyser. These measurements are shown through tables Table 3-11 to Table 3-17.

- **Measured Voltage Unbalance Factor (VUF)**

Voltage or current unbalance (VUF and IUF) is defined as the maximum deviation from the average of the three-phase voltages or currents, divided by the average of the three-phase voltages or currents, expressed in percentage, which is given by the Equation 2.36. The VUF and IUF in Table 3-11 and Table 3-12 are calculated using Equation 2.36. The voltage and the current unbalance factors for the factory distribution system are within the limit of the standard values according to Table 2-7 ($< 3\%$ for VUF and $< 10\%$ for the IUF). The values of both the VUF and IUF are measured using a device called Fluke power quality and energy analyser.

Table 3-11: Voltage Unbalance Factor for DBBF Distribution System

Voltages		Measured Value (V)	Mean of (U_{12} , U_{23} , U_{31}) (V)	MDBMM Value (V)	VUF(%)
Phase-to-Phase Voltage	U_{12}	398.8	397.77	1.07	0.27
	U_{23}	396.7			
	U_{31}	397.8			
Phase-to-Neutral Voltage	V_1	230.2	229.63	0.57	0.25
	V_2	229.3			
	V_3	229.4			

- **Measured Current Unbalance Factor**

Table 3-12: Current Unbalance Factor for DBBF Distribution System

Line Current Code	Measured Value (A)	Mean of (A_1 , A_2 , A_3) (A)	MDBMM Value (A)	IUF(%)
A_1	275.6	299.1	23.50	7.85
A_2	319.6			
A_3	302.1			

- **Measured Power Frequency Variation**

The allowable value of power frequency variations according to the IEEE standard for normal operation is ± 0.5 (49.5 Hz to 50.5 Hz at 50 Hz nominal frequency). Based on this standard, the measurement results as shown in the Table 3-13 indicates that the power frequency does not vary much from the permissible limits. The values of the frequencies in Table 3-13 are measured using Fluke power quality and energy analyser.

Table 3-13: Frequency Variation Measurements

No.	Time	Frequency (Hz)	Frequency variation
1.	8:40:00 AM	50.06	+0.06
2.	8:45:00 AM	49.99	-0.01
3.	8:50:00 AM	49.93	-0.07
4.	8:55:00 AM	49.92	-0.08
5.	9:00:00 AM	49.88	-0.12
6.	9:05:00 AM	50.08	+0.08
7.	9:10:00 AM	50.15	+0.15
8.	9:15:00 AM	50.11	+0.11
9.	9:20:00 AM	50.05	+0.05
10.	9:25:00 AM	50.09	+0.09

▪ **Measured Short- term (P_{st}) and the Long-term (P_{lt}) Flicker**

Power flicker is caused by voltage fluctuation, which can cause discomfort to our eyes and our brain. The short-term flicker (P_{st}) and the long-term flicker (P_{lt}) are indices characterizing the intensity of flicker. Table 3-14 shows the measured values of P_{st} over 10 minutes interval using a Fluke power quality and energy analyser at the load side of the factory's transformer. The long-term flicker severity (P_{lt}) for each phase is calculated using Equation 2.37 from a sequence of 12 P_{st} values over a two-hour interval and are putted in Table 3-14. Almost all the measured values of P_{st} and all the calculated values of P_{lt} are within the standard limit.

Table 3-14: Measured Values of P_{st} and P_{lt}

Phases	<i>i</i> -Values (<i>i</i> = Number of consecutive P_{st} measurements taken)												P_{lt} Calculated
	1	2	3	4	5	6	7	8	9	10	11	12	
	Measured P_{sti} (<i>i</i> =1,2,3, ... 12) Values over 10 minutes interval												
L ₁	0.4	0.4	0.9	0.3	0.4	0.4	0.4	0.4	0.3	0.5	0.5	0.6	0.513
L ₂	0.3	0.4	1.5	0.5	0.4	0.5	0.5	0.3	0.5	0.8	0.9	0.6	0.772
L ₃	0.3	0.4	0.9	0.4	0.4	0.5	0.4	0.4	0.6	1.2	0.8	0.7	0.658

▪ Measured THD for Voltage and Current

The recorded data for the percent values of voltage and current harmonic levels at each phase, THD_V and THD_I of the electric power of DBBF is shown in Table 3-15 and Table 3-16. These THD_V and THD_I values are measured at the load side of the factory's transformer in each phase using Fluke power quality and energy analyser device. The measured value of THD_V is within the standard limit ($< 5\%$) whereas the values of THD_I shows above the standard limit ($>10\%$).

Table 3-15: The Percent Values of Voltage and Current Harmonic Levels

Harmonic Order	Phase-1				Phase-2				Phase-3			
	V(V)	I(A)	V(%)	I(%)	V(V)	I(A)	V(%)	I(%)	V(V)	I(A)	V(%)	I(%)
1	227.72	402.30	100	100	226.40	437.80	100	100	228.92	381.90	100	100
3	2.04	10.06	0.9	2.5	2.26	13.13	1.0	3.0	2.29	11.08	1.0	2.9
5	2.73	59.14	1.2	14.7	3.40	67.89	1.5	15.5	2.98	57.67	1.3	15.1
7	2.50	60.75	1.1	15.1	2.93	70.49	1.3	16.1	2.98	61.10	1.3	16.0
9	2.28	4.43	1.0	1.1	2.72	6.57	1.2	1.5	2.52	3.44	1.1	0.9
11	0.68	3.62	0.3	0.9	0.68	3.94	0.3	0.9	0.92	2.30	0.4	0.6
13	0.46	1.81	0.2	0.45	0.68	2.01	0.3	0.46	0.67	1.57	0.3	0.41
15	0.46	1.37	0.2	0.34	0.45	1.53	0.2	0.35	0.46	0.80	0.2	0.21
	$THD_V(\%)=2.15$ $THD_I(\%)=21.28$				$THD_V(\%)=2.56$ $THD_I(\%)=22.63$				$THD_V(\%)=2.43$ $THD_I(\%)=22.22$			

Table 3-16: The THD_V and THD_I of the DBBF

No.	Time	Phase-1		Phase-2		Phase-3	
		THD_V (%)	THD_I (%)	THD_V (%)	THD_I (%)	THD_V (%)	THD_I (%)
1.	8:40:00 AM	2.5	26	2.5	22.1	2.6	22.3
2.	8:45:00 AM	2.4	21.9	2.4	18.5	2.5	18.3
3.	8:50:00 AM	2.5	23.5	2.5	20	2.5	19.6
4.	8:55:00 AM	2.6	23.6	2.7	20.5	2.6	19.4
5.	9:00:00 AM	2.3	23.7	2.7	20.7	2.6	19.5
6.	9:05:00 AM	2.5	21.7	2.5	19	2.5	18.1
7.	9:10:00 AM	2.4	22.1	2.3	19.2	2.4	18.2
8.	9:15:00 AM	2.2	23.9	2.2	20.2	2.3	19.1
9.	9:20:00 AM	2.1	19.8	2.2	16.9	2.1	15.9
10	9:25:00 AM	2.1	18.1	2.1	15.7	2.1	14.2

▪ Measured Harmonic Spectrum

Figure 3-9 shows the measured harmonic spectrum in the factory, graphically. It shows the odd order current harmonics are dominated by the 3rd, 5th, 7th, 9th and 11th harmonic numbers. Table 3-15 shows the percent values of the current harmonic levels at each phase which are measured using Fluke power quality and energy analyser. In addition, Figure 3-9 shows that the dominant current harmonics especially the 3rd, 5th, and the 7th should be minimized or eliminated.

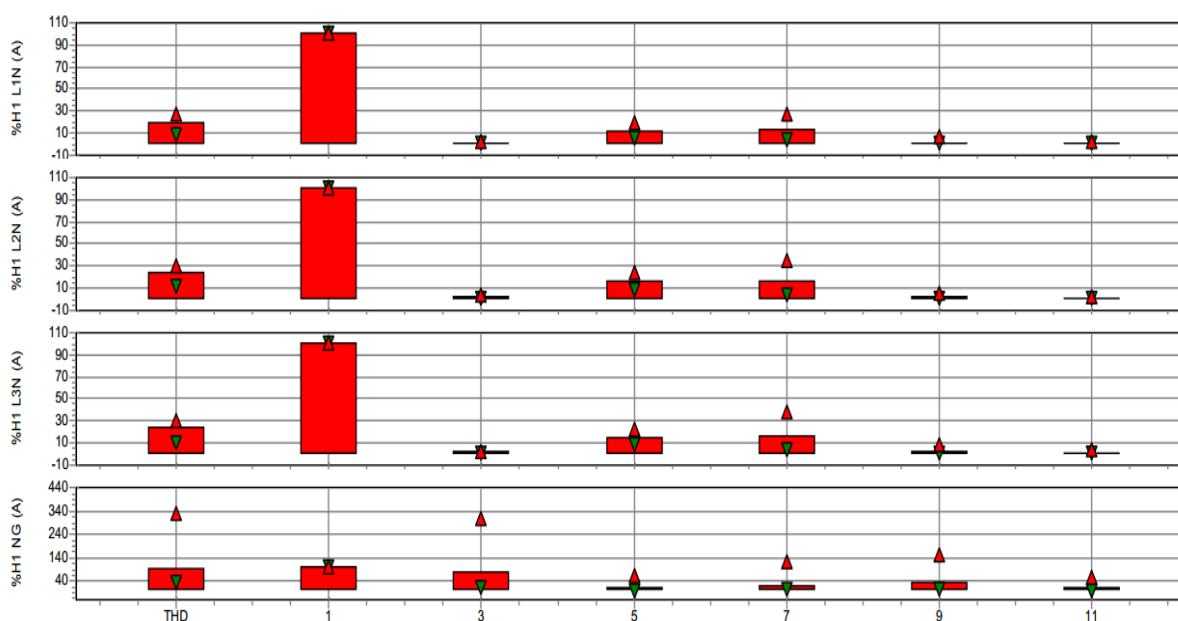


Figure 3-9: Measured Harmonics Spectrum of DBBF

▪ Measured Power and Power Factor at the Factory Transformer

The recorded data for the different types of power such as active power, reactive power, complex power and power factor of the factory's transformer during working operation of the factory. During this measurement, some machines of the factory were not working due to lack of input raw materials, lack of spare parts and maintenances. Therefore, this measurement is taken only for some working machines. The four cables (R, S, T, and N lines) of the Fluke power quality and energy analyser is connected to the factory's transformer as shown in Figure 3-10, secondary side or load side. Then the measuring device measures all the required measurements by the action of magnetic induction. All the measured values are given in Table 3-17.

Table 3-17: Recorded Data of the Power and Power Factor

Measured Load Data		
Measured Parameters	SI Unit	Measured Value
Complex Power (S)	kVA	240.01
Active Power (P)	kW	215.81
Reactive Power (Q)	kVAR	103.18
Power Factor (P.F)	-	0.89



Figure 3-10: The Connection of the Fluke Power Quality and Energy Analyser with the Factory's Transformer during Measurements

CHAPTER -4-

SIMULATION RESULTS, ANALYSIS AND DISCUSSION

4.1 Summary and Analysis of the Energy Assessment in the Factory

According to the walk-through audit conducted in the factory as well as information from the collected data, the major energy consuming areas in the factory, which have high energy saving opportunities, are identified. These areas are lightings, electric motors, air compressors, boilers, and power quality related problems. The following sections show the main summary, analysis, and discussion of the energy assessment within the factory.

4.1.1 Summary and Analysis of the Energy Breakdown and Energy Intensity of the Factory

Breakdown of electrical energy is done on the bases of the part of the electrical energy consumed, actual energy used, by different section of the plant based on their actual power measurement taken using a clamp meter. In these different sections of the factory, the electricity is used as the main source of energy. Table 4-1 shows the percent share of the electrical energy based on the actual measurements taken in each department.

Table 4-1: Percent Share of Electrical Energy in the Different Departments of the factory

No.	Department	Measured Actual Input Power (kW)	Percent Share of Electrical Energy (%)
1.	Material Preparation	114.46	12.81
2.	Dying and Drying Area	106.26	11.88
3.	Carding & Spinning	367.24	41.07
4.	Warp Preparation	21.93	2.45
5.	Weaving	177.10	19.80
6.	Blanket Raising & Shearing	63.95	7.15
7.	Last Touch Finishing	17.02	1.90
8.	Light	26.13	2.92

▪ Breakdown of Energy Use by Factory Process

From Table 4-1 and Figure 4-1, the carding & spinning department consumes 41.07% approximately 41% electrical energy of the factory, which is the greatest percent share. The weaving department consumes 20% electrical energy of the factory. The material preparation department consumes 13% electrical energy of the factory, and the finishing department consumes 2% electrical energy of the factory, which is the lowest percent share.

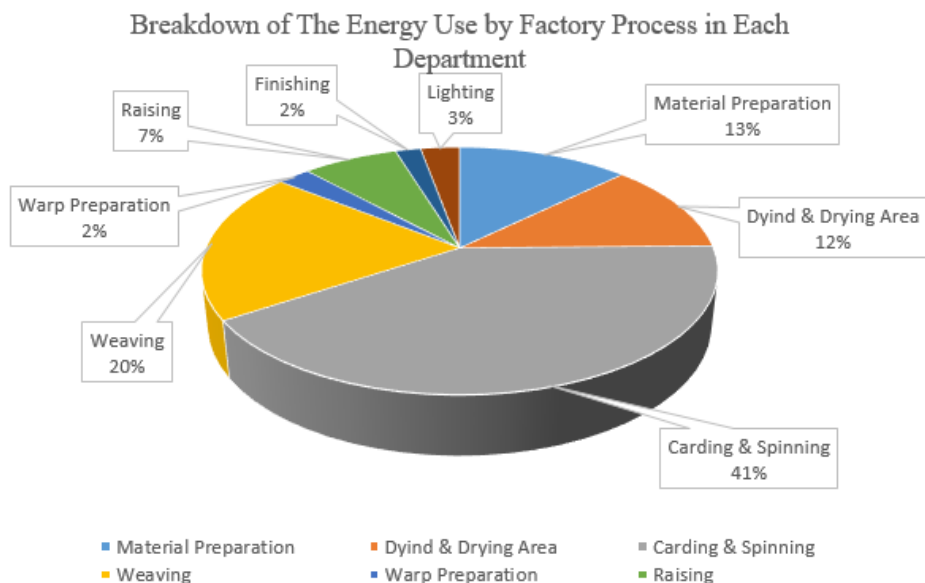


Figure 4-1: Breakdown of Energy Use (in %) by Factory Process in Each Department

▪ **Energy Breakdown in the Carding & Spinning Department Based on Machine Type**

Breakdown of electrical energy can be also done based on the machine type in each department. The electrical energy consumption, actual energy used by different machine type, measurement is taken using a clamp meter. Table 4-2 summarises the percent share of the electrical energy based on the actual measurements taken for the machine types in the carding and spinning department.

Table 4-2: Percent Share of Electrical Energy in the Carding & Spinning Department based on Machine Type

No.	Carding and Spinning Department Machines		
	Machine Description	Measured Actual Input Power (kW)	Percent Share (%)
1.	Spinning Begage-1	57.66	15.70
2.	Spinning Begage-2	38.28	10.42
3.	Card Beffama-1	108.20	29.46
4.	Card Beffama-2	27.01	7.35
5.	Spinning Single Side	22.61	6.15
6.	Spinning Double Side	113.48	30.90

Figure 4-2 and Table 4-2 show the breakdown of the electrical energy consumed based on the machine type in the spinning and carding department. As a result, the spinning double side machine type consumes 30.90% approximately 31% electrical energy of the spinning department, which is the greatest percent share. The card beffama-1 consumes 30% electrical energy of the spinning department, and the spinning single side consumes 6% electrical energy of the spinning department, which is the lowest percent share.

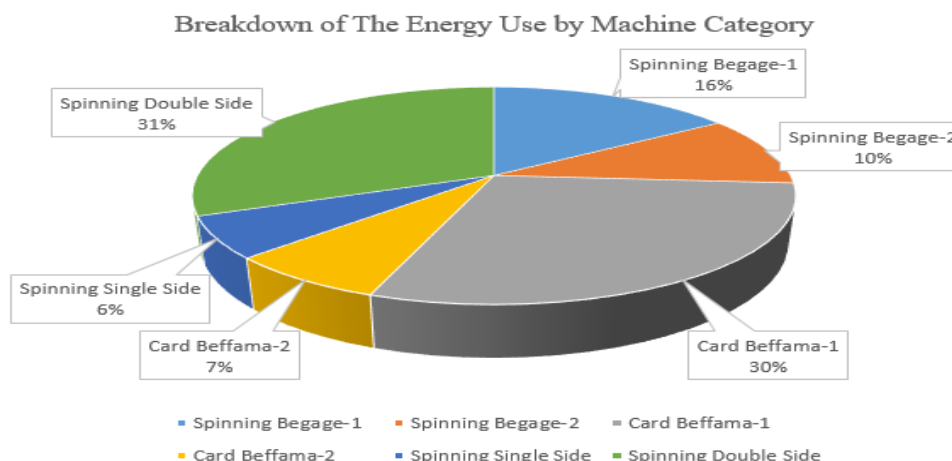


Figure 4-2: Breakdown of Energy Use in Carding & Spinning Department

▪ Energy Breakdown in Weaving Department Based on Machine Type

The electrical energy consumption, actual energy used by different machine type, measurement is taken using a clamp meter in the weaving department. Table 4-3 summarises the percent share of the electrical energy consumed based on the actual measurements taken for the machine types in the weaving department.

Table 4-3: Percent Share of Electrical Energy in the Weaving Department based on Machine Type

No.	Weaving Department Machines		
	Machine Description	Measured Actual Input Power (kW)	Percent Share (%)
1.	Jacked Loom	4.10	2.31
2.	Rapier Loom	150.20	84.81
3.	Nuovo Loom	22.80	12.87

Figure 4-3 and Table 4-3 show the breakdown of the electrical energy consumed based on the machine type in the weaving department. As a result, the rapier loom type consumes 84.81% approximately 85% electrical energy, which is the greatest, of the weaving department. The

nuovo loom consumes 13% electrical energy of the weaving department, and the jacked loom consumes 2% electrical energy of the weaving department, which is the lowest energy percent share.

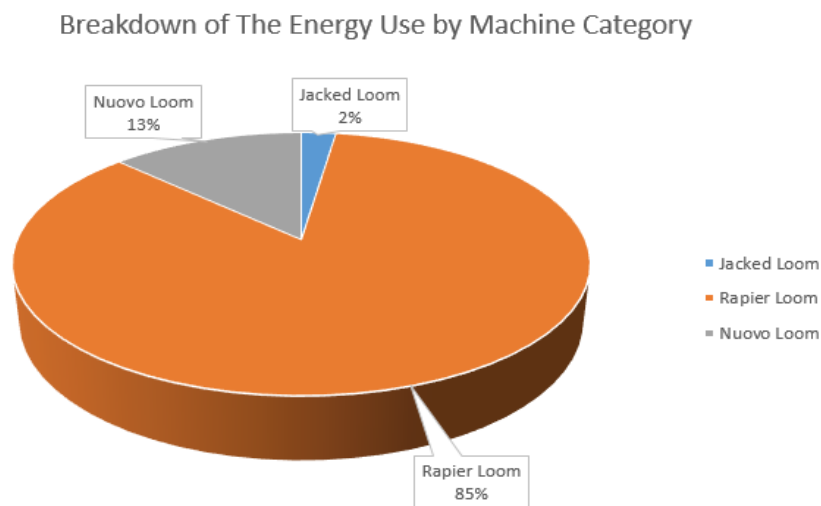


Figure 4-3: Breakdown of Energy Use in Weaving Department

▪ Summary and Analysis of the Energy Intensity of the Plant

Energy intensity is the amount of energy consumed to produce a unit amount of product and is a measure of the energy efficiency of the plant. The graphs on Figure 4-4 and Figure 4-5 show the plot of the energy intensity of the DBBF from years 2014/15-2017/18 G.C and the energy intensity of the selected textile plants taken as a benchmark, respectively. The graph also compares the specific energy of the DBBF and the selected benchmark textile plants. The selected benchmarks have higher energy efficiency performance as compared to other textile factories. The annual electric energy intensity at DBBF in the years 2014/15 to 2017/18 ranges from 5.58kWh/kg to 8.56kWh/kg for yarn and fabric production with an average energy intensity of 6.79kWh/kg. The total electric energy intensity of various plants taken as benchmark [35] shown in Figure 4-5, gives an average electric energy intensity of 3.65kWh/kg. Therefore, a difference of $(6.79 \text{ kWh/kg} - 3.65 \text{ kWh/kg})$ 3.14kWh/kg average electric energy intensity exists between the benchmark and DBBF. This result shows that the electrical energy efficiency performance of DBBF is lower as compared to the best practices or benchmarks. This also means there is unnecessary electrical energy loss in DBBF to produce a unit product. Therefore, there is inefficiency in electrical energy use.

Concerning fuel energy intensity of DBBF in the years 2014/15 to 2016/17 ranges between 8,440 kJ/kg to 12,238kJ/kg then goes down to 7,506 kJ/kg during 2017/18 of yarn and fabric production with average intensity of 9,495kJ/kg. The fuel energy intensity of various plants

taken as benchmarks shown in Figure 4-5, give average energy intensity of 11,120 kJ/kg. This result shows that the fuel energy intensity of DBBF is less than or near to the fuel energy intensity of the selected best practice or benchmark. Therefore, the efficiency in fuel energy use to produce a unit product is found in a good condition or near the benchmark.

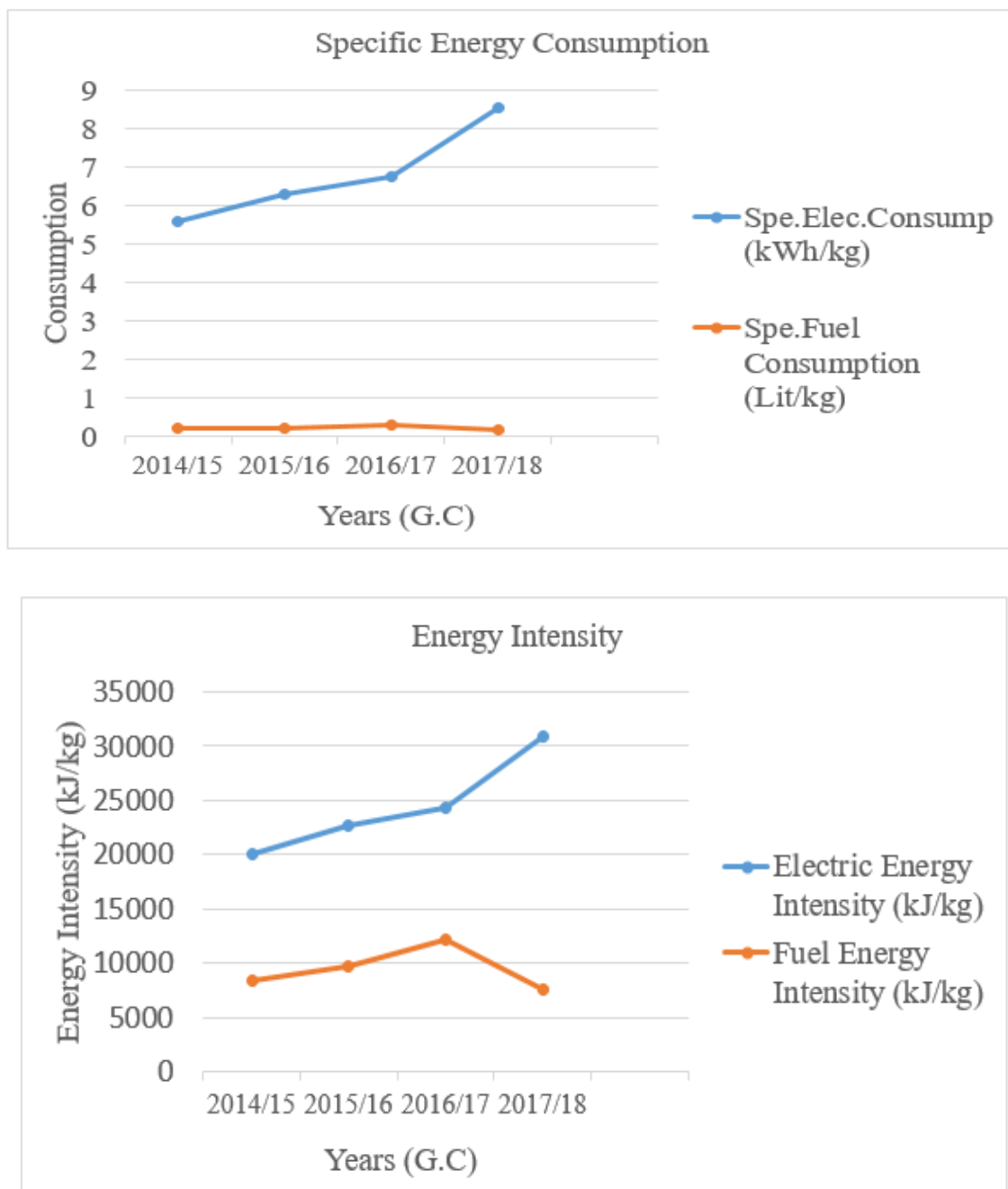


Figure 4-4: The Specific Energy and the Energy Intensity of DBBF

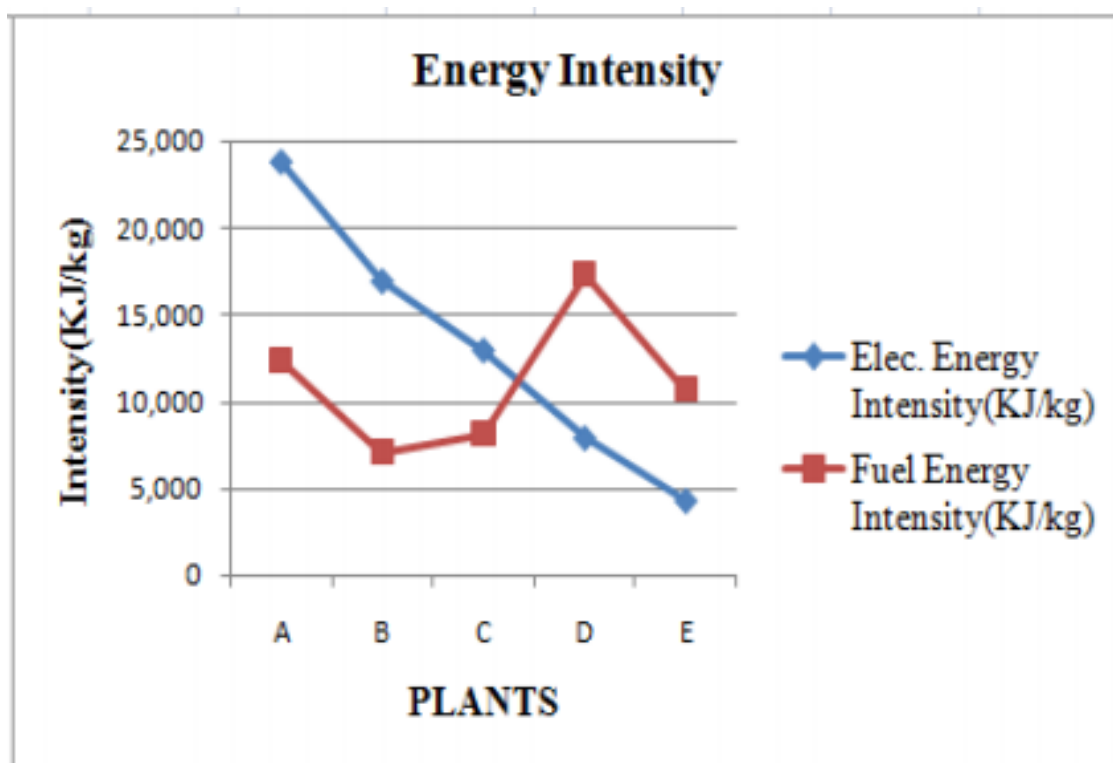
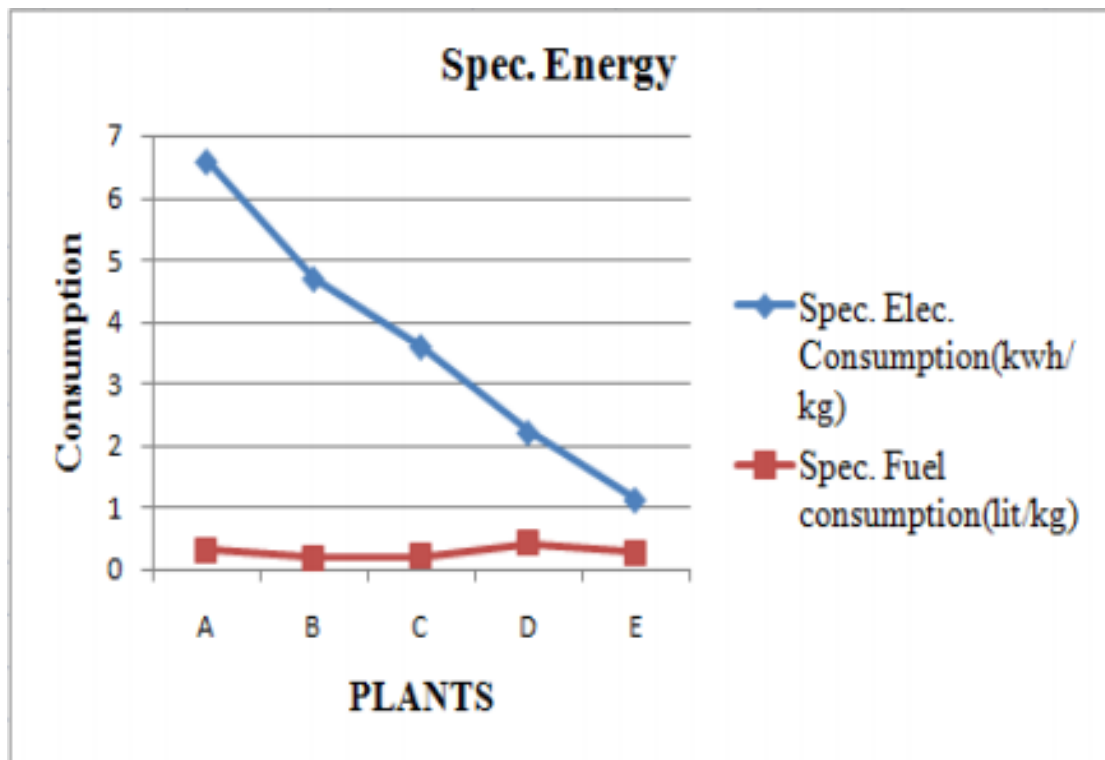


Figure 4-5: The Specific Energy and the Energy Intensity of Selected Plants [35]

▪ **Energy Saving Opportunity from Electric Energy Intensity**

From the analysis of the energy intensity of DBBF, it can be seen that there is a difference of 3.14kWh/kg between the electric energy intensity of DBBF as compared to the selected benchmarks plant experience. This shows that there is a room for improving the electrical energy efficiency of the plant. The following calculation clearly shows how much the factory is actually wasting electrical energy in producing a product.

- Annual average yarn production 260,068.4kg/yr.
- Cost of electricity = 0.0214 US \$/kWh.
- Cost of fuel oil = 0.5868 US \$/ Lit. (2016/17 G.C.)
- Specific heat of furnace fuel oil = 42,200kJ/Lit.
- Difference in average electricity energy intensity= 3.14kWh/kg

Annual cost due to inefficient use of electric energy intensity

$$\begin{aligned}
 &= \text{Electric consumption in kWh} \times \text{Cost of electricity} \\
 &= \text{Energy int. (kWh / kg)} \times \text{Production (kg)} \times \text{Cost of electricity} \\
 &= 3.14 \text{ kWh/kg} \times 260,068.4\text{kg} \times 0.0214 \text{ US } \$ / \text{kWh} \\
 &= \mathbf{17,475.55 \text{ US } \$ / \text{yr.}}
 \end{aligned}$$

This result shows that the factory can spend US \$ 17,475.55 money annually due to inefficient use of electrical energy and it needs to improve its electrical energy intensity use per a product.

4.1.2 Summary and Analysis of the Energy Assessment in the Existing Lighting System

▪ **Energy Saving Opportunity in the Illumination Optimization of the Light**

By referring, the lighting data on Table 3-3 in the previous chapter totally there are 1028 florescent lamps, 392 of which are 36-Watt and 636 are 60-Watt ratings, and are currently installed in the factory. The total installed capacity of the lighting system is 52.270 kW and a daily energy consumption is 836.32kWh. According to the lighting data on Table 3-3, the actual florescent lamps required in the factory is calculated and are 831 lamps. Therefore, there are around 197 unnecessary lamps installed. Because of this, there is electrical energy loss. There are a significant energy differences (ED) between the energy utilization (EU), due to currently install florescent lamps, and the actual energy required (ER). This shows that there are energy losses due to miss use of lighting systems in the factory.

According to the Table 3-3 and using the appropriate illumination, only 831 lamps would be required whereas the currently installed number of fluorescent lamps in the DBBF are 1,028. This result in total reduction of 197 lamps, which is equivalent to the following savings.

Power Saving (PS):

$$\begin{aligned} \text{PS} &= [(\text{Number of FL with 36W Rating}) + (\text{Number of FL with 60W Rating})] \\ &= [(73 \times 36\text{W}) + (124 \times 60\text{W})] \\ &= (2628\text{W} + 7440\text{W}) \\ &= \mathbf{10.06 \text{ kW}} \end{aligned}$$

Energy saving (ES):

$$\begin{aligned} \text{ES} &= (\text{Power Saved} \times \text{Hours of operation/day} \times \text{Number of days of operation/year}) \\ &= (10.06\text{kW} \times 16\text{hrs/day} \times 306\text{days/yr.}) \\ &= \mathbf{49,253.76 \text{ kWh/yr.}} \end{aligned}$$

Money saving (MS):

$$\begin{aligned} \text{MS} &= (\text{Annual Energy Saving} \times \text{Energy Cost Rate/kWh}) \\ &= (49,253.76 \times \text{US } \$ 0.0214) \\ &= \mathbf{1,054.03 \text{ US } \$/\text{yr.}} \end{aligned}$$

Simple Payback Period (SPP):

$$\begin{aligned} \text{Cost of implementation} &= \text{Small Money} \\ \text{SPP} &= \text{Investment} / \text{Money Saving} \\ &= \text{Small Money} / \text{Money Saving} \\ &= \mathbf{0 \text{ yr. (Immediate)}} \end{aligned}$$

Therefore, by optimization of the existing lighting system the DBBF can save an energy of 49,253.76 kWh annually.

- **Energy Saving Opportunity in Replacing T-12 FL Tubes by T-8 FL Tubes**

Almost all the type of fluorescent lamps that have been found in DBBF are T-12 tube florescent lamps. The initial output and energy consumption of these lights is high. These also have extremely poor efficiency, lamp life, lumen depreciation, and colour rendering index. T-8 tubes generally last 60% longer than T-12 tubes, which lead to savings in maintenance costs. Typical energy savings from the replacement of a T-12 lamp by a T-8 lamp are around 30% [30].

Referring to Table 3-3, there are 1028 T-12 tube lamps currently installed in the factory. After the correct installation, however, only 831 lighting points would be required. Replacing these 831 T-12 lamp tubes with T-8 lamp tubes, the factory can have the following savings.

Power Saving (PS):

$$\begin{aligned} PS &= (0.3 \times \text{Actual Lamp Required} \times \text{Lamp Rating})/1000 \\ &= (0.3 \times 279 \times 36W)/1000 + (0.3 \times 552 \times 60W)/1000 \\ &= \mathbf{12.94kW} \end{aligned}$$

ER = 622.81kWh/day (from Table 3-3)

Energy Saving (ES):

$$\begin{aligned} ES &= (0.3 \times \text{Energy Required/day} \times \text{Number of days of operation/year}) \\ &= (0.3 \times 622.81\text{kWh/day} \times 306 \text{ days/yr.}) \\ &= \mathbf{57,173.95 kWh/yr.} \end{aligned}$$

Money Saving (MS):

$$\begin{aligned} MS &= ES \times \text{Energy Cost Rate/kWh} \\ &= 57,173.95 \text{ kWh/yr.} \times 0.0214 \text{ US \$/kWh} \\ &= \mathbf{1,223.52 US \$/yr.} \end{aligned}$$

Simple Payback Period (SPP):

$$\begin{aligned} \text{Cost of implementation} &= \text{US \$ } 2,626.01 \\ \text{SPP} &= \text{Investment} / \text{Money Saving} \\ &= \text{US \$ } 2,626.01 / \text{US \$ } 1,223.52 \\ &= \mathbf{2.14\text{yrs.}} \end{aligned}$$

- **Energy Saving Opportunity in Removing Ballasts from Un-used Fluorescent Fixtures**

In many sections of the factory, it was observed a burn out FL. This can cause a reduction in plant illumination levels. Therefore, these ballasts should be removed from the fixtures as the ballasts consume energy even when the tubes are not alive. Table 3-4, in the previous chapter, provides a number of ballasts to be removed. According to this, we can get the following savings.

Power consumption per ballast = 20 Watt

Energy savings (ES):

$$\begin{aligned} \text{ES} &= [(\text{Number of ballast} \times \text{Watt/ballast} \times \text{hours of operation/year})] / 1000 \text{ kWh} \\ &= [(160 \times 20\text{W} \times 4960 \text{ hrs /yr.}) + (26 \times 20 \text{ W} \times 2480\text{hrs/yr.})] / 1000 \\ &= \mathbf{17,161.60 \text{ kWh/yr.}} \end{aligned}$$

Money savings (MS):

$$\begin{aligned} \text{MS} &= \text{ES} \times \text{Energy Cost Rate/kWh} \\ &= 17,161.6 \text{ kWh/yr.} \times 0.0214 \text{ US \$/kWh} \\ &= \mathbf{367.25 \text{ US \$/yr.}} \end{aligned}$$

Simple Payback Period (SPP):

$$\begin{aligned} \text{Cost of implementation} &= \text{Small Money} \\ \text{SPP} &= \text{Investment} / \text{Money Saving} \\ &= \text{Small Money} / \text{Money Saving} \\ &= \mathbf{0 \text{ yr. (Immediate)}} \end{aligned}$$

- **Energy Saving Opportunity in the Lighting Controls**

In the factory, there are only manual light control mechanisms. It is observed that there is a time by which some lights are not turned off during non-working time. Due to this, some light energy is wasted. Lights can be shut off during non-working hours by automatic controls, such as occupancy sensors, which turn off lights when a space becomes unoccupied. Occupancy sensors can save up to 10-20% of facility lighting energy use. Manual controls can be used in addition to automatic controls to save additional energy in the factory.

Table 4-4 summarises all the energy analysis for the existing lighting system of DBBF. In general, the factory can save a total of US \$ 2644.80 annually from the improvement of lighting system. Thus, the factory should implement all the energy saving opportunities from the lighting system.

Table 4-4: Summary and Energy Analysis of the Existing Lighting System at DBBF

Existing Lamps					
Number of Lamps		Total Rating (kW/day)		EU (kWh/day)	
1028		52.27		741.96	
Ways of Improvement					
1. Replacing T-12 Tubes with T-8 Tube Lamps	Replaced No. of lamps	ER (kWh/day)	ES (kWh/yr.) (30%ER)	Cost Saving (US \$/yr.)	
	831	622.81	57,173.95	1,223.52	
	SPP (yrs.) = Investment/Savings			2.14	
2. Illumination Optimization	Reduced No. lamps	Total rating (kW)	ER (kWh/day)	ES (kWh/yr.)	Cost Saving (US \$/yr.)
	197	10.06	622.81	49,253.76	1,054.03
	SPP (yrs.)			Immediate (0)	
3. Dead Ballasts to Remove	Number of ballasts to be removed		Energy Saving (kWh/yr.)	Cost Saving (US \$/yr.)	
	186		17,161.60	367.25	
	SPP (yrs.)			Immediate (0)	
Total US \$ Saving (Annually)				2,644.80	

4.1.3 Summary and Analysis of the Energy Assessment in the Electric Motor

- **Analysing Electric Motors of the factory with Motor Master + International Software**

Many motors of different power ratings are currently in operation in the factory. Most of these motors are old, rewound and not regularly maintained. At present, the motor technology is improved. Energy efficient motors are being designed to transfer the input energy to the shaft very efficiently. Efficient motors also tend to have a better relative performance at part load, which is of increased benefit for applications with variable load requirements. In this regard, there is a high opportunity to save energy in the factory. The under loaded motors can be

selected and analyse from Table 3-5 in previous chapter using Motor Master + international software.

Figure 4-6 through Figure 4-8 shows how Motor Master + international software selects the required motor to specific application and evaluates the energy saving potential and effectiveness of the efficient motors of the factory.

Figures 4-6 through 4-8 show a sample outputs of the Motor Master +international (IMSSA) software. The energy saving and simple payback period columns explain the kWh energy savings per year and the number of years required to recover the investment in energy efficient motors, respectively. The investment cost, which is paid in short payback period, needed to buy that energy efficient motors was effective. From the energy analysis summarized in Figure 4-8, i.e. to buy an energy efficient motor, the factory should pay US \$ 4,095 to purchase the motor, US \$ 222 for the installation. However, these costs will be back after 1.83 years with an energy savings of 31,354 kWh per year and 2,227 US \$/yr. of cost saving with reduction of 12.2 ton/yr. CO₂. This is due to replacement of under load motors with proper sized motors and standard electric motors with energy efficient electric motors.

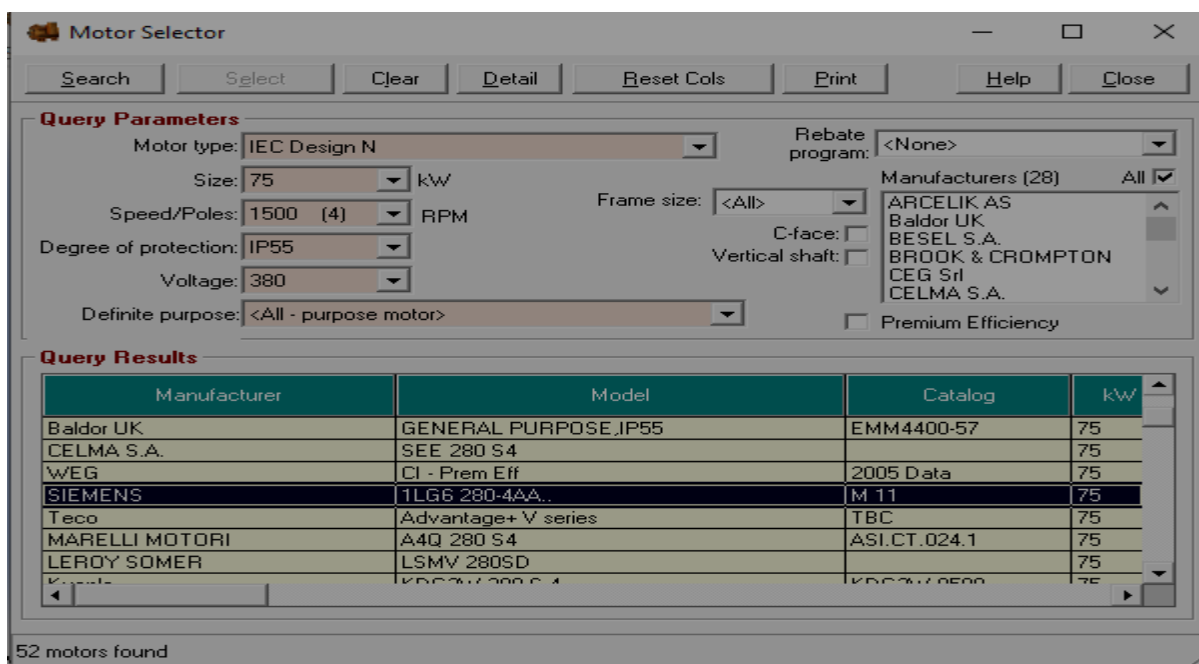


Figure 4-6: Energy Efficient Motor Selection from Motor Master Catalogue

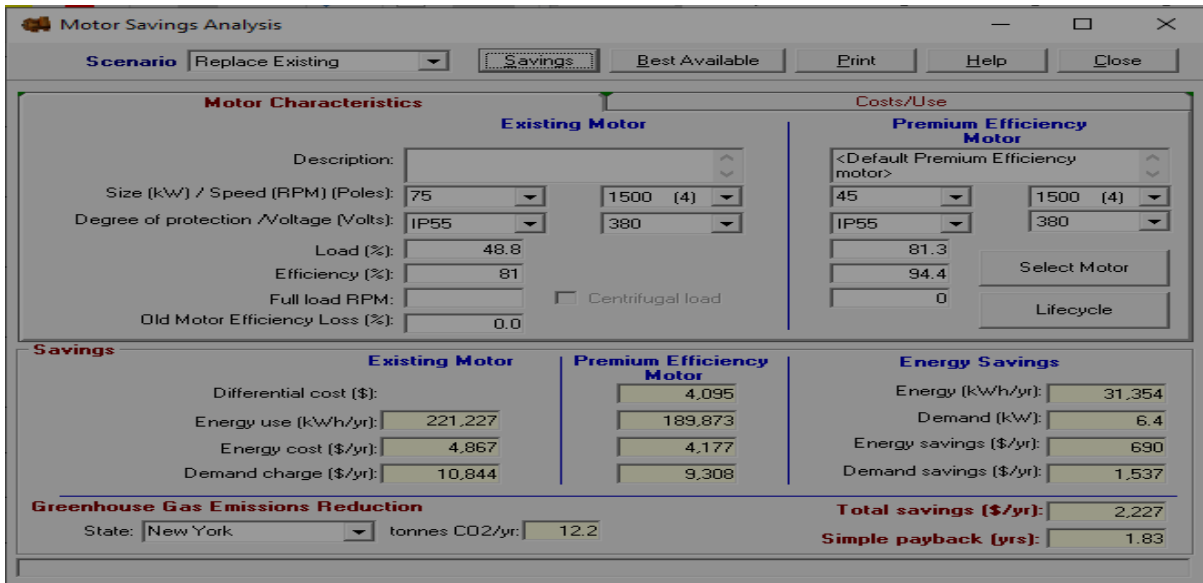


Figure 4-7: Energy Saving Potential of Energy Efficient Motor versus Existing (Standard) Motor

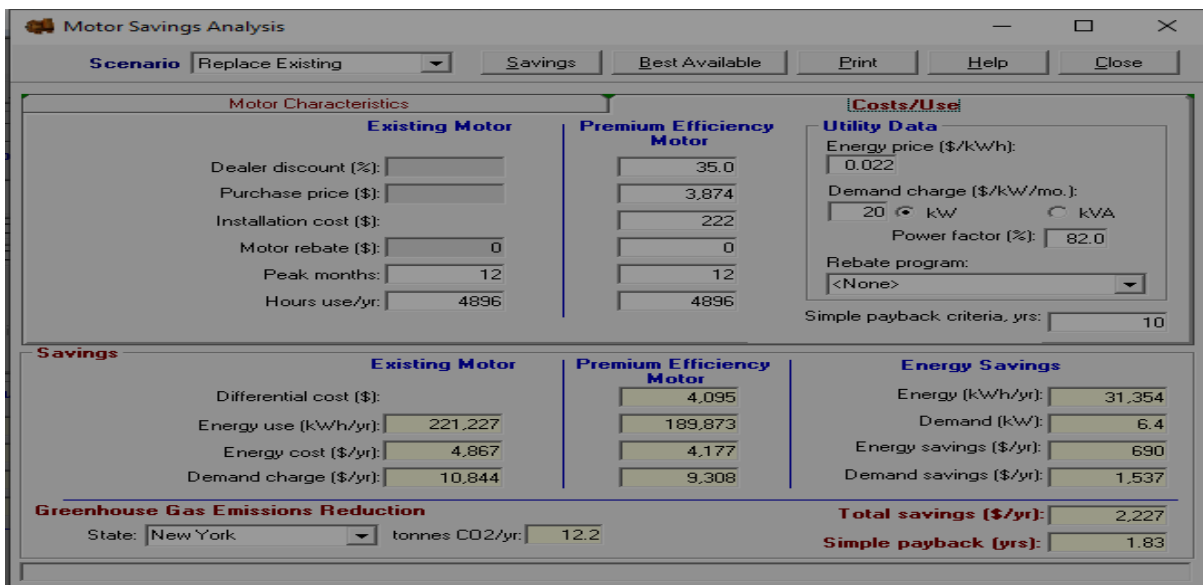


Figure 4-8: Saving Energy Potential and Utility Cost Effectiveness of Energy Efficient Motor as Compared to Existing (Standard) Motor

▪ **Energy Saving Opportunity in the Existing Under-Loaded Electric Motors**

The summarized potential of energy and cost saving of proper sized motors and energy efficient motors as compare with the existing (standard) inefficient electric motors of the factory are shown in Table 4-5. As discussed in chapter-3, motors operating below 75% of full load relatively reduces their efficiency and motors operating below 50% totally inefficient, electric motors operates under load should be replaced.

Replacement of large, partially loaded motors with smaller, full loaded motors from either company stock or new energy efficient motor is significant. As the result, replacement of standard motors with energy efficient motors i.e. replacement of under load motors with proper sized motor can save 120.3 MWh of energy and US \$ 8,545 of money per year and with pay back periods of ranging from 1.52 to 6.29 years.

Table 4-5: Summary of Electric Motors with Replacement of Under-load Operating Motors with Proper Sized Motors.

No.	Existing Motor				Replaced Efficient Motor				Invest. Cost (\$/yr)	Energy Saving (kWh/yr)	Money Saving (\$/yr)	SPP (yrs.)	CO ₂ Reduction (ton /yr)
	Motor Type	kW	Load (%)	η (%)	kW	Load (%)	η (%)	Motor Type					
1.	Standard	30.5	41.4	80	18.5	67.1	92.4	Premium Efficiency Motor	1,989	10,177	723	2.75	4
2.	Standard	3	47.7	75	1.5	95.4	85.3	Premium Efficiency Motor	399	1,124	80	4.99	0.4
3.	Standard	90	48.6	87.2	55	79.5	94.6	Premium Efficiency Motor	4,351	19,295	1,370	3.17	7.5
4.	Standard	2	39.8	75	1.1	79.6	84.1	Premium Efficiency Motor	276	618	44	6.29	0.2
5.	Standard	5.5	44.2	75.5	3.7	65.7	88.5	Standard Efficiency Motor	339	2,310	165	2.05	0.9
6.	Standard	44	42.1	80.3	22	86.1	93.1	Premium Efficiency Motor	2,259	15,915	1,130	1.99	6.2
7.	Standard	7.5	41.3	75	3.7	83.7	88.7	Standard Efficiency Motor	339	3,132	222	1.52	1.2
8.	Standard	5.5	44.5	80.3	3.7	66.1	88.5	Standard Efficiency Motor	339	1,389	101	3.34	0.5
9.	Standard	75	48.8	81	45	81.3	94.4	Premium Efficiency Motor	4,095	31,354	2,227	1.83	12.2
10.	Standard	11	28.3	75.5	4	77.8	88.7	Premium Efficiency Motor	657	2,997	213	3.08	1.2
11.	Standard	55	46.7	80.3	30	85.6	93.7	Premium Efficiency Motor	2956	22,459	1,595	1.85	8.8
12.	Standard	7.5	42.6	78	3.7	86.4	88.7	Standard Efficiency Motor	339	2,416	172	1.97	0.9
13.	Standard	18.5	43.2	78.5	11	72.7	91.5	Premium Efficiency Motor	1,111	7,079	503	2.20	2.8
Total									19,449	120,265	8,545		46.8

- **Other Energy Saving Opportunity in the Existing Electric Motors**

In DBBF, the maintenance condition of the motors is poor. This is because there is no a regular schedule for measuring the line voltages and currents to check the line imbalance and loading conditions of the motors. They do not inspect motors regularly for wear in bearings and housings, to reduce frictional losses, and for dust in motor ventilating ducts, to ensure proper heat dissipation. Although more motors do have their own ventilating fan for cooling, there are some motors, which do not have fan for ventilation. Also appropriately, lubrication is not done according to the manufacturer's recommendations. Thus, a proper on going motor maintenance program should be applied to minimize unnecessary energy and efficiency loss.

Motor rewinding is also another common practice in DBBF. However, there are some problems in the process, removing the old winding, selecting wires of appropriate size, slot size design and rewinding the motors more than one times. All these have an impact on the efficiency of the rewound motor. However, if proper measures are taken, the motor efficiency can be maintained after rewinding.

4.1.4 Summary and Analysis of the Energy Assessment in the Air Compressor

During the audit, electrical and non-electrical compressor performance parameters were measured using different instruments to yield efficiency statistics. In addition, using the important mathematical formulas Equation 2.16 through Equation 2.33 and Table 4-6 summarise all the useful results. See the mathematical calculation in Appendix-D.

From Table 4-6, the annual energy loss from both air compressors is calculated and it is 72,536.76 kWh, which is equivalent to US \$ 1,552.27 annually. Some of the reasons for such energy losses are dirty intake air filter, air leaks from the pipes, and unnecessary use of air for cleaning purpose.

Therefore, it is advisable to avoid or minimize all the causes for such energy losses by regularly cleaning and changing the entire intake air filter and by arresting all the air leaks around the piping system. This can be done by investing a very negligible money and making a regular maintenance.

Table 4-6: Summary of Energy Analysis and Saving from Compressor No-1 and No-2

No.	FAD TEST and NO-LOAD TEST		
	FAD TEST		
	Parameter	Results	
1.	Air Compressor Type	Air compressor no.1	Air compressor no.2
2.	Air Speed (m/s)	14.1300	14.9333
3.	Inlet Air Suction Area (m ²)	0.00678	0.0059
4.	Actual Flow Rate (m ³ /min)	4.3260	3.9419
5.	Average Loading Power (kW) / Loading Pressure (Bar)	16.64 / 6.6	26.89 / 6.8
6.	Average Loading Time (Sec)	21.59	24.28
7.	Average Un-loading Power (kW) / Un-loading Pressure (Bar)	7.85 / 7.8	9.25 / 7.8
8.	Average Un-loading Time (Sec)	29.56	33.04
9.	Design Flow Rate (m ³ /min)	6.0760	3.54
10.	Actual SPC (kW/cfm)	0.1077	0.1910
11.	Design SPC (kW/cfm)	0.1013	0.1867
12.	Deviation SPC (kW/cfm)	0.0064	0.0042
	Deviation kW (Loss power due to FAD Test)	0.9887 kW	0.5912 kW
	Air- Leak (NO-LOAD) TEST		
13.	Loading Pressure (Bar)	6.5	6.8
14.	Un-Loading Pressure (Bar)	7.2	7.8
15.	Average Loading Time (Sec)	21.59	24.28
16.	Average Un-Loading Time (Sec)	29.56	33.04
17.	% of Leakage During Loading Time	42.20 %	42.35 %
18.	Actual Free Air Leakage (cfm)	65.1947	59.6212
	Equivalent Power Loss Due to Leakage	7.0214 kW	11.9788 kW
	Total Energy/ Money Loss	29,413.08 kWh/yr.	43,123.68 kWh/yr.
	Total Energy/ yr & US \$/yr	629.43 US \$/yr. & 922.84 US \$/yr.	
	Total Energy/ yr & US \$/yr	72,536.76 kWh/yr. & 1,552.27 US \$/yr.	
	Possible Reasons	-Dirty intake air filter, air leaks	- Air leakages, dirty intake air filter & unnecessary use of air (cleaning)
	Recommendation	- Arresting leakages - Clean filter	- Arresting leakages - Clean intake air filter
	Investment, (US \$)	-Negligible (Setting & Regular Maintenance)	- Negligible (Setting & Regular Maintenance)
	SPP (yrs.)	0 (Immediate)	0 (Immediate)

4.1.5 Summary and Analysis of the Energy Assessment in the Boiler

- **Boiler Efficiency Assessment**

The summary of losses due to each loss component (Such as LDFG, LH₂F, LMF, LMA, LIC, LRC losses) using Equation 2.35 for the Boiler No-1 is given in Table 4-7.

Table 4-7 shows that the boiler efficiency is somewhat in a good sate. However, the boiler side temperature was found to be in the range of 70-81 °C and body temperature in the range of 48-55°C, which is somehow larger than the expected. This shows that the insulation of the boiler is not satisfactorily insulated and need to be maintained. The boiler steam lines have been observed that some steam lines have not been insulated.

The steam line just at the out let of the boiler is not insulated and the condensate line at the header inlet is not insulated. So, the factory is expected to insulate all.

Table 4-7: Summary of Loses of Boiler No-1

Particulars	Unit	Boiler No-1
Heat loss due to dry flue gas losses	%	10.8930
Heat loss due to H ₂ fuel	%	7.0840
Heat loss due to moisture in fuel	%	0.0327
Heat loss due to moisture in air	%	0.2867
Heat loss due to incomplete combustion	%	0
Heat loss due to surface radiation & convection	%	2.5
Boiler efficiency, $\eta=100$ - (Summation of all losses)	%	79.20

- **Boiler Energy Conservation and Saving Opportunities**

The temperature of the flue gas was measured and found to be 209 °C from boiler no-1, which is being wasted as a flue without any use. The flue temperature can be recovered and used as a preheat for furnace or feed water using economizer as shown in Figure 4-10.

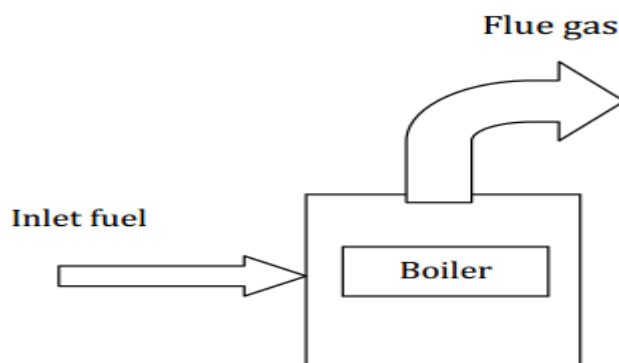


Figure 4-9: Existing Boiler System

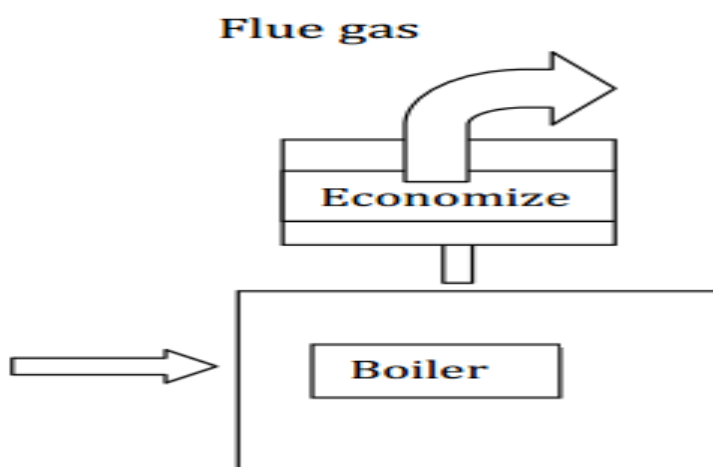


Figure 4-10: After Correction of the Boiler System

The dry flue gas loss in the Boiler No-1 is 10.89%. This is due to the excess air supply in the boiler. Oxygen percentage obtained at the stack in Boiler No-1 is 9.1 %, which is larger than the standard O₂ % of light fuel oil (4-6%) and the CO₂ percentage is 11.4 % which is in the range of the standard. The actual excess air quantity obtained for Boiler No-1 is about 76.47%, which is higher than the standard allowable excess air to light fuel oil (LFO) fired boiler, which is in the range of (10-20%). Energy wastage occurs in cases where it uses too much excess air, as the energy that transfers to the steam is instead used to heat the air. Boilers operating with less than 15% excess air, on the other hand, hold significant energy saving potential by reducing excess air (Approximately 0.06% efficiency rise per every 1% reduction in excess air according to the Indian Bureau of Energy Efficiency). Therefore, the factory expected to reduce the excess air in order to reduce the amount heat, which is a wastage through the stack.

Table 4-8: Energy Conservation Measures for Boiler No-1

Boiler	Finding / Recommendation	Energy Saving
Boiler No-1	<p>Finding: Excess Air - Oxygen = 9.1% - Excess Air = 76.47% - Allowable Excess Air = 20% max - Excess Air amount to reduce = 56.47%.</p> <p>Recommendation: - Reduce Excess Air to allowable value (15% -20%) - Each 1% reduction in Excess Air raises efficiency approximately by 0.06%. -Efficiency gain. This can be done by controlling the air inlet blower.</p>	<p>-Excess Air to reduce = 76.47% - 20% = 56.47%</p> <p>-Efficiency Raise = 56.47% × 0.06 = 3.38%</p> <p>- Annual Furnace oil Consumption = 65,015.6 Lit</p> <p>- Annual FO Savings = 2,197.52 Lit</p> <p>- Price per Unit of Sale = 0.5926 US \$ - Saving in US \$ = 0.5926 × 2,197.5 = 1,302.23 US \$/yr.</p> <p>- Remedy = control excess air - Investment = Negligible - SPP (yrs.) = Immediate (0)</p>

4.1.6 Summary and Analysis of the Power Quality Problems

- **Voltage and Current Unbalance Factors**

Referring to the Chapter-3, from the Table 3-11 and Table 3-12, the voltage and the current unbalance factors for the factory distribution system are within the standard values according to Table 2-7 (< 3% for voltage and <10% for the current). Therefore, no need of mitigation.

- **Power Frequency Variations**

The permissible value of power frequency variations according to the IEEE standard for normal operation is ± 0.5 (49.5 Hz to 50.5 Hz at 50 Hz nominal frequency). Based on this standard, the measurement results as shown in the Table 3-13 indicates that the power frequency does not vary much from the permissible limits.

- **Flickers**

By comparing the measured values of P_{st} and P_{lt} from Table 3-14 with the IEC-61000-3-7 standard limits the short-term flicker (P_{st}) (almost all) (i.e. $P_{st} < 1.0$) and the long-term flicker (P_{lt}) (all) values are within the acceptable limits (i.e. $P_{lt} < 0.8$). In addition, in the factory there are no luminance fluctuations. Therefore, the problem of flickering is not a concern and this is due to the absence of high power loads drawing a fluctuating current.

- **Harmonics**

As shown in Table 3-15 and Table 3-16 , the voltage distortion THD_V values obtained in the three phases are within the permissible range of the IEEE voltage distortion limits (i.e. $THD_V < 5\%$), but for current distortion THD_I , it is beyond the limit (i.e. $THD_I > 10\%$). Therefore, the THD_I needs a mitigation.

Table 4-9: The Percent Values of Voltage and Current Harmonic Levels at Each Phase

Harmonic Order	Phase-1				Phase-2				Phase-3			
	V(V)	I(A)	V(%)	I(%)	V(V)	I(A)	V(%)	I(%)	V(V)	I(A)	V(%)	I(%)
1	227.72	402.30	100	100	226.40	437.80	100	100	228.92	381.90	100	100
3	2.04	10.06	0.9	2.5	2.26	13.13	1.0	3.0	2.29	11.08	1.0	2.9
5	2.73	59.14	1.2	14.7	3.40	67.89	1.5	15.5	2.98	57.67	1.3	15.1
7	2.50	60.75	1.1	15.1	2.93	70.49	1.3	16.1	2.98	61.10	1.3	16.0
9	2.28	4.43	1.0	1.1	2.72	6.57	1.2	1.5	2.52	3.44	1.1	0.9
11	0.68	3.62	0.3	0.9	0.68	3.94	0.3	0.9	0.92	2.30	0.4	0.6
13	0.46	1.81	0.2	0.45	0.68	2.01	0.3	0.46	0.67	1.57	0.3	0.41
15	0.46	1.37	0.2	0.34	0.45	1.53	0.2	0.35	0.46	0.80	0.2	0.21
	$THD_V(\%) = 2.15, THD_I = 21.28$				$THD_V = 2.56, THD_I = 22.63$				$THD_V = 2.43, THD_I = 22.22$			

From the Table 4-9, TDD value can be computed using the Equation 2.38 for the rated current of 437.80A as follow:

$$TDD(\%) = \frac{\sqrt{\sum_{h=2}^{\infty} (I_h)^2}}{I_L} \times 100$$

$$\sqrt{\sum_{h=2}^{\infty} (I_h)^2} = 99.07A$$

$$TDD(\%) = \frac{99.07A}{437.80A} \times 100$$

$$= 22.63\%$$

According to Table 2-5, the result of TDD, 22.63%, is out of the limit (>8%). It is therefore necessary to install harmonic filters for filtering out the harmonics to meet the IEEE standards. By applying the recommended procedures, shown in Equation 2.39 through Equation 2.56, the mathematical calculations for the design and validation of single-tuned passive harmonic filters for 3rd, 5th and 7th harmonics are summarized in Appendix-F. Therefore, the designed parameters of the multi-branch single-tuned passive harmonic filters are summarised in Table 4-10.

Table 4-10: Design Parameters of Multi-branch Passive Harmonic Filter

Branch	$Q_C(kVAR)$	$V_C(V)$	$X_C(\Omega)$	$C(mF)$	$X_L(\Omega)$	$L(mH)$
3 rd	15.00	480.00	15.36	0.2072	1.70	5.4110
5 th	60.00	480.00	3.84	0.8289	0.153	0.4870
7 th	60.00	480.00	3.84	0.8289	0.078	0.2482

• Mitigation of Harmonic Pollution

The solutions for harmonic pollutions have been simulated using MATLAB Simulink software and the MATLAB model is shown in Figure 4-11 and Figure 4-16. The MATLAB model shown in Figure 4-11 shows the modelling of the DBBF's power source and the load. The power source is modelled using a three-phase source and the load harmonic is modelled using a current source for each current harmonics, the 3rd, 5th, and 7th for each phase lines, which are injected to the source side. The designed multi-branch harmonic filters F-3, F-5, and F-7 for 3rd, 5th, and 7th harmonic currents respectively are simulated to see if they can efficiently reduce the distortion levels to acceptable values.

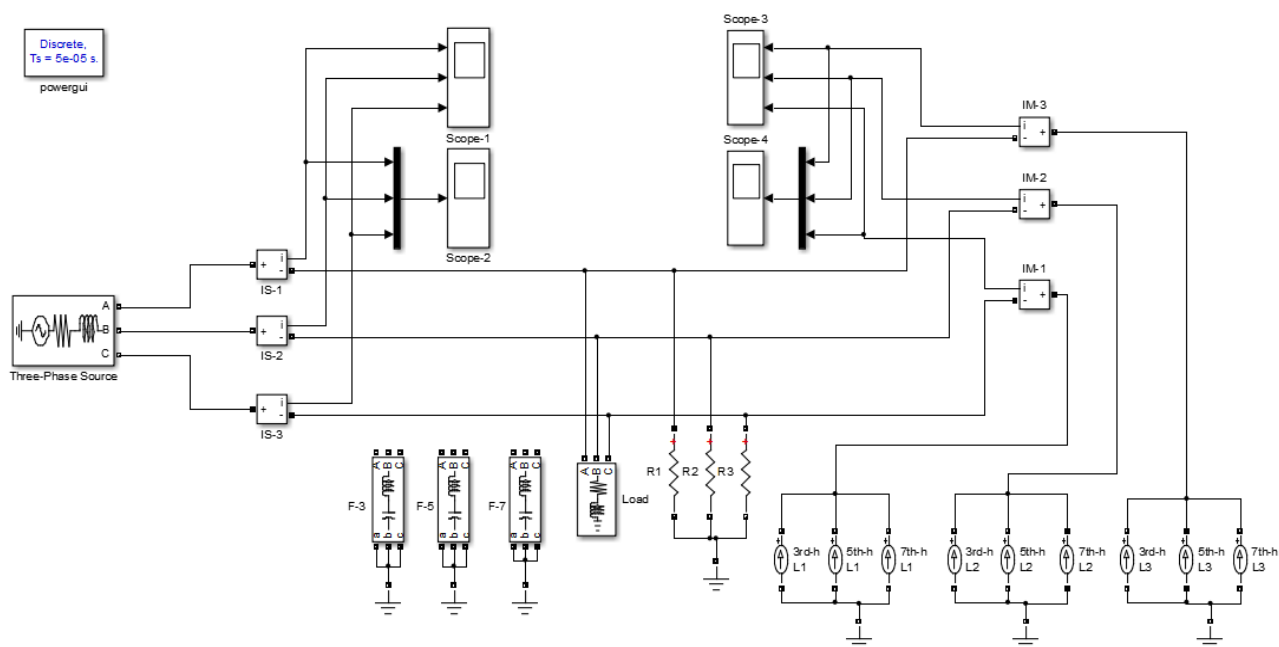


Figure 4-11: MATLAB Simulation Model of the Factory's Power Source and the Load without the Harmonic Filter

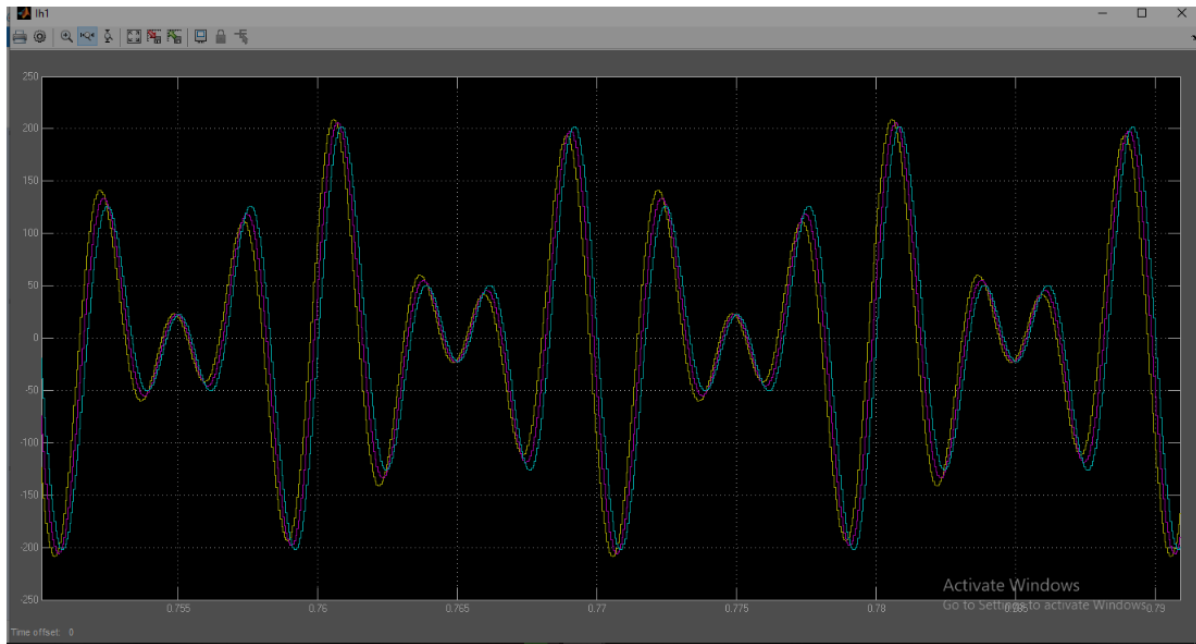


Figure 4-12: Output of Harmonic Currents Injected by Non-Linear Loads

The current waveforms before and after filtering are present for comparison in Figure 4-13 and Figure 4-17 respectively.

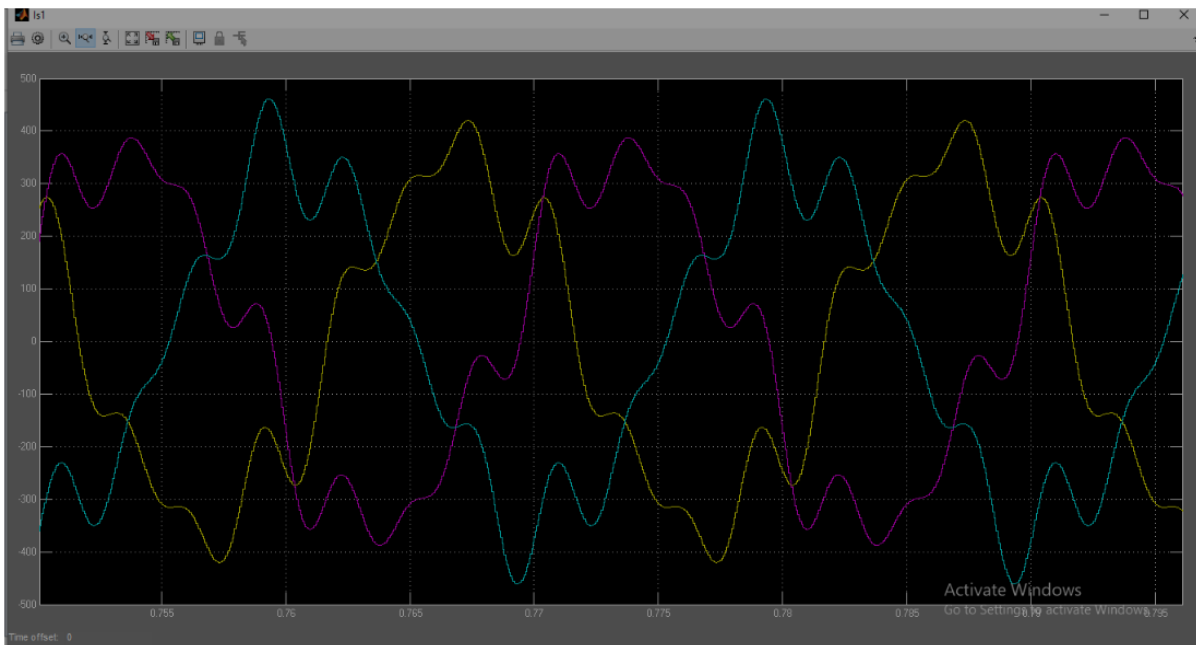


Figure 4-13: Output of Current Waveform without Filter

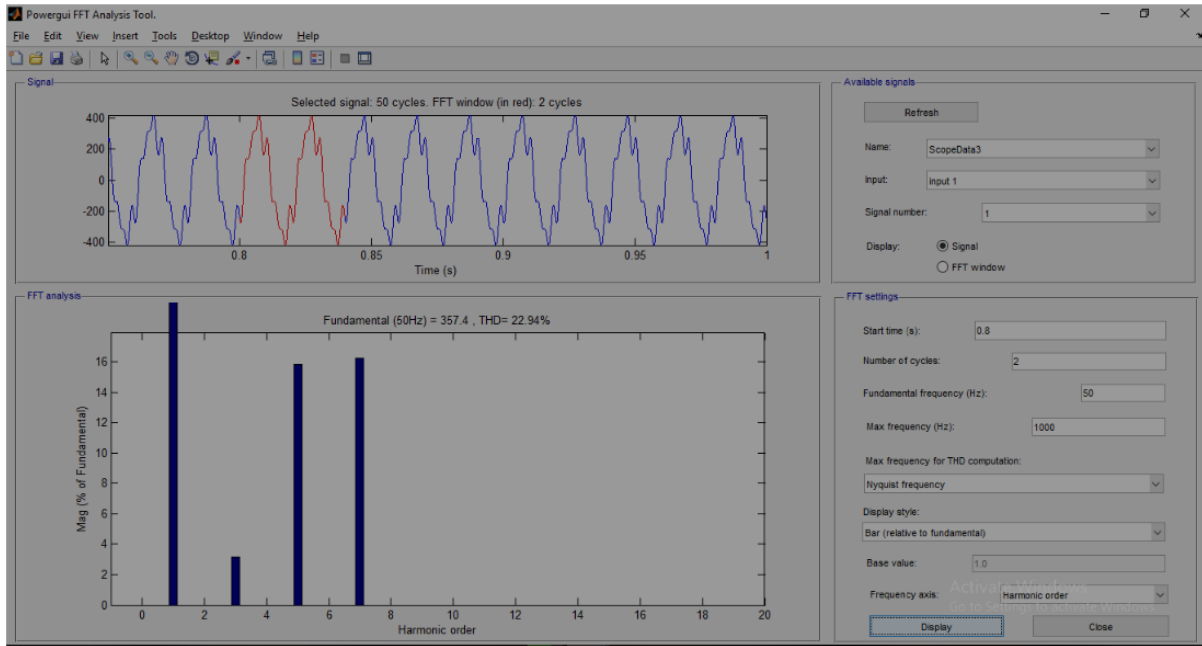


Figure 4-14: Output of FFT Analysis of the Harmonic Currents before Filtering

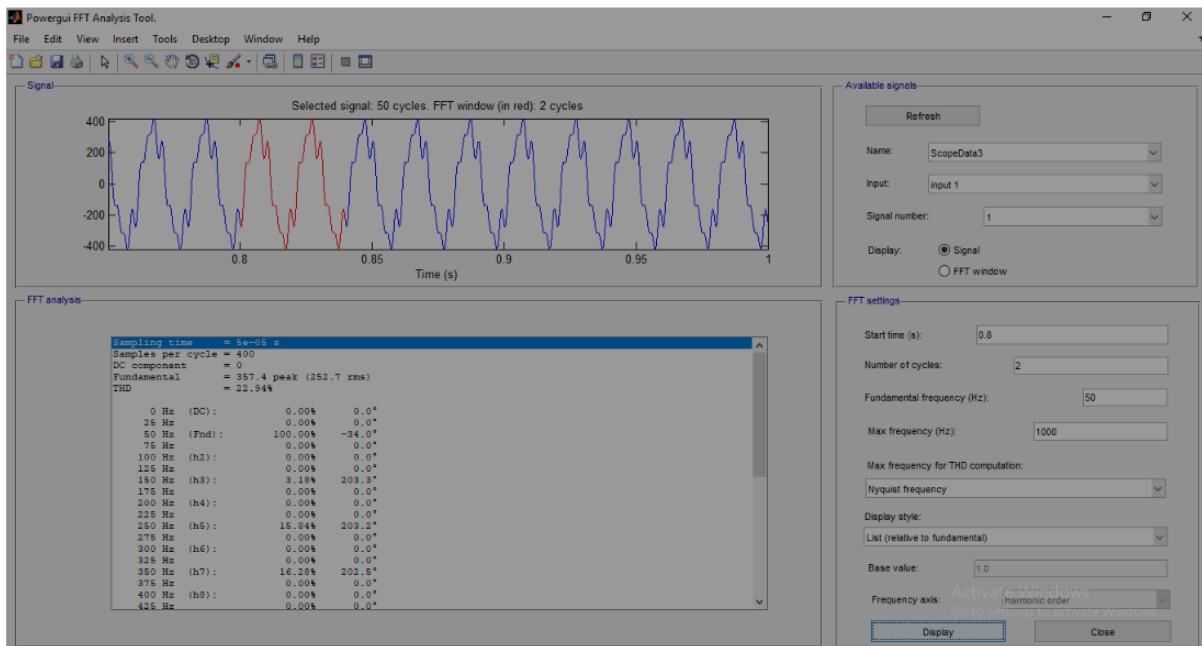


Figure 4-15: Output of FFT Analysis of the Harmonic Currents before Filtering

As it is observed from Figure 4-13, the problem of harmonics produces a distorted waveform and in Figure 4-14, from the Fast Fourier Transform (FFT) analysis, the harmonic distortion levels for the 3rd, 5th, and the 7th are 3.18%, 15.84%, and 16.28% respectively. In addition, THD

value is 22.94, which is above the IEEE acceptable limit, i.e. 10% for this study. Therefore, to alleviate the problem, single-tuned passive harmonic filters for 3rd, 5th and 7th harmonics are used as shown in Figure 4-16. The three designed harmonic filters F-3, F-5, and F-7 are installed now to filter out the 3rd, 5th, and 7th harmonic currents which are injected from the load side.

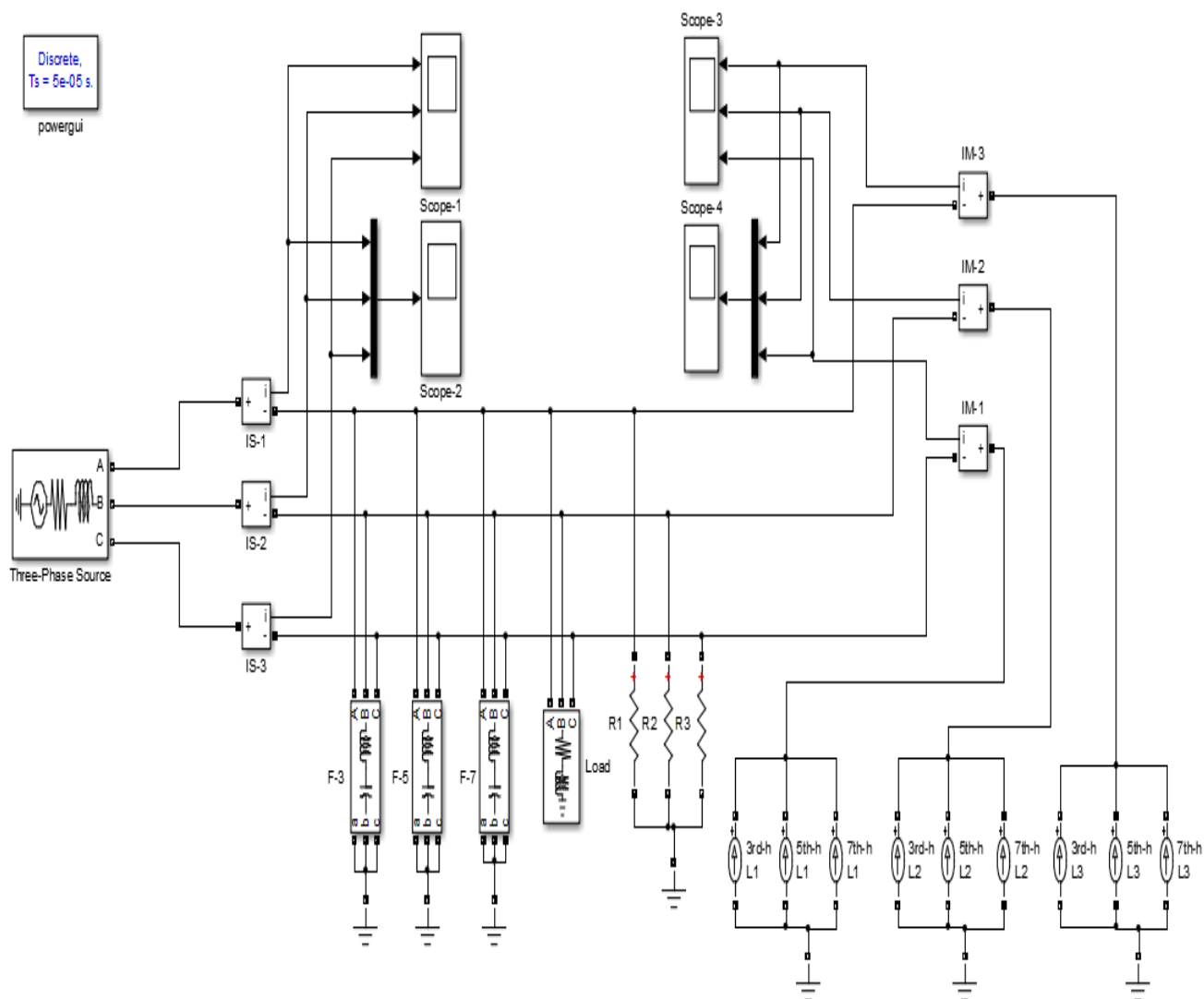


Figure 4-16: MATLAB Simulation Model of the Factory's Power Source and the Load with Installing the Harmonic Filter

Consequently, the resulting waveform after the harmonic filters are installed will be pure sinusoidal, as shown in Figure 4-17.

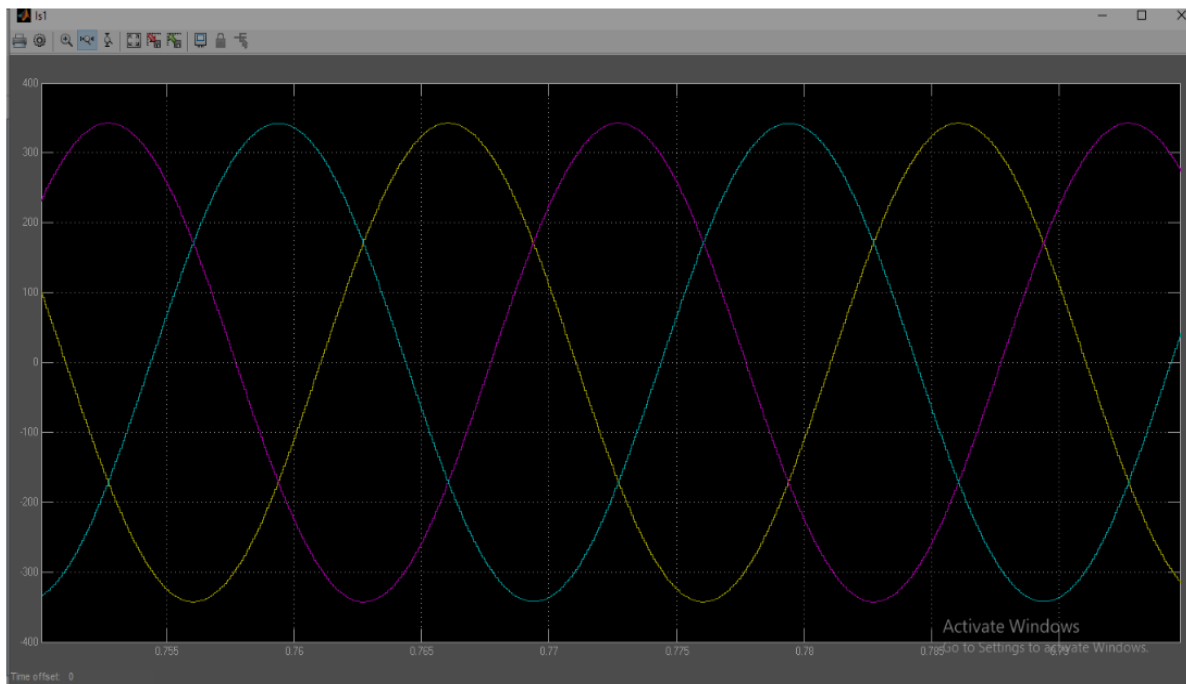


Figure 4-17: Output of Current waveform with harmonic filters installed

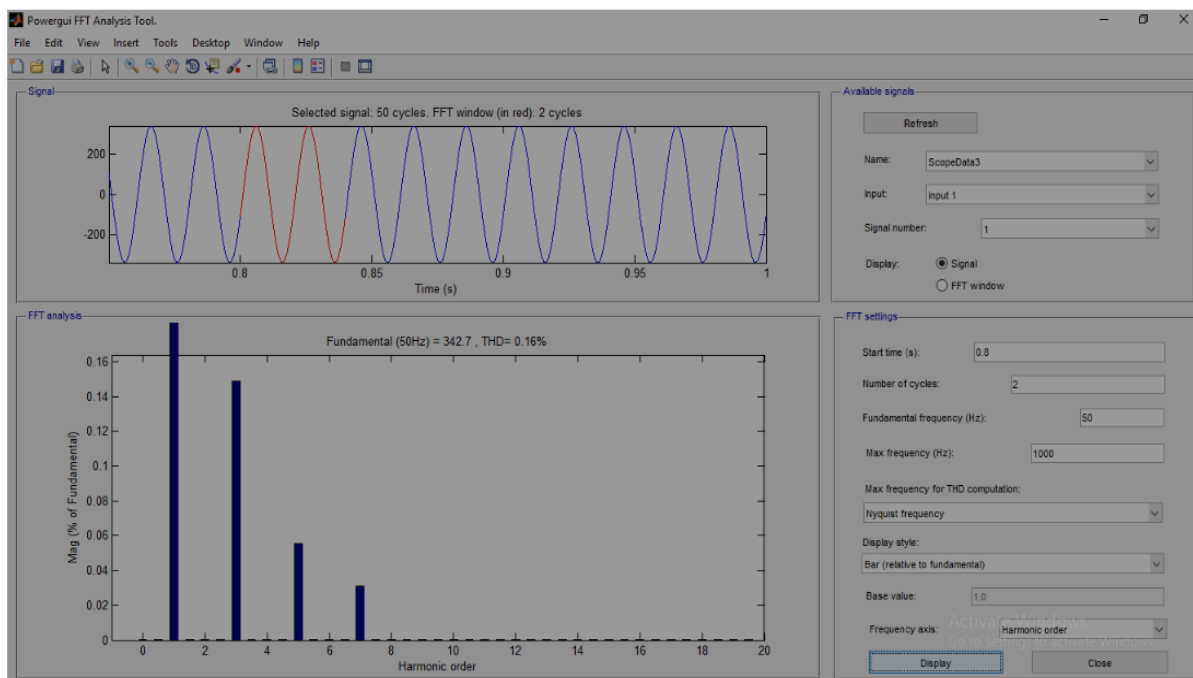


Figure 4-18: Output of FFT Analysis of the Harmonic Currents after Filtering

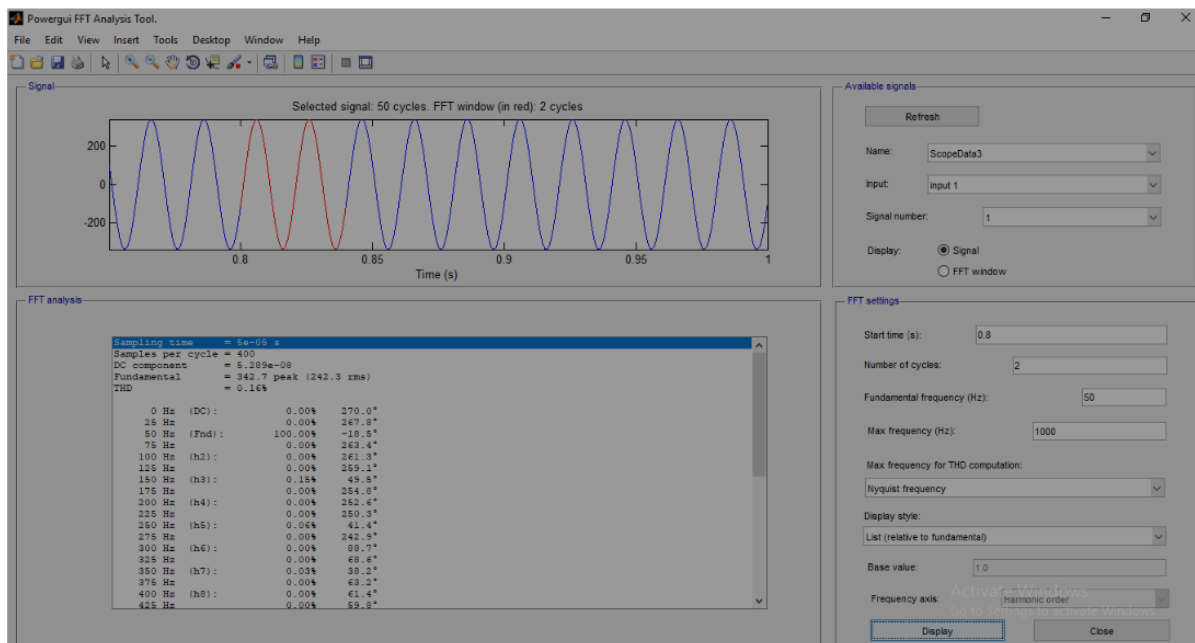


Figure 4-19: Output of FFT Analysis of the Harmonic Currents after Filtering

The results obtained in Figure 4-17 through Figure 4-18 show the multi-branch single tuned filter has significantly reduced the harmonic distortion levels of the 3rd, 5th, and 7th in to 0.15%, 0.06%, and 0.03% respectively. In addition, the current THD level reduces from 22.94 % to 0.16 %, due to the compensation provided by the multi-branch harmonic filter. It is clear that the filters effectively reduce the distortion level to the acceptable magnitude, which is less than 10 %.

CHAPTER -5-

CONCLUSIONS, RECOMMENDATIONS AND SUGGESTIONS FOR FUTURE WORK

5.1 CONCLUSIONS

Debre Berhan Blanket Factory gives good attention on how they are profitable by producing many products. However, they give low attention on follow-up of their energy utilization and energy efficiency. This implies a lot of unnecessary expenditure on energy due to inefficient use of their energy. This study may help them for analysing the progress of their energy utilization and energy efficiency, especially on their lighting system, air compressor, and boiler. Also, on their majority electric motors by using Motor Master + International software. The software helps them on how they can get the energy efficiency opportunities to improve the system.

This study shows that energy efficiency improvement opportunities in some areas. These areas includes optimizing the illumination of the existing lighting system by which the factory can save 49,253.76 kWh/yr. or a money of US \$ 1,054.03 annually. Also by replacement of existing lamps with energy efficient lamps which saves up to 30% of the energy required by the existing lamps. Because of this, the factory can save 57,173.95 kWh/yr. or a money of US \$ 1,223.52 annually.

In addition, replacement of energy efficient motors with the standard motors, selecting of proper sized motors, can save 120.3 MWh of energy and US \$ 8545 of money per year with pay back periods of ranging from 1.52 to 6.29 years. Assessing the energy saving opportunity in air compressor due to dirty intake air filter, air leaks, unnecessary use of air (e.g. cleaning) can save an energy of 72,536.76 kWh/yr. or a money of US \$ 1552.27 annually with a an immediate simple payback period .

Moreover, by reducing the excess air in the existing boiler from 76.47% to allowable excess air value (15% -20%) , there is an opportunity of fuel oil saving of 2,197.52 Lit/yr. or money saving of US \$ 1,302.23 annually with an immediate simple payback period. This can be done simply by controlling the excess air regularly.

Assessment of power quality problems such as voltage unbalance factor, current unbalance factor, and harmonic distortions have been studied and comparisons against the IEEE power

quality standards were made and filters are designed. It is found that the voltage and current unbalance factors, total voltage harmonic distortion (THD_v), power frequency variations, flickers are within the acceptable limits of the IEEE standards. However, the total current distortion (THD_i) were violating the prescribed limit by 45.40%. This was because the factory's transformer supplies non-linear loads like fluorescent lamps, drivers, and induction motors. The designed filters were observed to reduce the total harmonic distortion of the current (THD_i) from 22.94% to 0.16%. In addition, the individual harmonic distortion of the current i.e. the 3rd order current harmonic decrease from 3.18% to 0.15%, the 5th order current harmonic decreases from 15.84% to 0.06%, and also the 7th order current harmonic decreases from 16.28% to 0.03%.

The results meet the IEEE-519 recommended harmonic standards. This reduction in distortion level shows how important a filter is to get rid of the ill effects, additional heating, false tripping and equipment malfunction associated with harmonics. Therefore, by implementing the energy efficiency measures and technologies in this thesis work, the factory can get different benefits by reducing the energy losses and costs.

In general, Table 5-1 summarises all the areas of energy conservation opportunities (ECO) in the DBBF and their respective energy saving and money saving annually.

Table 5-1: Areas of ECO, Annual Energy Saving, and Money Saving

No.	Area of ECO	Energy Save (kWh/yr.)	Money Save (US \$/yr.)
1.	Energy Intensity	-	17,475.55
2.	Lighting System	123,589.31	2644.80
3.	Electric Motor	120,265.00	8545.00
4.	Air Compressor	72,536.76	1,552.27
5.	Boiler	2,197.52 Liter	1,302.23
Total		316,391.07 kWh + 2,197.52 Lit fuel oil	31,519.85 (1,071,674.90 Birr)
6.	Power Quality	- Harmonic reduction by installing harmonic filters	

5.2 RECOMMENDATIONS

If this factory uses Motor Master + International software properly, to select the energy efficient electric motor, they can have best understanding on the electric motor of their energy efficiency, energy saving potentials and on having proper documentation about electric motor operating specifications before the motor disturb the system like fail or name plate paint out.

The factory managers & their staff give low care on how their energy uses resourcefully, which is a means of most successful and cost-effective way of bringing optimum energy consumption. Thus, improving the efficiency of new technologies alone cannot achieve optimal savings, but when combined with a strong energy management program such as good operational and maintenance practices, day to day follow-up on their energy utilization and efficiency as well as understanding on systems perspective can lead to significant savings. The results of this thesis have shown that there is unnecessarily energy lost in DBBF due to the existence of low energy efficient motors, Accessories, lightings etc. thus replacement with energy efficient equipment and proper lighting installation is necessary. The MATLAB simulation results found have also indicated that effective filters parallel to the loads are required to install to reduce the effects of current harmonics.

The factory should acquire additional instrumentation and test equipment, described as follow:

- ✓ Boiler test kit, including either a chemical or electronic flue gas analyzer, thermocouples, or a smoke tester. Boilers should be tested at least daily to confirm that optimum combustion efficiency is being attained.
- ✓ Additional electric consumption/demand meters to be installed in each department to monitor the use of electricity within the department.
- ✓ Some of the boiler steam lines such as the steam line just at the out let of the boiler is not insulated. Detected bare flanges and valves on various section of the steam line should be insulated.
- ✓ Steam meters, which is used to monitor the use of steam by various process departments and equipment.
- ✓ A portable thermocouple/temperature indicator and stethoscope, which are used to check the appropriate operation of steam traps.
- ✓ A portable humidity meter (to replace the inoperative meter owned by the plant), which is used to test moisture content of fabrics being dried in the stenter to prevent over-drying.

- ✓ It is good to the DBBF totally left the fuel furnace and use an electrical boiler machine for better cost minimization.

Thus, the Ethiopian government in collaborate with institutions such as Ethiopian Energy Authority should involve on the technical and financial expenditure of improving energy efficiency and power quality issues of different industries in the country.

5.3 SUGGESTIONS FOR FUTURE WORK

- In this thesis, the FAD test for energy analysis of compressors is carried-out using suction velocity method. Conversely, this method is a little bit less precise than the pump up method, which is desirable for its precise results. Therefore, a future researcher can analyse the FAD test-using pump up method for better results and compare the results of the two methods.
- Some of the energy savings opportunities in this thesis are quick and low cost measures, which can be implemented in the existing systems immediately. The high cost measures such as installing economisers around the boiler flue gas outputs may need further detailed audit and analysis.
- In this thesis, single-tuned passive harmonic filters are designed to avoid harmonics effects in the factory. Other options like active filters, phase-shifting transformers and series reactors can be considered in future research.

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Appendix-A

Sample Data of a Daily Yarn Production during Data Collection

Page _____

DEBRE BERHAN BLANKET FACTORY

BIN CARD

Description _____ Maximum Quantity _____
 Account No. _____ Minimum Quantity _____
 Identification No. _____ Recorder Level _____
 Location _____ Unit of Measure _____

Date	Receiving Report No. / Issue Voucher No.	QUANTITY			
		Receipts	Issues	Balance	Initial
02-10-17	S/B			4251.7	
03-10-17	Y-227	1627.1		5878.8	
" " "	WV-227		1240.7	4638.1	
04-10-17	Y-228	1606.0		6244.1	
" " "	WV-228		1267.7	4976.4	
05-10-17	Y-229	1621.6		6598.0	
" " "	WV-229		1544.4	5053.6	
06-10-17	Y-230	1744.4		6798.0	
" " "	WV-230		1529.5	5268.5	
07-10-17	Y-231	1625.2		6894.3	
" " "	WV-231		1722.7	5171.6	
08-10-17	Y-232	1670.9		6842.0	
" " "	WV-232		1246.2	5595.8	

ABC Printing Press

Form No. C-01
Page _____

DEBRE BERHAN BLANKET FACTORY

BIN CARD

Description ALL Total Maximum Quantity _____
 Account No. 1-7 Minimum Quantity _____
 Identification No. _____ Recorder Level _____
 Location _____ Unit of Measure _____

Date	Receiving Report No. / Issue Voucher No.	QUANTITY			
		Receipts	Issues	Balance	Initial
19-7-17	WV-163		779.0	50406.7	
20-7-17	Y-164	1116.6		51523.3	
" " "	WV-164		1112.6	50410.7	
21-7-17	Y-165	954.7		51365.4	
" " "	WV-165		1322.7	49992.7	
22-7-17	Y-166	1004.6		50987.3	
" " "	WV-166		1153.9	49833.4	
24-7-17	Y-167	835.9		50670.0	
" " "	WV-167		822.5	49847.5	
25-7-17	Y-168	1159.0		51006.5	
" " "	WV-168		1819.9	49186.6	
26-7-17	Y-169	1127.0		50313.6	
" " "	WV-169		1701.0	48612.6	

ABC Printing Press

Appendix-C

Common Capacitor Specifications

Terminal-to-Terminal Voltage	kVAR	No. of Phases	BIL, kV
216	5, 7.5, 13.3, 20, and 25	1 and 3	30
240	2.5, 5, 7.5, 10, 15, 20, 25, and 50	1 and 3	30
480	5, 10, 15, 20, 25, 35, 50, 60, and 100	1 and 3	30
600	5, 10, 15, 20, 25, 35, 50, 60, and 100	1 and 3	30
2,400	50, 100, 150, and 200	1	75
2,770	50, 100, 150, and 200	1	75
4,160	50, 100, 150, and 200	1	75
4,800	50, 100, 150, and 200	1	75
6,640	50, 100, 150, 200, 300, and 400	1	95
7,200	50, 100, 150, 200, 300, and 400	1	95
7,620	50, 100, 150, 200, 300, and 400	1	95
7,960	50, 100, 150, 200, 300, and 400	1	95
8,320	50, 100, 150, 200, 300, and 400	1	95
9,540	50, 100, 150, 200, 300, and 400	1	95
9,960	50, 100, 150, 200, 300, and 400	1	95
11,400	50, 100, 150, 200, 300, and 400	1	95
12,470	50, 100, 150, 200, 300, and 400	1	95
13,280	50, 100, 150, 200, 300, and 400	1	95 and 125
13,800	50, 100, 150, 200, 300, and 400	1	95 and 125
14,400	50, 100, 150, 200, 300, and 400	1	95 and 125
15,125	50, 100, 150, 200, 300, and 400	1	125
19,920	100, 150, 200, 300, and 400	1	125
20,800	100, 150, 200, 300, and 400	1	150 and 200
21,600	100, 150, 200, 300, and 400	1	150 and 200
22,800	100, 150, 200, 300, and 400	1	150 and 200
23,800	100, 150, 200, 300, and 400	1	150 and 200
23,940	100, 150, 200, 300, and 400	1	150 and 200
4,160 GrdY/2400	300 and 400	3	75
4,800 GrdY/2770	300 and 400	3	75
7,200 GrdY/4160	300 and 400	3	75
8,320 GrdY/4800	300 and 400	3	75
12,470 GrdY/7200	300 and 400	3	95
13,200 GrdY/7620	300 and 400	3	95
13,800 GrdY/7960	300 and 400	3	95
14,400 GrdY/8320	300 and 400	3	95

Appendix-D

Free Air Delivery (FAD) Test Calculation for Compressors

1. FAD Test for Compressor No -1

- Measurement of the Inlet Air Velocity of the Compressor:

Measured inlet air velocity using an Anemometer

Measurement	Measured Air Velocity (m/s)
V_1	14.9
V_2	13.6
V_3	15
V_4	13.2
Measurement	Measured Value
Loading Pressure (Bar)	6.6
Unloading Pressure (Bar)	7.8
Air flow rate (FAD)	$3.85 m^3/min$ or 137.5 cfm

$$(1cfm = 0.028 \frac{m^3}{min})$$

- Average Velocity:

$$\begin{aligned} \text{Average Velocity, } V_{av} &= \left(\frac{V_1+V_2+V_3+V_4}{4} \right) \\ &= \left(\frac{14.9+13.6+15+13.2}{4} \right) \\ &= 14.13 m/s \end{aligned}$$

- Area of the Air inlet tube(A) = πr^2 (Assuming a circle tube)

Measured Tube Diameter, D = 9.3 cm Or Radius, r = 0.0465m

$$\begin{aligned} \text{Area of the Air inlet tube(A)} &= \pi r^2 = \pi \times (0.0465)^2 \\ &= 0.00678 m^2 \end{aligned}$$

$$\begin{aligned} \text{But 25\% of the inlet air was closed} &= \left(\frac{75}{100} \right) \times 0.00678 \\ &= 0.0051 m^2 \end{aligned}$$

- The Actual Inlet Air Flow (Q_{actual}) :

$$\begin{aligned}
 Q_{actual} &= V_{av} \times A \\
 &= 14.13 \frac{m}{s} \times 0.0051 m^2 \\
 &= 0.0721 \frac{m^3}{s} \\
 &= 4.326 \frac{m^3}{min} \\
 &= 154.49 cfm
 \end{aligned}$$

From the nameplate of the compressor, the rated flow rate was found as:

$$Q_{rate} = 217 cfm \text{ or } 6.076 \frac{m^3}{min}$$

- Measurement of Input Power of the Compressor:

Measured Input Power of the Compressor

Measurement	Measured Power (kW)
P ₁	18.31
P ₂	16.10
P ₃	15.52

- Average Power, $P_{av} = \left(\frac{P_1 + P_2 + P_3}{3} \right)$
- $$\begin{aligned}
 &= \left(\frac{18.31 + 16.10 + 15.52}{3} \right) \\
 &= 16.64 kW
 \end{aligned}$$

Therefore, Loading Power = 16.64 kW

Measured Unloading Power = 7.85 kW

- Specific Power Consumption Per cfm (SPC/cfm):

$$\begin{aligned}
 SPC_{actual} &= \frac{P_{av}}{Q} \\
 &= \frac{16.64}{154.49} \\
 &= 0.1077 \frac{kW}{cfm}
 \end{aligned}$$

- Measurement of Loading and Unloading Time:

Measured Loading and Unloading Time

Measured Loading Time (T_L) (sec)	Measured Un-Loading Time (T_{UL}) (sec)
$T_{L1} = 21.13$	$T_{UL1} = 29.31$
$T_{L2} = 22.05$	$T_{UL2} = 29.82$

- Average Loading Time (T_{Lav}):

$$\begin{aligned} T_{Lav} &= \frac{(T_{L1} + T_{L2})}{2} \\ &= \frac{(21.13 + 22.05)}{2} \\ &= 21.59 \text{ sec} \end{aligned}$$

Average Un-Loading Time (T_{ULav}):

$$\begin{aligned} T_{ULav} &= \frac{(T_{UL1} + T_{UL2})}{2} \\ &= \frac{(29.31 + 29.82)}{2} \\ &= 29.56 \text{ sec} \end{aligned}$$

- Percent of Leakage During Loading and Un-Loading Time (Leak, Load and Leak, Un-Load):

$$\begin{aligned} \% \text{ Leak, Load} &= \frac{T_{Lav}}{T_{Lav} + T_{ULav}} \\ &= \frac{21.59}{21.59 + 29.56} \\ &= 0.4220 = 42.20\% \end{aligned}$$

$$\begin{aligned} \% \text{ Leak, Un - Load} &= \frac{T_{ULav}}{T_{Lav} + T_{ULav}} \\ &= \frac{29.56}{21.59 + 29.56} \\ &= 0.5779 = 57.79\% \end{aligned}$$

- The Leak Quantity During Loading Time (LQ_{Load}):

$$\begin{aligned} LQ_{Load} &= Q_{actual} \times \% \text{ Leak, Load} \\ &= 154.49 \text{ cfm} \times 0.4220 \\ &= 65.1947 \text{ cfm} \end{aligned}$$

- Percent of Leakage in kW:

$$\begin{aligned} Leak (kW) &= SPC_{actual} \times LQ_{Load} \\ &= 0.1077 \frac{kW}{cfm} \times 65.1947 cfm \\ &= 7.0214 kW \end{aligned}$$

Therefore, the Power Loss due to Leakage (ΔkW_1) during Loading is;

$$\Delta kW_1 = 7.0214 kW$$

- Power Loss due to Specific Power Consumption (SPC) Deviation:

$$\begin{aligned} Design SPC &= \frac{P_{nameplate}}{Q_{nameplate}} \\ &= \frac{22kW}{217 cfm} \\ &= 0.1013 kW/cfm \end{aligned}$$

The change in SPC can be determined as follow;

$$\begin{aligned} \Delta SPC &= (SPC)_{Actual} - (SPC)_{Design} \\ &= 0.1077 - 0.1013 \\ &= 0.0064 kW/cfm \text{ (SPC deviation)} \end{aligned}$$

Therefore, the Power Loss due to SPC deviation (ΔkW_2) can be determined as follow;

$$\begin{aligned} \Delta kW_2 &= \Delta SPC \times Q_{actual} \\ &= 0.0064 \frac{kW}{cfm} \times 154.49 cfm \\ &= 0.9887 kW \end{aligned}$$

Therefore,

$$\begin{aligned} Total Loss &= \Delta kW_1 + \Delta kW_2 \\ &= 7.0214 + 0.9887 \\ &= 8.0101 kW \end{aligned}$$

- Determining the Efficiency (η) of the air compressor:

$$\begin{aligned} \eta &= 1 - \frac{Total Loss}{P_{av,input}} \\ &= 1 - \frac{8.0101 kW}{16.64 kW} \end{aligned}$$

$$= 51.86\%$$

- Annual Energy and Money Loss :

$$\begin{aligned} \text{Energy Loss}_{\text{Annual}} &= 8.0101 \text{ kW} \times \frac{306 \text{ days}}{\text{year}} \times \frac{12 \text{ hrs}}{\text{day}} \\ &= 29,413.08 \frac{\text{kWh}}{\text{year}} \end{aligned}$$

$$\begin{aligned} \text{Money Loss}_{\text{Annual}} &= 29,413.08 \frac{\text{kWh}}{\text{year}} \times 0.0214 \frac{\text{US \$}}{\text{kWh}} \\ &= 629.43 \frac{\text{US \$}}{\text{yr}} \end{aligned}$$

2. FAD Test for Compressor No -2

By following the same procedures, as in FAD Test for Compressor No -1, finally the following results are obtained:

$$\begin{aligned} \eta &= 1 - \frac{\text{Total Loss}}{P_{\text{av,input}}} \\ &= 1 - \frac{11.9788 \text{ kW}}{26.89 \text{ kW}} \\ &= 49.51\% \end{aligned}$$

- Annual Energy and Money Loss :

$$\begin{aligned} \text{Energy Loss}_{\text{Annual}} &= 11.9788 \text{ kW} \times \frac{306 \text{ days}}{\text{year}} \times \frac{12 \text{ hrs}}{\text{day}} \\ &= 43,123.68 \frac{\text{kWh}}{\text{year}} \end{aligned}$$

$$\begin{aligned} \text{Money Loss}_{\text{Annual}} &= 43,123.68 \frac{\text{kWh}}{\text{year}} \times 0.0214 \frac{\text{US \$}}{\text{kWh}} \\ &= 922.84 \frac{\text{US \$}}{\text{yr}} \end{aligned}$$

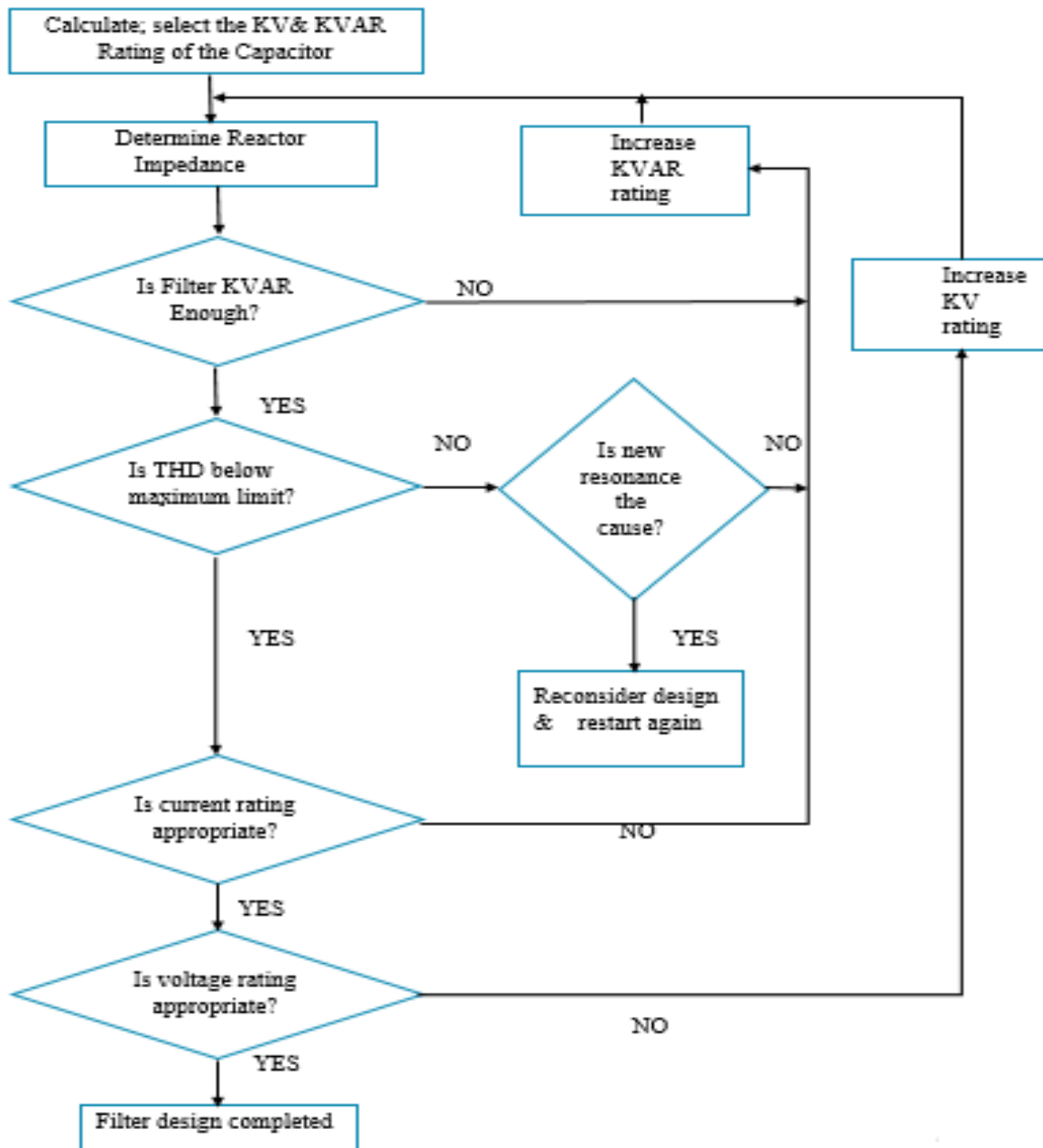
Therefore, the total annual energy and money loss from both Compressors test is:

$$\begin{aligned} \text{Energy Loss}_{\text{Annual}} &= 29,413.08 + 43,123.68 \\ &= 72,536.76 \frac{\text{kWh}}{\text{year}} \end{aligned}$$

$$\begin{aligned} \text{Money Loss}_{\text{Annual}} &= 629.43 + 922.84 \\ &= 1,552.27 \frac{\text{US \$}}{\text{yr}} \end{aligned}$$

Appendix-E

Decision Flow Chart for Single-Tuned Filter [32]



Appendix-F

Single-Tuned Passive Harmonic Filter Design Calculation

Step 1: The first step is to determine the reactive power to be provided by the filter capacitor banks and to calculate the value of the capacitor reactance from it.

$$\begin{aligned}
 Q_{com} &= P \times (\tan \theta_2 - \tan \theta_1) = P \times [\tan(\cos^{-1} \theta_2) - \tan(\cos^{-1} \theta_1)] \\
 &= 215.81 \times [\tan(\cos^{-1}(0.89)) - \tan(\cos^{-1}(0.96))] \\
 &= 215.81 \times [\tan(27.12) - \tan(16.26)] \\
 &= 215.81 \times [0.2205] = 47.586 \text{ kVAR}
 \end{aligned}$$

Where, Q_{com} = reactive power to be compensated.

For a multiple parallel single-tuned filter system, the capacitances corresponding to the h^{th} harmonics are obtained using the equations given above. The reactive power is distributed among 3rd, 5th and 7th harmonic filters using Equation 2.41 as follows:

$$\begin{aligned}
 Q_{f3} &= Q_{com} \times \frac{I_3}{I_3+I_5+I_7} = 47.586 \times \frac{13.30}{13.30+67.89+70.49} = 4.17 \text{ kVAR} \\
 Q_{f5} &= Q_{com} \times \frac{I_5}{I_3+I_5+I_7} = 47.586 \times \frac{67.89}{13.30+67.89+70.49} = 21.29 \text{ kVAR} \\
 Q_{f7} &= Q_{com} \times \frac{I_7}{I_3+I_5+I_7} = 47.586 \times \frac{70.49}{13.30+67.89+70.49} = 22.11 \text{ kVAR}
 \end{aligned}$$

Where, Q_{f3} , Q_{f5} and Q_{f7} are reactive power share of 3rd, 5th and 7th harmonic filters respectively.

For 3rd Harmonic Filter:

Equation 2.45, determines the voltage across the capacitor.

$$V_C = \left(\frac{h^2}{h^2-1} \right) \times V_{sys} = \left(\frac{3^2}{3^2-1} \right) \times 0.4 \text{ kV} = 0.45 \text{ kV}$$

Where, $V_{sys} = 400 \text{ V}$

The standard voltage available near this value (0.45kV) is 480 V. The reactive power to be supplied by the capacitor is calculated using Equation 2.42,

$$Q_C = \frac{h^2}{h^2-1} \times Q_{f3} = \frac{3^2}{3^2-1} \times 4.17 \text{ kVAR} = 4.69 \text{ kVAR}$$

Referring to Appendix-C, near to this standard value is 5.00 kVAR. Then X_c is determined by Equation 2.46,

$$X_c = \frac{V_c^2}{Q_c} = \frac{(0.48)^2}{5} \times 1000 = 46.080\Omega$$

For 5th Harmonic Filter:

Using similar procedure, voltage across the capacitor is,

$$V_C = \left(\frac{h^2}{h^2-1} \right) \times V_{sys} = \left(\frac{5^2}{5^2-1} \right) \times 0.4kV = 0.417 kV$$

Where, $V_{sys} = 400V$

The standard voltage available near this value (0.417kV) is 480 V. The reactive power to be supplied by the capacitor is calculated using Equation 2.42,

$$Q_C = \frac{h^2}{h^2-1} \times Q_{f5} = \frac{5^2}{5^2-1} \times 21.29 kVAR = 22.18 kVAR$$

Referring to Appendix-C, near to this standard value is 25.00 kVAR. Then X_c is determined by Equation 2.46,

$$X_c = \frac{V_c^2}{Q_c} = \frac{(0.48)^2}{25} \times 1000 = 9.216\Omega$$

For 7th Harmonic Filter:

Using similar procedure, voltage across the capacitor is,

$$V_C = \left(\frac{h^2}{h^2-1} \right) \times V_{sys} = \left(\frac{7^2}{7^2-1} \right) \times 0.4kV = 0.408 kV$$

Where, $V_{sys} = 400V$

The standard voltage available near this value (0.408kV) is 480 V. The reactive power to be supplied by the capacitor is calculated using Equation 2.42,

$$Q_C = \frac{h^2}{h^2-1} \times Q_{f7} = \frac{7^2}{7^2-1} \times 22.11 kVAR = 22.57 kVAR$$

Referring to Appendix-C, near to this standard value is 25.00 kVAR. Then X_c is determined by Equation 2.46,

$$X_c = \frac{V_c^2}{Q_c} = \frac{(0.48)^2}{25} \times 1000 = 9.216\Omega$$

Step 2: The second step is to calculate the reactor size providing the resonance, for the filters is given by Equation 2.49,

$$\text{For 3}^{\text{rd}} \text{ Harmonics:} \quad X_L = \frac{X_c}{h^2} = \frac{46.08\Omega}{3^2} = 5.120\Omega$$

$$\text{For 5}^{\text{th}} \text{ Harmonics:} \quad X_L = \frac{X_c}{h^2} = \frac{9.216\Omega}{5^2} = 0.368\Omega$$

$$\text{For 7}^{\text{th}} \text{ Harmonics:} \quad X_L = \frac{X_c}{h^2} = \frac{9.216\Omega}{7^2} = 0.188\Omega$$

Step 3: The third step is to determine whether capacitor-operating parameters, RMS current through the filter, VAR limit, RMS & peak voltage values fall within IEEE-18 recommended limits. First, the designed values for 3rd harmonic filter are compared with the standard values.

For the 3rd Harmonics:

The designed values for the VAR limit, RMS current through the filter, RMS and peak voltage values are calculated as follows,

Let $X_c = X_{c1} = 46.08\Omega$ and $X_L = X_{L1} = 5.120\Omega$ then,

$$X_{c3} = \frac{X_{c1}}{h} = \frac{46.08\Omega}{3} = 15.360\Omega$$

$$X_{L3} = hX_{L1} = 3 \times 5.120\Omega = 15.360$$

$$V_{cpeak} = \sqrt{2}(V_{c1} + V_{ch})$$

$$V_{c1} = X_{c1}I_{c1}$$

$$I_{c1} = (1.05) \frac{V_{L-N}}{(X_{c1} - X_{L1})} = (1.05) \left[\frac{\left(\frac{V_{L-L}}{\sqrt{3}}\right)}{(X_{c1} - X_{L1})} \right]$$

$$I_{c1} = (1.05) \left[\frac{\left(\frac{400}{\sqrt{3}}\right)}{(46.08 - 5.12)} \right] = 5.920A$$

$$V_{c1} = X_{c1}I_{c1} = 46.08 \times 5.920 = 272.793V$$

$$V_{ch} = X_{ch}I_{ch}$$

$$V_{c3} = X_{c3}I_{c3} = 15.36 \times 11.423 = 175.457V$$

$$V_{cpeak} = \sqrt{2}(272.793 + 175.457) = 633.92$$

$$V_{crms} = \sqrt{(V_{c1}^2 + V_{ch}^2)} = \sqrt{(272.793^2 + 175.457^2)} = 324.347V$$

$$I_{crms} = \sqrt{(I_{c1}^2 + I_{ch}^2)} = \sqrt{(5.920^2 + 11.423^2)} = 12.865A$$

$$\begin{aligned}
 kVAR_{Cap(wye),total} &= \sqrt{3}I_{crms,total} \times \sqrt{3}kV_{L-L,Cap(crms,total)} \\
 &= \sqrt{3} \times 12.865 \times \sqrt{3} \times 0.324347 \\
 &= 12.518kVAR
 \end{aligned}$$

In addition, $kVAR_{Cap,rated}$ is given as

$$kVAR_{Cap,rated} = \sqrt{3}I_{Cap,rated} \times kV_{L-L,Cap(rated)}$$

From this $I_{Cap,rated}$ can be calculated as

$$I_{Cap,rated} = \frac{kVAR_{Cap,rated}}{\sqrt{3}kV_{L-L,Cap(rated)}} = \frac{5}{\sqrt{3} \times 0.48} = 6.014A$$

Now compare the designed values for 3rd harmonic filter with the standard values.

Comparison Table-1: Comparing Filter Duty Limit of 3rd Harmonic Filter

Duty	Definition	Limit (%)	Actual Values	Actual Values (%)
kVAR	$\frac{kvar_{Cap(wye),total}}{kvar_{Cap,rated}}$	135	2.50	250
RMS Voltage	$\frac{V_{L-G,Cap(rms,total)}}{V_{rated}}$	110	1.15	115
Peak Voltage	$\frac{V_{L-G,Cap(max,peak)}}{V_{rated,peak}}$	120	1.58	158
RMS Current	$\frac{I_{rms,total}}{I_{Cap,rated}}$	135	2.13	213

Not all the designed values are within the IEEE-18 recommended limits for the 3rd harmonics. According to the Appendix-E, the IEEE-18, Comparison Table-1, is not met. Therefore, the process requires more than one iteration to resize the capacitor bank. Let us check for the remaining harmonics.

For the 5th Harmonics:

The designed values for the VAR limit, RMS current through the filter, RMS and peak voltage values are calculated as follows,

Let $X_c = X_{c1} = 9.216\Omega$ and $X_L = X_{L1} = 0.368\Omega$ then,

$$X_{c5} = \frac{X_{c1}}{h} = \frac{9.216\Omega}{5} = 1.843\Omega$$

$$X_{L5} = hX_{L1} = 5 \times 0.368\Omega = 1.840\Omega$$

$$V_{cpeak} = \sqrt{2}(V_{c1} + V_{ch})$$

$$V_{c1} = X_{c1}I_{c1}$$

$$I_{c1} = (1.05) \frac{V_{L-N}}{(X_{c1} - X_{L1})} = (1.05) \left[\frac{\left(\frac{V_{L-L}}{\sqrt{3}}\right)}{(X_{c1} - X_{L1})} \right]$$

$$I_{c1} = (1.05) \left[\frac{\left(\frac{400}{\sqrt{3}}\right)}{(9.216 - 0.368)} \right] = 27.405A$$

$$V_{c1} = X_{c1}I_{c1} = 9.216 \times 27.405 = 252.564V$$

$$V_{ch} = X_{ch}I_{ch}$$

$$V_{c5} = X_{c5}I_{c5} = 1.843 \times 61.567 = 113.467V$$

$$V_{cpeak} = \sqrt{2}(252.564 + 113.467) = 517.646V$$

$$V_{crms} = \sqrt{(V_{c1}^2 + V_{ch}^2)} = \sqrt{(252.564^2 + 113.467^2)} = 276.881V$$

$$I_{crms} = \sqrt{(I_{c1}^2 + I_{ch}^2)} = \sqrt{(27.405^2 + 61.567^2)} = 67.390A$$

$$\begin{aligned} kVAR_{Cap(wye),total} &= \sqrt{3}I_{crms,total} \times \sqrt{3}kV_{L-L,Cap(crms,total)} \\ &= \sqrt{3} \times 67.390 \times \sqrt{3} \times 0.276881 \\ &= 55.977kVAR \end{aligned}$$

In addition, $kVAR_{Cap,rated}$ is given as

$$kVAR_{Cap,rated} = \sqrt{3}I_{Cap,rated} \times kV_{L-L,Cap(rated)}$$

From this $I_{Cap,rated}$ can be calculated as

$$I_{Cap,rated} = \frac{kVAR_{Cap,rated}}{\sqrt{3}kV_{L-L,Cap(rated)}} = \frac{25}{\sqrt{3} \times 0.48} = 30.07A$$

Now compare the designed values for 5th harmonic filter with the standard values.

Comparison Table-2: Comparing Filter Duty Limit of 5th Harmonic Filter

Duty	Definition	Limit (%)	Actual Values	Actual Values (%)
kVAR	$\frac{kvar_{Cap(wye),total}}{kvar_{Cap,rated}}$	135	2.23	223
RMS Voltage	$\frac{V_{L-G,Cap(rms,total)}}{V_{rated}}$	110	0.98	98
Peak Voltage	$\frac{V_{L-G,Cap(max,peak)}}{V_{rated,peak}}$	120	1.29	129
RMS Current	$\frac{I_{rms,total}}{I_{Cap,rated}}$	135	2.24	224

Not all the designed values are within the IEEE-18 recommended limits for the 5th harmonics. According to the Appendix-E, the IEEE-18, Comparison Table-2, is not met. Therefore, the process requires more than one iteration to resize the capacitor bank.

For the 7th Harmonics:

The designed values for the VAR limit, RMS current through the filter, RMS and peak voltage values are calculated as follows,

Let $X_c = X_{c1} = 9.216\Omega$ and $X_L = X_{L1} = 0.188\Omega$ then,

$$X_{c7} = \frac{X_{c1}}{h} = \frac{9.216\Omega}{7} = 1.316\Omega$$

$$X_{L7} = hX_{L1} = 7 \times 0.188\Omega = 1.316\Omega$$

$$V_{cpeak} = \sqrt{2}(V_{c1} + V_{ch})$$

$$V_{c1} = X_{c1}I_{c1}$$

$$I_{c1} = (1.05) \frac{V_{L-N}}{(X_{c1} - X_{L1})} = (1.05) \left[\frac{\left(\frac{V_{L-L}}{\sqrt{3}}\right)}{(X_{c1} - X_{L1})} \right]$$

$$I_{c1} = (1.05) \left[\frac{\left(\frac{400}{\sqrt{3}}\right)}{(9.216 - 0.188)} \right] = 26.859A$$

$$V_{c1} = X_{c1}I_{c1} = 9.216 \times 26.859 = 247.532V$$

$$V_{ch} = X_{ch}I_{ch}$$

$$V_{c7} = X_{c7}I_{c7} = 1.316 \times 64.113 = 84.372V$$

$$V_{cpeak} = \sqrt{2}(247.532 + 84.372) = 469.383$$

$$V_{crms} = \sqrt{(V_{c1}^2 + V_{ch}^2)} = \sqrt{(247.532^2 + 84.372^2)} = 261.516V$$

$$I_{crms} = \sqrt{(I_{c1}^2 + I_{ch}^2)} = \sqrt{(26.859^2 + 64.113^2)} = 69.511A$$

$$kVAR_{Cap(wye),total} = \sqrt{3}I_{crms,total} \times \sqrt{3}kV_{L-L,Cap(crms,total)}$$

$$= \sqrt{3} \times 69.511 \times \sqrt{3} \times 0.261516$$

$$= 54.534kVAR$$

In addition, $kVAR_{Cap,rated}$ is given as

$$kVAR_{Cap,rated} = \sqrt{3}I_{Cap,rated} \times kV_{L-L,Cap(rated)}$$

From this $I_{Cap,rated}$ can be calculated as

$$I_{Cap,rated} = \frac{kVAR_{Cap,rated}}{\sqrt{3}kV_{L-L,Cap(rated)}} = \frac{25}{\sqrt{3} \times 0.48} = 30.07A$$

Now compare the designed values for 7th harmonic filter with the standard values.

Comparison Table-3: Comparing Filter Duty Limit of 7th Harmonic Filter

Duty	Definition	Limit (%)	Actual Values	Actual Values (%)
kVAR	$\frac{kvar_{Cap(wye),total}}{kvar_{Cap,rated}}$	135	2.18	218
RMS Voltage	$\frac{V_{L-G,Cap(rms,total)}}{V_{rated}}$	110	0.92	92
Peak Voltage	$\frac{V_{L-G,Cap(max,peak)}}{V_{rated,peak}}$	120	1.17	117
RMS Current	$\frac{I_{rms,total}}{I_{Cap,rated}}$	135	2.31	231

Not all the designed values are within the IEEE-18 recommended limits for the 7th harmonics. According to the Appendix-E, the IEEE-18, Comparison Table-3, is not met. Therefore, the process requires more than one iteration to resize the capacitor bank.

So, let us resize the value of kVAR of the capacitor bank until IEEE-18 is met. This is done by resizing the capacitor bank (Q_{com}) to the value of 125 kVAR. Then, follow the same

mathematical procedure as above calculations. By doing this, the following results in Table-4 are obtained .

For the 3rd Harmonics:

Comparison Table-4: Comparing Filter Duty Limit of 3rd Harmonic Filter

Duty	Definition	Limit (%)	Actual Values	Actual Values (%)
kVAR	$\frac{kvar_{Cap(wye),total}}{kvar_{Cap,rated}}$	135	1.18	118
RMS Voltage	$\frac{V_{L-G,Cap(rms,total)}}{V_{rated}}$	110	0.99	99
Peak Voltage	$\frac{V_{L-G,Cap(max,peak)}}{V_{rated,peak}}$	120	1.17	117
RMS Current	$\frac{I_{rms,total}}{I_{Cap,rated}}$	135	1.17	117

All the designed values are within the IEEE-18 recommended limits for the 3rd harmonics. Now calculate the capacitance and inductance values for the 3rd harmonics.

As calculated above, $X_c = 15.36\Omega$ and $X_L = 1.70\Omega$ then the capacitance will be

$$C = \frac{1}{2\pi f X_c}$$

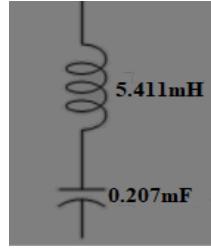
$$C = \frac{1}{2\pi \times 50 \times 15.36} = 2.072 \times 10^{-4} F = 0.2072 mF$$

Moreover, the inductance will be

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{1.70}{2\pi \times 50} = 5.411 \times 10^{-3} H = 5.411 mH$$

Therefore, the 3rd harmonic filter configuration looks as shown in Figure F-1

Figure F-1: 3rd Harmonic Filter Branch with Designed Values**For the 5th Harmonics:**Comparison Table-5: Comparing Filter Duty Limit of 5th Harmonic Filter

Duty	Definition	Limit (%)	Actual Values	Actual Values (%)
kVAR	$\frac{kvar_{Cap(wye),total}}{kvar_{Cap,rated}}$	135	1.15	115
RMS Voltage	$\frac{V_{L-G,Cap(rms,total)}}{V_{rated}}$	110	0.911	91.1
Peak Voltage	$\frac{V_{L-G,Cap(max,peak)}}{V_{rated,peak}}$	120	1.06	106
RMS Current	$\frac{I_{rms,total}}{I_{Cap,rated}}$	135	1.24	124

All the designed values are within the IEEE-18 recommended limits for the 5th harmonics. Now calculate the capacitance and inductance values for the 5th harmonics.

As calculated above, $X_C = 3.84\Omega$ and $X_L = 0.153\Omega$ then the capacitance will be

$$C = \frac{1}{2\pi f X_C}$$

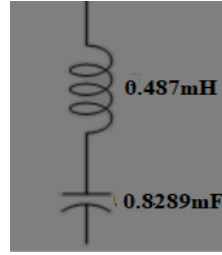
$$C = \frac{1}{2\pi \times 50 \times 3.84} = 8.289 \times 10^{-4} F = 0.8289 mF$$

Moreover, the inductance will be

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{0.153}{2\pi \times 50} = 4.870 \times 10^{-4} H = 0.487 mH$$

Therefore, the 5th harmonic filter configuration looks as shown in Figure F-2

Figure F-2: 5th Harmonic Filter Branch with Designed Values**For the 7th Harmonics:**Comparison Table-6: Comparing Filter Duty Limit of 7th Harmonic Filter

Duty	Definition	Limit (%)	Actual Values	Actual Values (%)
kVAR	$\frac{kvar_{Cap(wye),total}}{kvar_{Cap,rated}}$	135	1.26	126
RMS Voltage	$\frac{V_{L-G,Cap(rms,total)}}{V_{rated}}$	110	0.87	87
Peak Voltage	$\frac{V_{L-G,Cap(max,peak)}}{V_{rated,peak}}$	120	1.003	100.3
RMS Current	$\frac{I_{rms,total}}{I_{Cap,rated}}$	135	1.26	126

All the designed values are within the IEEE-18 recommended limits for the 7th harmonics. Now calculate the capacitance and inductance values for the 7th harmonics.

As calculated above, $X_C = 3.84\Omega$ and $X_L = 0.078\Omega$ then the capacitance will be

$$C = \frac{1}{2\pi f X_C}$$

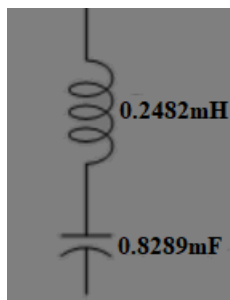
$$C = \frac{1}{2\pi \times 50 \times 3.84} = 8.289 \times 10^{-4} F = 0.8289 mF$$

Moreover, the inductance will be

$$L = \frac{X_L}{2\pi f}$$

$$L = \frac{0.078}{2\pi \times 50} = 2.482 \times 10^{-4} H = 0.2482 mH$$

Therefore, the 7th harmonic filter configuration looks as shown in Figure F-3

Figure F-3: 7th Harmonic Filter Branch with Designed Values

According to the above mathematical calculations, Table 7 shows all the summarised results of the required filter parameters.

Table 7: Design Parameters of Multi-branch Harmonic Filter

Branch	$Q_c(kVAR)$	$V_c(V)$	$X_c(\Omega)$	$C(mF)$	$X_L(\Omega)$	$L(mH)$
3 rd	15.00	480.00	15.36	0.2072	1.70	5.4110
5 th	60.00	480.00	3.84	0.8289	0.153	0.4870
7 th	60.00	480.00	3.84	0.8289	0.078	0.2482

Appendix-G

Some Pictures Taken during the Measurements in the Different departments of the DBBF



ENERGY AUDIT & POWER QUALITY IMPROVEMENT IN DEBRE BERHAN BLANKET FACTORY

