Sudan University of

Science &Technology

College of Graduate Studies

Mitigation of Harmonics Effects on Power Quality

Case Study (White Nile Sugar Factory)

التقليل من آثار التوافقيات على نوعية الطاقة

(دراسة حالة: مصنع سكر النيل الأبيض)

A Thesis Submitted as a Partial Fulfillment of the requirements for the degree of master in Mechatronics Engineering

By

KHIDIR FAISAL ADAMALDEAN SALIH

Supervisor

Dr. ZAKARIA ANWAR ZAKARIA

April 2017

بسم الله الرحمن الرحيم

Sudan University of Science & Technology

College of Graduate Studies

Mitigation of Harmonics Effects on Power Quality

Case Study (White Nile Sugar Factory)

A Thesis Submitted as a Partial Fulfillment of the requirements
for the degree of master in Mechatronics Engineering

By

KHIDIR FAISAL ADAMALDEAN SALIH

Supervisor

Dr. ZAKARIA ANWAR ZAKARIA

April 2017

بسم الله الرحمن الرحيم

الآية

قال تعالى :

﴿اللَّهُ لَا إِلَٰهَ إِلَّا هُوَ الْحَيُّ الْقَيُّومُ ۚ لَا تَأْخُذُهُ سِنَةٌ وَلَا نَوْمٌ ۚ لَّهُ مَا فِي السَّمَاوَاتِ وَمَا فِي الْأَرْضِ ۗ مَن ذَا الَّذِي يَشْفَعُ عِندَهُ إِلَّا بِإِذْنِهِ ۚ يَعْلَمُ مَا بَيْنَ أَيْدِيهِمْ وَمَا خَلْفَهُمْ ۖ وَلَا يُحِيطُونَ بِشَيْءٍ مِّنْ عِلْمِهِ إِلَّا بِمَا شَاءَ ۚ وَسِعَ كُرْسِيُّهُ السَّمَاوَاتِ وَالْأَرْضَ ۖ وَلَا يَئُودُهُ حِفْظُهُمَا ۚ وَهُوَ الْعَلِيُّ الْعَظِيمُ﴾

صدق الله العظيم

سورة البقرة الآية (255)

Dedication

I dedicate this thesis to God Almighty my creator, my strong pillar, my source of inspiration, wisdom, knowledge and understanding. I also dedicate this work to my wife, all my family and friends who encouraged me to finish this work.

Acknowledgement

I would like to express my gratitude to the many people who pushed me to do this thesis and to all those who provided support. I would like to thank Engineer Algaili Dafaalseed who encourage me to start this M.Sc program.

I would like to thank my supervisor Dr. Zakaria Anwar Zakaria, whose contribution and constructive criticism has pushed me to expend the kind of efforts I have exerted to make this work as original as it can be. Thanks to him I have experienced true research and my knowledge on the subject matter has been broadened.

Abstract

This thesis presents the definitions of harmonics, generation, causes, and solutions due to IEEE 519 standard of harmonics. The basic aim of the study is how to mitigate the Harmonics effect on power quality.

The Harmonics in power Systems comes from transformers or saturable reactors, arc furnace, welding machines, florescent lamps, rotating machines and power electronics devices. In general, the non linear loads in which the relationship between the voltage and current is not constant.

It is considered that there is no risk of harmful perturbation from 5 to 10%, above 10% problems will certainly occur.

Equipments can be affected by the harmonics like transformers and motors with increase of losses, risk of overheating, noise and even insulation stress problems. Cables that can heat too much due to Kelvin effect above 400 Hz. Induction relays and meters that are pertubated by harmonic torques giving incorrect tripping and readings.

The solutions that can be used to mitigate the harmonics effects on power quality and to protect the electrical and electronics equipments that by using harmonic filters and other mitigation techniques.

المستخلص

تقدم هذه الأطروحة تعريف التوافقيات، وتوليدها وأسبابها، والحلول و ذلك حسب ما ورد بالقياسيه (IEEE 519). والهدف الأساسي من هذه الدراسة هو كيفية التقليل من تأثير التوافقيات على انظمة القدره الكهربائيه.

التوافقيات في نظم القدره الكهربائيه تأتي من المحولات أو المفاعلات، الافران لكهربائيه، ماكنات الحام، ومصابيح الفلورسنت، الآلات الدوارة وأجهزة القدرة الالكترونيه. و بشكل عام الاحمال الغير خطية التي بها تكون العلاقة بين الجهد والتيار غير ثابته. ولا توجد خطوره اذا وصلت مستوى التوافقيات من 5 إلى 10٪ اما أكثر من ذلك فتشكل مشكله حقيقيه.

الاجهزه والمعدات التى يمكن أن تتأثر بالتوافقيات مثل المحولات والمحركات حيث تزيد فيها الضياعات الكهربائيه ومخاطر ارتفاع درجة الحرارة والضوضاء وحتى مشاكل الإجهاد و يؤدى ذلك الى اتلاف ملفاتها، الكابلات ايضا تعانى من ارتفاع الحراره و ذلك بسبب تأثير كلفن اعلى من 400 هرتز. الريليهات واجهزة القياس تتأثر ايضا بالتوافقيات وتعطى اشارات وقراءات خاطئه.

الحلول التي يمكن استخدامها للتخفيف من آثار التوافقيات على انظمة القدره الكهربائيه وحماية المعدات الكهربائية والإلكترونية وذلك باستخدام مرشحات التوافقية وتقنيات التخفيف الأخرى.

Table of Contents

List of Tables

List of Figures

List of Symbols and Abbreviations

IEEE	Institution of Electrical and Electronic Engineering for Building and Equipments.
FC	Frequency Resonance
H.D	Individual Harmonic Distortion
H.F	Harmonic Factor
H	Harmonic Order
I_1	Rated Current (fundamental)
I_h	Harmonic Current
LCDH	Losses in Capacitors Due to Harmonics
N	Harmonic Resonance
VFD	Variable Frequency Driver
Q	Capacitors Output
R.M.S	Root Mean Square
T.H.D	Total Harmonic Distortion
T_{CC}	Short Circuit Voltage of the transformer
T_{ECL}	Total Eddy-Current Losses
A LEAD	Amps lead Volts
A LAG	Amps lag Volts
CF	Crest Factor (Ratio of a wave form's peak value to its r.m.s value)
PDF	Displacement Power Factor $\cos \varphi$ (fundamental)
Hz	Frequency of selected harmonic in hertz
PF	Power Factor
KF	K Factor

%THD-F	Total Harmonic Distortion as (% of fundamental)
%THD_R	Total Harmonic Distortion as (% of r.m.s total)
V_{RMS}	Volts r.m.s (includes dc component)
cos φ	cosine of the angle between the voltage at any single frequency
V_{pk}	Peak volts
V_{DC}	Volts DC
V_{HM}	Harmonic Volts r.m.s
KVA	Kilo Volt Ampere
KVAR	Kilo Volt Ampere Reactive
ECL_1	Eddy Current Loss at rated fundamental current
AC	Alternator Current
DC	Direct Current

List of Appendices

Appendix No	TITLE
A	List of motors failed in process house up to end of 2nd crop.
B	Harmonics reading in process house station-4 after filters installed and some modification done.

CHAPTER ONE

Overview

1.1 Introduction

Power quality is generic term applied to a wide variety of electromagnetic in the electrical power system. Quite often the term power quality is associated with specific problems with equipment or system for example equipment damage, data problem or loss, equipment malfunction or complete system failure. The duration of these phenomena range from a few nanoseconds (e.g. transient) to a few milliseconds (e.g., voltage sags) to steady-state disturbances (harmonic distortion and voltage fluctuations). Power quality is concept of powering and grounding sensitive equipment in a manner that is suitable to the operation of that equipment (IEEE std. 1100 & IEEE std. 1159).

It is important to note that power quality has been an intrinsic feature of the electrical power systems since the earliest times. Yet in recent decades power quality has become an increasingly troublesome disturbance, giving rise to inconvenience and even considerable economic loss. The reason is due to the fact that some modern electricity utilization equipment, either in White Nile Sugar Factory or because of control features incorporated in it, has become more sensitive to power quality events.

Power quality actually encompasses many type of power system phenomenon, such as: Voltage Flicker; Voltage Notching; Voltage Sag; Voltage Swells; Voltage Unbalance; Overvoltage; Undervoltage; Harmonics; System phase jumps; Interruptions; Transients ; Power system faults (weather, equipment failure, vandalism, etc.); Industrial process(such as Welding, compressor loads, Electric Arc Furnaces); Consumer processes (such as computer loads, heat and cooling loads); Weather issues such as lighting, wind, etc. and Power system degradation.

The definitions of sags and swells have evolved over the past fifteen years, as have the power quality instruments that measure them. Sags or dips as they are referred to in the European communities, were initially any reduction in voltage below a user- defined low limit for between one cycle and 2.55 seconds. Swells, originally referred to as surges, and were similar to sags, except that the voltage exceeded a user-defined high limit. While various definitions relative to the amplitude and duration are still in use, the IEEE 1159-1995 Recommended Practice on Monitoring Electric Power Quality has defined them as follows:

- **Sags**: A decrease in rms voltage or current at power frequency for durations of 0.5 cycles to 1 minute. A voltage sag to 10% means that the line voltage is reduced to 10 % of the nominal value. Typical values are 0.1 to 0.9 pu.
- **Interruptions**: The complete loss of voltage (below 0.1 pu) on one or more phase conductors for a certain period of time. Momentary interruptions are defined as lasting between 0.5 cycles and 3 s, temporary interruptions have a time span between 3s and 60s, and sustained interruptions last for a period longer than 60s.
- **Swells**: A temporary increase in rms voltage or current of more than 10 % of the nominal value at power system frequency which lasts from 0.5 cycles to 1 minute. Typical rms values are 1.1 to 1.8 pu.
- **Transients**: These pertain to or designate a phenomena or quantity varying between two consecutive steady states during a time interval which is short compared with the time scale of

interest. A transient can be a unidirectional impulse of either polarity, or a damped oscillatory wave with the first peak occurring in either polarity.

- **Overvoltage**: When used to describe a specific type of long-duration variation, this refers to a voltage having a value greater than the nominal voltage for a period of time greater than 1 minute. Typical values are1.1 to 1.2 pu.
- **Undervoltage**: Refers to a voltage having a value less than the nominal voltage for a period of time greater than one minute. Typical values are 0.8 to 0.9 pu.
- **Harmonics**: Sinusoidal voltages or currents having frequencies that are multiples of the fundamental power frequency. Distorted waveforms can be decomposed into a sum of the fundamental frequency wave and the harmonics caused by nonlinear characteristics of power system devices and loads. [1,2]

1.2 Problem Formulation

The non linear devices such as variable frequency driver, power supplies and other devices utilizing sold state switches are widely using in White Nile Sugar Factory, unfortunately the effect of harmonics distortion has increased in factory power system and caused more than fifty motors burnt and other electronic and protection devices damaged. The solution of this problem is to improve power factor and reduce the T.H.D using one or two types of harmonics mitigation techniques.

1.3 Scope and Objective

1.3.1 Scope

Study the harmonics effects in White Nile sugar factory and how to mitigate it.

1.3.2 Objective

The objective of this dissertation is to study and evaluate the harmonics effects on power quality (case study: White Nile Sugar Factory). It is important to define the concepts of the harmonics and generation and its effects.

1.4 Important of study

The basic aim of this study is to mitigate the harmonics effects on power quality in White Nile sugar factory.

1.5 Methodology

This thesis firstly presents an overall harmonics in the White Nile Sugar Factory. A comprehensive data bank of harmonics has been constructed from instrumentation and calculation from the side of mills and process house. The data has been collected for solving the problem of harmonics and to perform network harmonic analysis. Then presents the filters as one of the solutions for the harmonics problems, the instrument of the harmonics in the White Nile Sugar Factory, reading, graphs, calculation and analysis of data to the suitable solution to solve the problem.

Lastly the Matlab program well is used to do analysis of data.

1.6 Thesis Outlines

This study consists of five chapters, chapter one has presented an introduction of power quality (PQ) in White Nile sugar factory, many type of power system phenomenon, such as voltage flicker; voltage notching; voltage sag; voltage swells; and harmonics. Also presented importance, methodology, objectives and overview of the thesis. In chapter two a literature survey about harmonics on power quality and its effects. Chapter three concerned with the harmonics mitigation techniques. Chapter four presented the analysis of electrical failures and corrective actions in process house plant in White Nile sugar factory, simply the thesis's results and its discussions.

Finally the research had closed with conclusion and recommendations for further study.

CHAPTER TWO

Literature Review

2.1 Harmonics on power quality

A pure sinusoidal voltage is a conceptual quantity produced by an ideal AC generator built with finely distributed stator and field windings that operate in a uniform magnetic field. Since neither the winding distribution nor the magnetic field are uniform in a working AC machine, voltage waveform distortions are created, and the voltage-time relationship deviates from the pure sine function. The distortion at the point of generation is very small (about 1% to 2%), but nonetheless it exists. Because this is a deviation from a pure sine wave, the deviation is in the form of a periodic function, and by definition, the voltage distortion contains harmonics.

When a sinusoidal voltage is applied to a certain type of load, the current drawn by the load is proportional to the voltage and impedance and follows the envelope of the voltage waveform. These loads are referred to as linear loads (loads where the voltage and current follow one another without any distortion to their pure sine waves). Examples of linear loads are resistive heaters, incandescent lamps, and constant speed induction and synchronous motors.

In contrast, some loads cause the current to vary disproportionately with the voltage during each half cycle. These loads are classified as nonlinear loads, and the current and voltage have waveforms that are nonsinusoidal, containing distortions, whereby the 50-Hz waveform has numerous additional waveforms superimposed upon it, creating multiple frequencies within the normal 50-Hz sine wave. The multiple frequencies are harmonics of the fundamental frequency.

Normally, current distortions produce voltage distortions. However, when there is a stiff sinusoidal voltage source (when there is a low impedance path from the power source, which has sufficient capacity so that loads placed upon it will not effect the voltage), one need not be concerned about current distortions producing voltage distortions.

Examples of nonlinear loads are battery chargers, electronic ballasts, variable frequency drives, and switching mode power supplies. As nonlinear currents flow through a facility's electrical system and the distribution-transmission lines, additional voltage distortions are produced due to the impedance associated with the electrical network. Thus, as electrical power is generated, distributed, and utilized, voltage and current waveform distortions are produced.

Power systems designed to function at the fundamental frequency, which is 50-Hz in Sudan and so in White Nile Sugar Factory, are prone to unsatisfactory operation and, at times, failure when subjected to voltages and currents that contain substantial harmonic frequency elements. Very often, the operation of electrical equipment may seem normal, but under a certain combination of conditions, the impact of harmonics is enhanced, with damaging results. [2,3]

2.2 Definition

Harmonics provides a mathematical analysis of distortions to a current or voltage waveform. Based on Fourier series, harmonics can describe any periodic wave as summation of simple sinusoidal waves which are integer multiples of the frequency. One can give the following definitions [4]:

Individual harmonic Distortion:

$$H.D = \frac{V_h}{V_1} \times 100 \quad \text{...(2.1)}$$

Total harmonic distribution:

$$T.H.D = \frac{\sqrt{\sum_2^P V_h^2}}{V_1} \times 100 \quad \text{...(2.2)}$$

Generally p is limited to 25.

Utilities tend to limit these distortions. For example, in France, the limitation, in the medium voltage, is the following:

H.D $\leq$ 1% for odd harmonics

$\leq$ 0.6% for even harmonics

T.H.D $\leq$ 1.6%

2.3 Harmonic Distortion

Any repetitive distorted (nonsinusoidal) waveform can be broken down into pure sine waves whose frequencies are integral multiples of the fundamental frequency. These pure sine waves that make up the nonsinusoidal waveform are the harmonic components. Fourier analysis is used to determine the frequencies. Fig. 1 shows a typical example of the distorted waveform. There are an infinite number of harmonics that make up a distorted wave. As the frequencies of these harmonics increase, their amplitudes tend to decrease in an inverse manner. The Fast Fourier Transform (FFT) is a short version of the Fourier analysis which limits the calculated number of harmonic component to 50 (within significant error). After the transform of a nonsinusoidal voltage or current waveform is completed, the harmonic distortion resulting from each frequency can be calculated. Harmonic distortion describes the condition that occurs when a waveform is changed from its original shape by the addition of a harmonic frequency. Total Harmonic

Distortion (THD) describes the change that occurs when all harmonic frequencies are considered. [5]

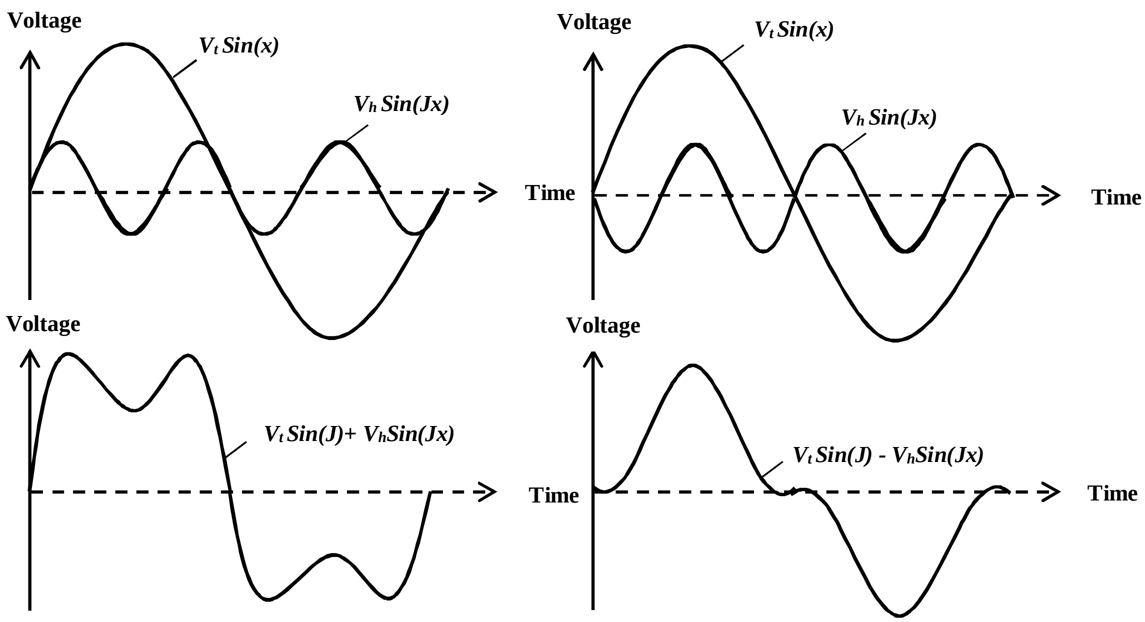


Fig (2.1) Harmonic Distortion

2.4 Harmonic Generation

The conventional harmonic generators that can be listed are:

1. Rotating machines
2. Cyclo-Converters
3. Static VAR Converters
4. Power electronics apparatus, i.e. drives (ac or dc), UPS, galvanizing plants
5. Transformers or saturable reactors
6. Fluorescent lighting, welding machines, arc furnaces
7. Electronic applications such as rectifiers or inverters

Formerly, in most of the applications, the devices mentioned above (arc furnaces and obviously electronic application) do not generate enough harmonics to give serious perturbations [9, 3].

However, in recent years, the development of modern thyristor technology has led to constant increases of converters fed loads. The new equipments were marginal some years ago, they must no be disregarded nowadays. They are the major cause of concern in harmonic problems.

The most common existing type of static power converter that is being used today is of six-pulse three-phase bridge connection design. Such devices will produce harmonic current in the order of h = kq ± 1 with q = 6 and k is integer 1, 2, 3 …

As a first approximation, the current amplitude of such harmonics is:

$$I_h = {}^{I_1}/_{h} \quad \text{..........} (2.1)$$

Where:

I_1: is the amplitude of the fundamental and h is the order of harmonic.

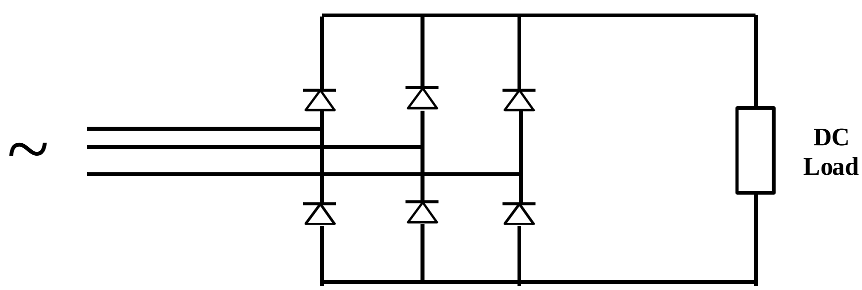


Fig (2.2) Electronic Application

k: integer 1, 2, 3 …

h = kq ± 1 p: pulse number

h: harmonic order

Example, for p = 6 » h = 5, 7, 11, 13 …

$I_h = {}^{I_1}/_{h}$

I_h: Amplitude of harmonic

I_1 : Amplitude of fundamental

h: harmonic order

Example » I5 ≠ 0.2I1

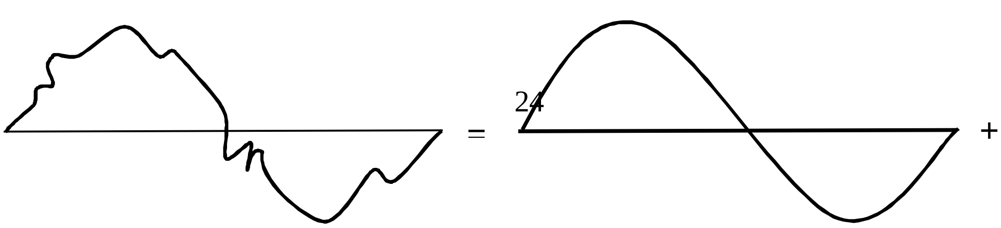


Fig (2.3) Fourier series Decomposition:

$I = I1 + I2 + I3 + \dots In$

The harmonic spectrum of the current for each SCR driver can be represented as follows:

$$n = k\alpha \pm 1$$

Where n= harmonic order, k= 1, 2, 3 …, and α= thyristors number.

The amplitude with reference to the fundamental is:

$$I_h = 1/n$$

For example, with 6 thyristors (6 pulses)

Harmonic	5	7	11	13	17
% of Fundamental	20	14	9	8	6

Table (2.1) Harmonic Order with Percent of Fundamental

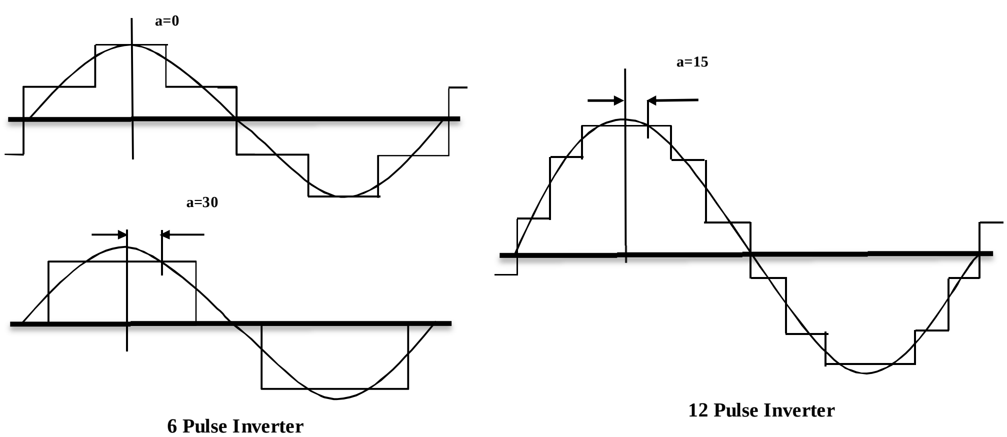


Fig (2.4) 6 &12 Inverter Pulses

ypical harmonic currents, expressed as a percentage of the fundamental current. For these devices are as shown in table (2.1):

Order of Harmonic	Percentage Harmonic Current	
	6 Pulse	12 Pulse
1	100	100
5	20	--
11	14	--
13	9	9
17	8	8
19	6	--
23	5	--
25	4	4
	4	4

Table (2.2) Harmonic Currents as a Percent Current of the Device

2.5 Harmonic sources

There are numerous sources of harmonics. In general; the harmonics sources can be classified as [4]:

1. Previously known harmonics sources
2. New harmonics sources

2.5.1 Previously Harmonic sources

The previously known harmonics sources include:

1. Tooth ripples or ripples in the voltage waveform of the rotating machines.
2. Variations in air-gap reluctance over synchronous machine pole pitch.
3. Flux distortion in the synchronous machine from sudden load changes
4. Non sinusoidal distribution of the flux in the air-gap of the synchronous machine.
5. Transformer magnetizing currents.

6. Network nonlinearities from load such as rectifiers, inverters, welders, arc furnaces, voltage controllers, frequency converters, etc…

2.5.2 New harmonic source

While the established sources of harmonics are still present, the power network is also subjected to new harmonics sources:

1. Energy conservation measures, such as those for improved motor efficiency and load matching, which employ power semiconductor devices and switching for their operation. These devices often produce irregular voltage and current waveforms that are rich in harmonics
2. Motor control devices such as speed controls for traction
3. High-voltage dc power conversion and transmission
4. Interconnection of wind and solar power converters with distribution systems
5. Static-VAR Compensators which have largely replaced synchronous condensers as continuously variable-VAR sources
6. The development and potentially wide use of electric vehicles that require a significant amount of power rectification for battery charging
7. The potential of direct energy conversion devices, such as magnetohydodynamics, storage batteries and full cells that require dc, ac power converter.

2.6 Effects of Harmonics

Periodic voltage or current distorted waveforms can be represented by the sum of series of multiple frequency terms of varying magnitudes and phase.

The component at 50Hz is fundamental, the multiples are the harmonics. In this way it is possible to calculate the current, the voltage etc. adding the effects of each term

When the T.H.D is smaller than 5%, we consider there is no risk of harmful perturbation. From 5 to 10% we may have problems. Above 10% problems will certainly occur.

One of the greatest concerns is the effect of voltage distortion on motor loads and electronic controls.

For the motors, in some cases the level can be high enough to cause rotating machinery failure.

Voltage distortion can also affect electronic controls for power conversion, speed controllers and power supplies.

These devices depend on accurate zero crossing signals to develop timing for thyristor firing. If the wave form is distorted, then the timing is inaccurate. [9]

CHAPTER THREE

Harmonics and System Power Factor

(Problems and Solutions)

3.1 Introduction

The different electrical devices used will convert energy transformed into various forms: mechanical, light, thermal, etc. this energy corresponds to a useful or active power, similar to that consumed by a resistor. This power is known as active power, and it's expressed in watts (w).

Electrical devices making use of the effect of an electro-magnetic field require power for the effective or useful work and power to set up the magnetic field. This effective energy corresponds to a reactive power being 90^o out of phase with the active power. This power is expressed in Volt-Ampere Reactive (VAR). The product of the current and the voltage is called apparent power.

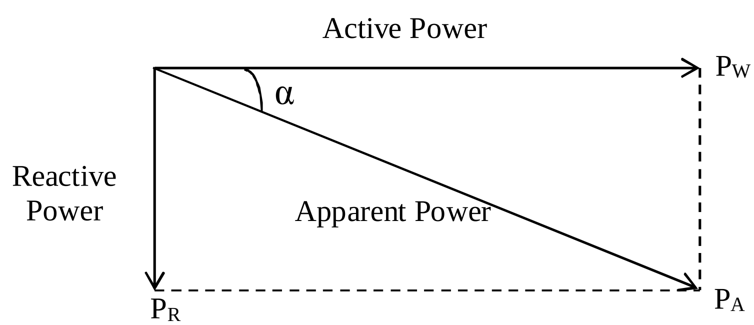


Fig (3.1) power angle

The total power (KVA) consists of real power (Kw) which produces energy and reactive power (KVAR) generated by inductive machines. The reactive power decreases the capacity of the power supply system and creates additional losses.

Figure (3.1) shows the power triangle.

3.2 Power Factor and Power Factor Correction

The power factor of an AC electrical power system is defined as the ratio of the real power flowing to the load to the apparent power in the circuit, and is a dimensionless number in the closed interval of -1 to 1. A power factor of less than one means that the voltage and current waveforms are not in phase

However, as the corrected power factor moves nearer to unity, the effectiveness of capacitors in improving the power factor, decreasing the Kilo volt amperes in power system, increasing the load capacity, or reducing line copper losses by decreasing the line current sharply decreases. Therefore, the correction of power factor to unity becomes more expensive with regard to the marginal cost of capacitors installed [12, 16].

3.2.1 Power Factor in Systems with Linear Loads

In power systems containing only linear loads, the vector relationship between voltage and current, the power factor (cos ϴ) can be illustrated as figure (3.2) below [12].

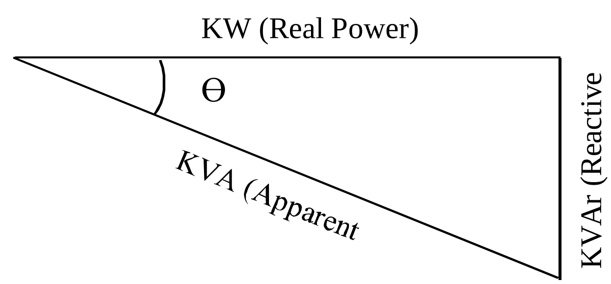


Figure (3.2) Power Factor Components in System with Linear Load

$$Power\ Factor\ (pf) = \frac{KW\ (Real\ Power)}{KVA\ (Total\ Power)} \quad (3.1)$$

3.2.2 Linear Load Power Factor Correction

This linear load power factor correction enables the overall power factor to be brought within acceptable limits, using linear techniques. The power factor correction for a linear load can therefore be supplied by presenting a reactive load of the equal and opposite sign. The linear load power factor correction is therefore applied by adding capacitors where there is an inductive load, and adding inductors where there is a capacitive load. Motors typically present an inductive load to the supply, and therefore capacitors are added to neutralize the effect of the inductance and bring the power factor back to, or much closer to a figure of unity [12, 13, 17].

3.2.2.1 Automatic capacitor linear power factor correction

To ensure that the correct level of linear load power factor correction is applied, automatic systems are often employed. Automatic linear power factor correction systems incorporate a number of capacitors that can be switched in according to the load and power factor correction required. This assumes an inductive load which is normally the case. The linear power factor correction unit measures power factor of the network and then switches in the required number of capacitors to give the necessary power factor correction. In this way the linear power factor correction unit is able to maintain the power factor above a certain level regardless of the load in the system.

3.2.2.2 Synchronous motor corrector

Linear load power factor correction can be applied by using an unloaded synchronous motor to supply the reactive power. The system works because the reactive power drawn by the synchronous motor is a function of its field excitation and this can be altered under these conditions to provide a capacitive load. This form of linear load power factor correction is referred to as a synchronous condenser. The motor is started and connected to the electrical network where it operates at a leading power factor, thereby applying a reactive element to the system as required. The level can obviously be changed to meet the requirements of the time. The great advantage of this form of linear power actor correction is that it can be varied more easily to give the required level of power factor correction.

3.2.2.3 Semiconductor power factor correction systems

Increasingly, semiconductor based systems are being used for linear power factor correction, particularly for high voltage and rapidly varying loads. Semiconductor systems are able to respond more rapidly and also they require considerably less maintenance as the contactors used in capacitor systems will ultimately require replacement and synchronous motors have a limited life and require attention.

3.2.3 The relationship between P.F Correction and Harmonics

It is not advisable to install the power factor correction without considering the harmonic content of a system. This is because, even if we could manufacture capacitors that can withstand high overloads, capacitors produce an increase of harmonic content with the negative effects when an inductive reactance is equal to the capacitive one (resonance phenomena).

$$\omega L = \frac{1}{\omega C} \quad \text{......} \quad (3.2)$$

The resonance is calculated by:

$$N = \sqrt{\frac{S_{CC}}{Q}} = \sqrt{\frac{A.100}{Q.V_{CC}\%}} \quad (3.3)$$

Scc: short circuit power of the network (MVA)

Q: output of the power factor correction bank (KVAR)

A: rated power transformer (KVA)

Vcc%: short-circuit voltage

N: harmonic order

Where the solution is the detuned filter formed introducing a filter reactor in series with the capacitors, making this a more complex resonant circuit but with the desired feature of having a resonance frequency below the first existing harmonic.

3.2.4 Power Factor in Power System with Harmonics

In power systems which contain non-linear loads like rectifiers (such as used in a power supply), and arc discharge devices such as fluorescent lamps, electric welding machines, or arc furnaces. Because current in these systems is interrupted by a switching action, the current contains frequency components that are multiples of the power system frequency. Distortion power factor is a measure of how much the harmonic distortion of a load current decreases the average power transferred to the load. [12]

$$distortion\ power\ factor = \frac{1}{\sqrt{1+THD_i^2}} = \frac{I_{1,rms}}{I_{rms}} \quad (3.4)$$

Where:

THD_i is the total harmonic distortion of the load current

$I_{1,rms}$ is the fundamental component of the current

I_{rms} is the total current – both are root mean square-values

3.3 Harmonics Mitigation Techniques

The majority of electrical nonlinear equipment, especially three phase types, normally associated with larger powers will often cause the need for the addition of mitigation equipment in order to attenuate the harmonic currents and associated voltage distortion to within the necessary limits. Depending on the type of solution desire, the mitigation may be supplied as an integral part of nonlinear equipment (e.g., an AC line reactor for AC PWM drive) or as a discrete item of mitigation equipment (e.g., an active filter connected to a switchboard) [7].

3.3.1 Filters

Utilities use harmonic filters to mitigate harmonics on their distribution systems. Filters can be used inside the plant as well. Typically, harmonic filters are either passive or active. Passive harmonic filters use inductors and capacitors to block harmonics or shunt them to ground, depending on the inductor also increases, whereas the impedance of a capacitor decreases. Passive filters may become ineffective if harmonics change due to varying loads. Line reactors and transformers are used for limited harmonic control with ac drives. However, most of them are installed to protect the drive from transients. Significant harmonic control can only be achieved when the inductor has been sized correctly, when the source impedance is low, or when the drive does not contain an integrated dc bus choke. A passive harmonic filter may contain a series/shunt capacitor/inductor network and a series inductor or transformer. This type of filter often is added to an electrical system as a peripheral to a drive system. It must be tuned to the individual drive. Multiple drives require multiple filters.

Active harmonic filters are sometimes called active power line conditioners. Rather than block or shunt harmonic currents, active filters attempt to condition them. Active harmonic filters monitor and sense harmonic currents electronically, and generate corresponding waveforms to counter the original harmonic currents. The generated waveform is injected back into the electrical supply to cancel the harmonic current generated by the load. Ideally, electrical systems would be designed so that harmonics are not produced. Some equipment available today features circuitry that can reduce the generation of harmonics. Active and passive filters can help mitigate harmonics.[7,]

3.3.2 Oversizing Neutral Conductors

In three phase circuits with shared neutrals, it is common to oversize the neutral conductor up to 200% when the load served consists of non-linear loads. In feeders that have a large amount of non-linear load, the feeder neutral conductor and panel board bus bar should also be oversized [11]

3.3.3 Using Separate Neutral Conductors

On three phase branch circuits, another philosophy is to not combine neutrals, but to run separate neutral conductors for each phase conductor. This increases the copper use by 33%. While this successfully eliminates the addition of the harmonic currents on the branch circuit neutrals, the panel board neutral bus and feeder neutral conductor still must be oversized. [12]

3.3.4 K-Rated Transformers

Special transformers have been developed to accommodate the additional heating caused by these harmonic currents. Oversizing Transformers and Generators: The oversizing of equipment for increased thermal capacity should also be used for transformers and generators which serve harmonics-producing loads. The larger equipment contains more copper.[11]

3.3.5 24-Pulse Rectification

Connecting two 12-pulse circuits with a 15° phase shift produces a 24-pulse system. Figure 10 shows one such system in which the two 12-pulse circuits are connected in parallel to produce the required 24-pulse system. The 11th and 13th harmonics now disappear from the supply current waveform leaving the 23rd as the first to appear. Only harmonics of the order , where = 1, 2, 3, 4, and so forth, will be present in a 24-pulse system[14,11].

CHAPTER FOUR

Results and Discussions

4.1 Introduction

The collection of the data of given interconnected distribution system (load) is the first step for studying any case. In such type of problem, we find that the White Nile Sugar Factory has many types of the nonlinear loads such as power converters, fluorescent lamps, computers, light dimmers, and variable frequency drives (VFDs) used in conjunction with industrial pumps, fans, and compressors and the VFDs are available in many levels of power and voltages from 1.1KW up to 1.2MW and the voltage levels are(400V,690V,3.3KV), all of those equipments have made the harmonic distortion a common occurrence in electrical power networks. In such type of problem, we find that the plant is suffering from the following:

- Excessive heating and failure of motors, there are 48 motors failed in Process house in first and second season.
- Frequent failure of IGBTs / LCL Filters.
- Tripping coils and control cards of circuit breakers failed.
- More than 50 motor protection relays failed.
- Poor power factor.

In case of distribution system harmonics study, the data required are:

- Simplified line diagram of system
- Supply transformer-rating KVA and % impedance
- Cable length, size and type between the transformer and the loads.
- System voltage and frequency
- Source of harmonics-AC, DC drives …

- Type of harmonic generating equipment 6-12 pulse …
- Details of any additional harmonic producing equipment that will be installed.
- Ratings of any existing capacitors.
- Rating of proposed new power factor correction capacitors.

4.2 Network harmonics study for mills station

The purpose of this study is to perform network harmonic analysis for 24 pulses Diode Front End (DFE) based GEPC MV7303 Flat Pack drives, which are drive the mills motors. And there are some assumptions and considerations in this study:

- 11kV network where GEPC drives are connected is considered as Point of Common Coupling (PCC).
- Voltage and Frequency fluctuations are not considered in the study.
- The minimum and maximum short circuit power at 11kV PCC is considered as 300 and 550MVA respectively. Harmonic study is done considering Minimum short circuit power of 300MVA.
- Upstream cables to 11kV network are not taken into account (for resonance, etc.)
- Background harmonics coming from consumers other than Power Conversion drives are assumed zero.
- Residual harmonics of 5% is considered for this study.
- Harmonics are observed at 11kV PCC considering all 6 drives (Line1) in operation.

Stander IEEE519 standard for Voltage & Current emissions

4.2.1 Quasi 24 Pulse Concept – Considering 2 Drives in Operation

The DFE has been considered operating in Quasi 24 pulse by connecting two 12 pulse transformers with the phase shift as mentioned below. One 12 pulse transformer has phase shifting at the secondary of the transformer by +15° and -15° i.e (D0 d +15d -15) and the second 12 pulse three winding transformer with Dd0y11 configuration. Refer figure in figure 4.1

Each transformer sees a six pulse waveform at its Secondary and each transformer primary sees a 12 pulse waveform. When operating together, it behaves as Quasi 24 pulse configuration and this effect is seen at PCC. Refer to the waveform in 4.2

Hence out of a total of 6 transformers, 3 transformers are provided with a Phase shifting secondary of+15°/-15° (D0 d +15d-15) , while the other 3 transformers are 3 winding transformers (Dd 0y11)

Harmonic Study is done at 11kV PCC and Voltage & Current harmonics are tabulated. Since the standard to which the harmonics should comply is not mentioned, the harmonics are compared with IEEE519 Standard limits.

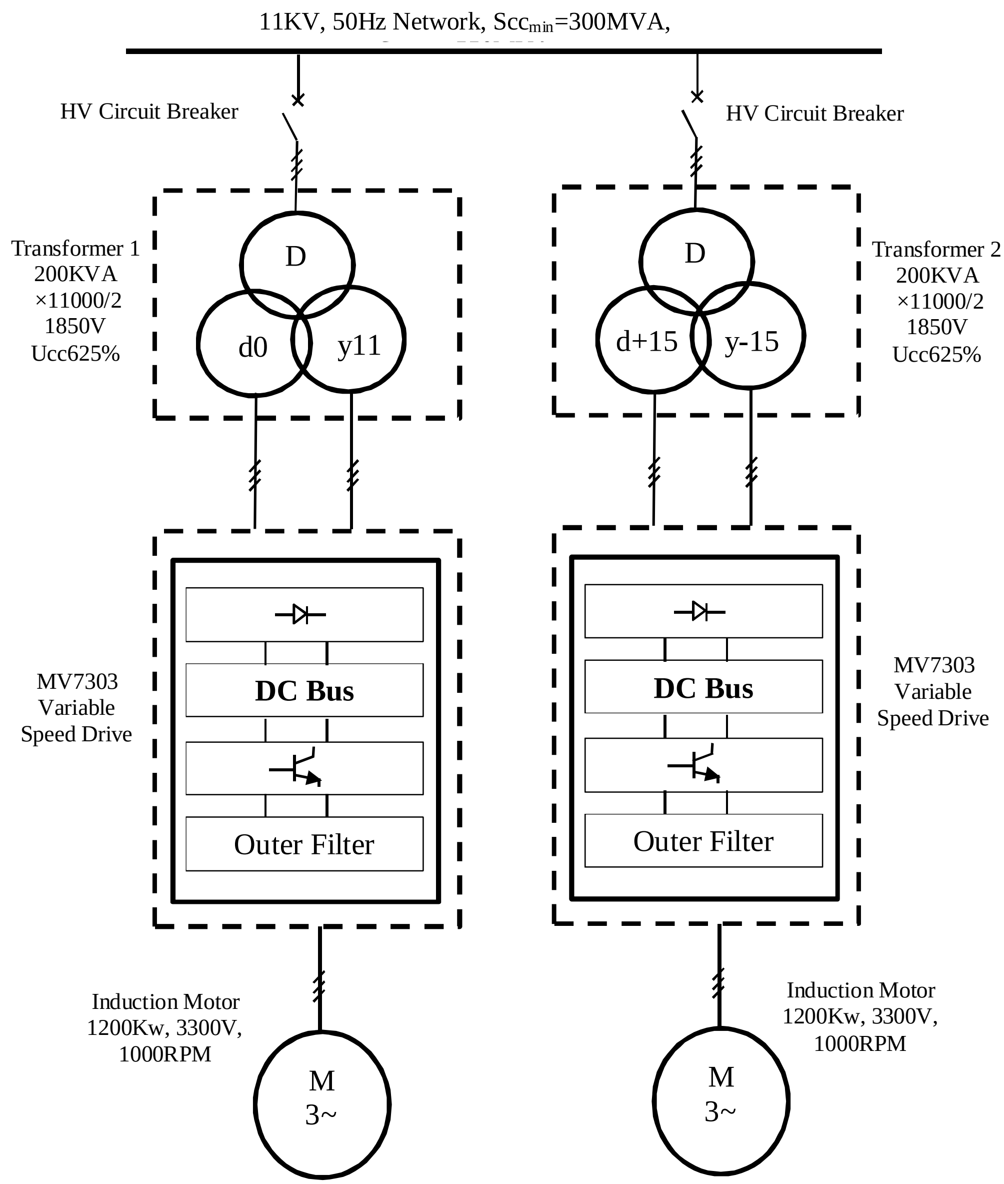


Fig. (4.1) Quasi 24 Pulse Configuration – Considering 2 Drives in Operation

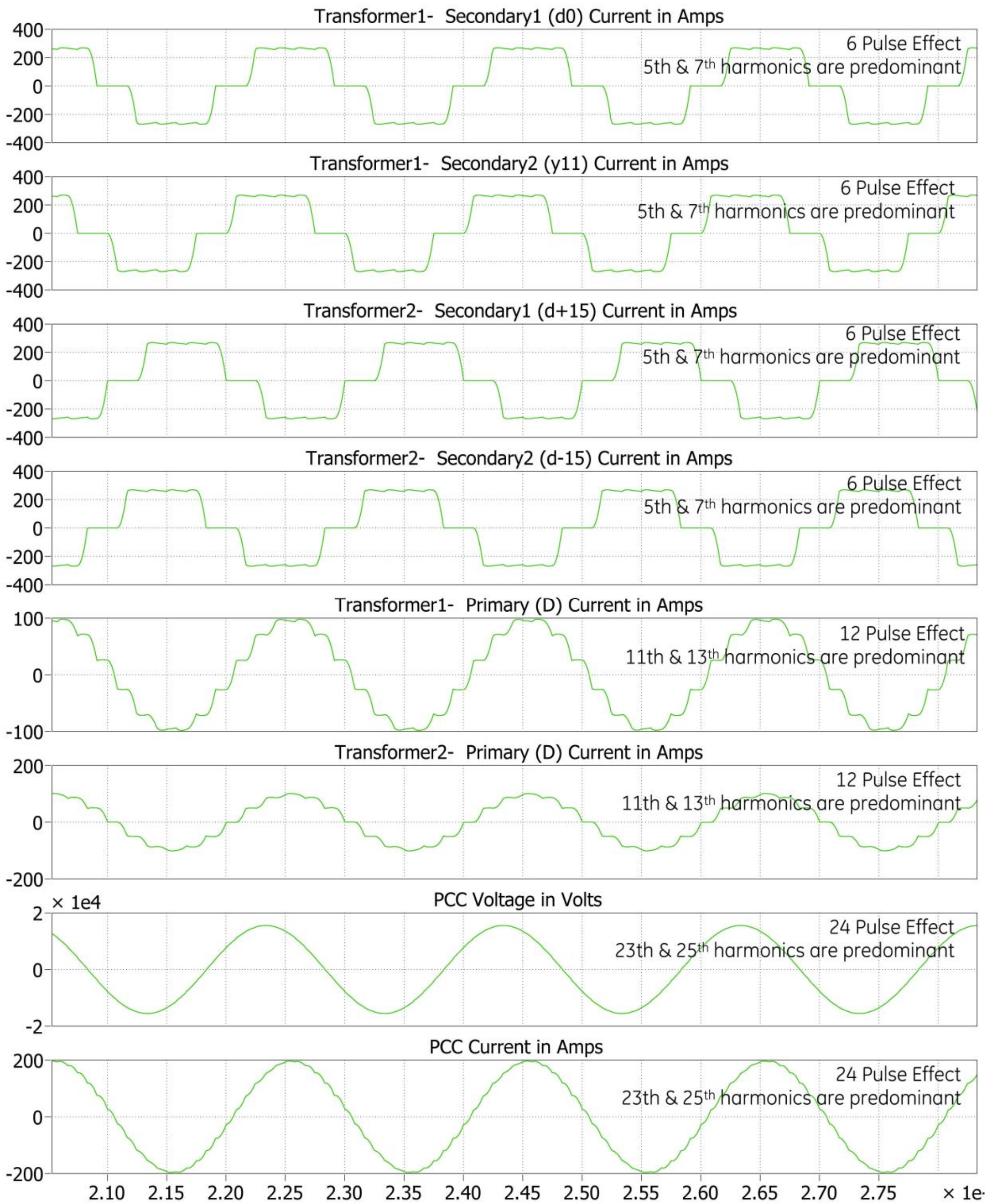


Fig. (4.2) Quasi 24 Pulse Waveform- Considering 2 Drives In Operation

4.2.2 Data Survey

The survey covered the following items:

Voltage (V)	11kV (+/-10%)
Frequency (F)	50 Hz (+/-3%)
Short circuit power Sscmin / Sscmax	300 / 550 MVA

Table (4.1) GRID DATA

	Drive Transformer	
Apparent Power (S)	2 MVA	
Configuration	3 transformers - **Dd0y11**	3 Transformers - **D0 d+15d-15**
Frequency (F)	50 Hz	
Primary Voltage	11 kV	
No-load secondary Voltage (U 2vo)	2x1850 V	
SN base	2 MVA	
% impedance Ucc	6.25%	
Quantity	06 (Line1)	

Table (4.2) DRIVE TRASFORMER DATA

Drive	**MV7303 DFE**
Drive input voltage	3300V
DC bus voltage	5000V
Drive efficiency	97.8%
Quantity	06 (Line1)

Table (4.3) DRIVE DATA

	Induction machine
Rated Power (MW)	1.2MW
Rated Voltage (V)	3300V
Power factor (cosφ)	0.82
Speed	1000 rpm
Frequency	50Hz
Quantity	06 (Line1)

Table (4.4) MACHINE DATA

4.2.3 IEEE 519 Network Harmonics Limit

- **Voltage Limit According to IEEE519 Standard**

This standard gives the following voltage harmonic distortion limits at 11kV[10].

Voltage Level	Total Harmonic Voltage (THD)	Individual Harmonic Voltage
69kV and below (11kV)	5.0%	3.0%

Table (4.5) IEEE519 Std

Current Limitation According to IEEE519 Standard

Current limits for 120V through 69kV.this standard gives the following current harmonic distortion limits at 11KV[6,10].

Individual Harmonic Order (Odd Harmonics)						
I_{SC}/I_L	$<1_1$	$11 \leq h<17$	$17 \leq h<23$	$23 \leq h<35$	$35 \leq h$	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

Table (4.6) IEEE Std 519

I_L= maximum demand load current (fundamental frequency component) at PCC.

I_{sc} = maximum short circuit current at PCC.

This table is applicable to six-pulse rectifiers and general distortion situations. However, when phase shift transformers or converters with pulse numbers (q) higher than six are used, the limits for the characteristic harmonic orders are less than 25% of the limits specified in the above table.

IEEE519 CURRENT HARMONIC LIMIT CALCULATION

Given Short Circuit Power = 300 MVA

I_s = **15746 A**

Maximum demand load current is calculated by considering motor to be loaded 100%

Motor power = 1.2MW

Where: motor η = 0.96, Drive η = 0.97, Drive PF = 0.96, Transformer η = 0.99

Hence Motor Power at PCC= (1.2e6)/(0.97*0.96*0.99*0.96) = 1.355MVA

When 6 drives are in operation, the total motor power = 8.13MVA

Voltage at PCC =11kV

IL = (8.13e6) / (1.732*11e3) = **426.7A**

Isc/IL = 15746 / 426.7 = **36.9**

Hence it is considered as I SC/I L **20<50** in table 4.3

Rank	Limits (%)
5	1.75
7	1.75
11	0.88
13	0.88
17	0.63
19	0.63
23	2.00
25	2.00
29	0.25
31	0.25
35	0.13
37	0.13
41	0.13
43	0.13
47	1.00
49	1.00
THD	**8.00**

Table (4.7) Current harmonic Limits for 6 DFE's connected to common PCC (11kV)

	Limits (%)	Values (%)
H5	3.00%	0.07%
H7	3.00%	0.07%
H11	3.00%	0.06%
H13	3.00%	0.05%
H17	3.00%	0.04%
H19	3.00%	0.03%
H23	3.00%	0.71%
H25	3.00%	0.62%
H29	3.00%	0.02%
H31	3.00%	0.02%
H35	3.00%	0.02%
H37	3.00%	0.02%
H41	3.00%	0.01%
H43	3.00%	0.01%
H47	3.00%	0.34%
H49	3.00%	0.33%
THD	**5.00%**	**1.07%**

Table (4.8) Voltage harmonic at 11KV PCC

Voltage THD (foreseen): 1.07%

Voltage THD (limit)): 5.0%

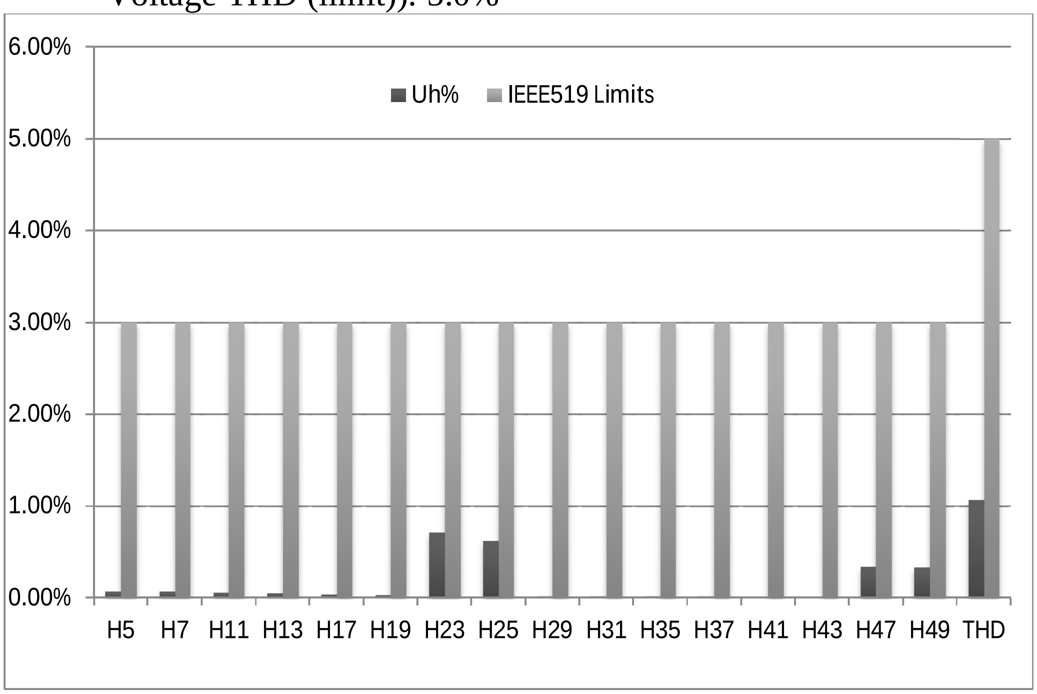


Fig. (4.3) Voltage harmonic at 11KV PCC

	Limits (%)	Values (%)
H5	1.75%	0.94%
H7	1.75%	0.63%
H11	0.88%	0.33%
H13	0.88%	0.25%
H17	0.63%	0.14%
H19	0.63%	0.10%
H23	2.00%	1.14%
H25	2.00%	0.92%
H29	0.25%	0.04%
H31	0.25%	0.03%
H35	0.13%	0.03%
H37	0.13%	0.03%
H41	0.13%	0.02%
H43	0.13%	0.02%
H47	1.00%	0.27%
H49	1.00%	0.26%
THD	**8.00%**	**1.94%**

Table (4.9) Current harmonics at 11KV PCC

Current THD (foreseen): 1.94%
Current THD (limit)): 8.0%

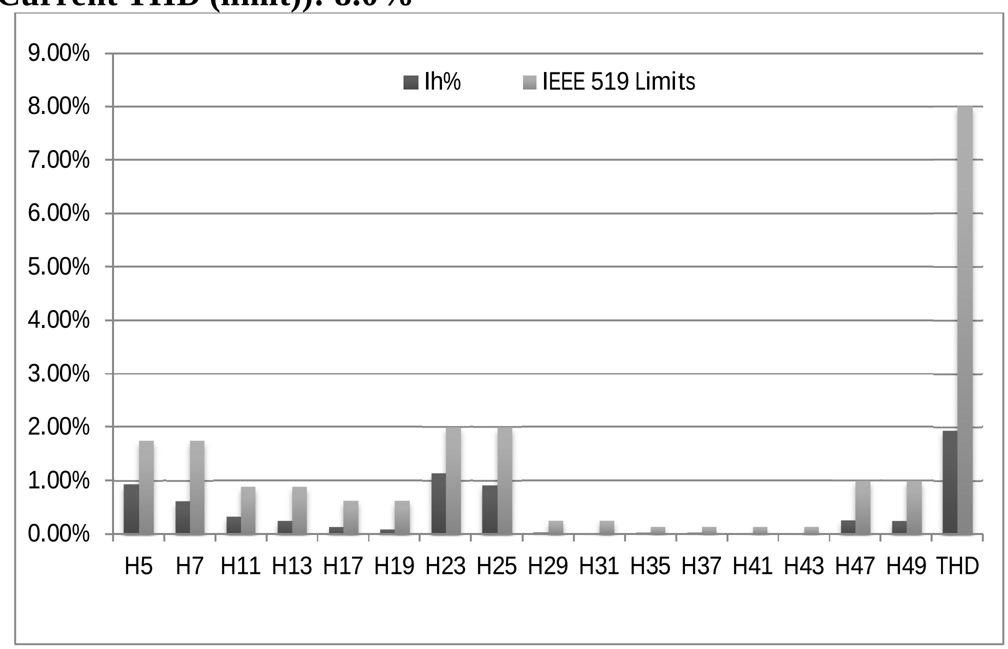


Fig. (4.4) Current harmonics at 11KV PCC

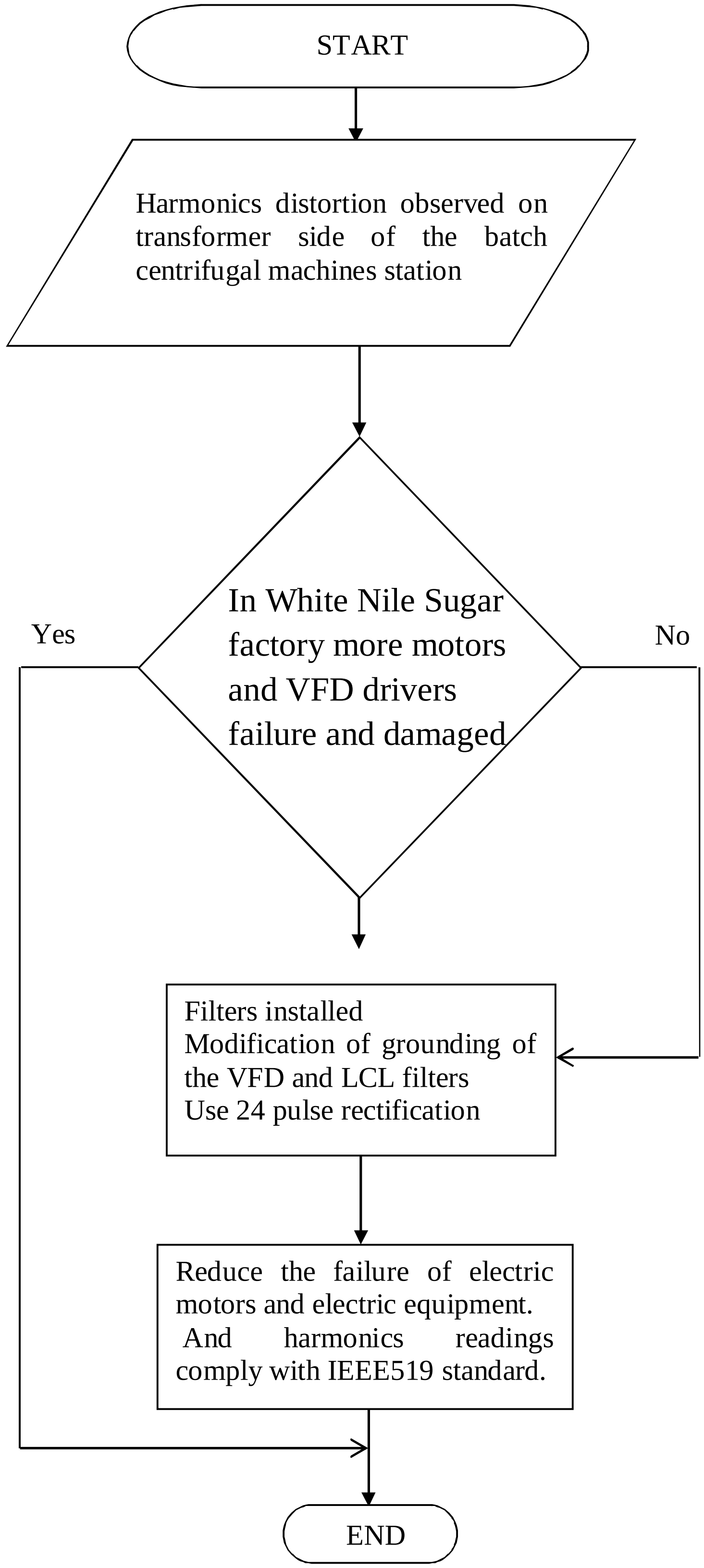
Note: Harmonic limits calculations are done, considering 6 drives in operation at 11kV network

4.3 Analysis of electrical failures and corrective actions in process house plant

Few electric motors in process house plant failed during crops 2012-2013 and 2013-2014. Then analysis have been done to know the causes of such failures, as first analysis was carried out regarding the causes of failure of the one no. 280 KW VFD duty motor and components of VFD panels for high grade batch centrifugal machines. After analyzing the harmonic distortion observed on the transformer side of the batch centrifugal station, it was decided to study the grounding/earthing of the VFD panels for batch centrifugal machines as well as surrounding electrical equipments. A result of study and inspection of grounding/ earthing found that improper earthing of VFD panels was cause failure of the electric motors and components in VFD panels of batch centrifugal machines, then carried out modifications at side by providing dedicated for all VFD panels including LCL filters and connected them to dedicated earth pits.

After the above corrective steps, harmonics study has been carried out on the transformer side of Batch Machine, it was observed that the harmonics level has got corrected to acceptable limits.

4.4 Flow Chart:



4.5 Discussion and Results

In recent years, the modernization of industrial process and the sophistication of electrical equipment and machines have led to considerable development in power electronics. These equipments represent "nonlinear" loads in which the current consumption does not reflect the supply voltage. And most loads in White Nile Sugar Factory are nonlinear loads, and the main reason of generating harmonic in the factory is VFDs, more motors, instruments and electrical equipments failure. Harmonics study is done for mills station by considering all 6 drives in operation connected to 11kV, the VTD, ITHD , Individual voltage and current harmonics comply with IEEE 519 standard under steady state condition. And in process house LCL filters installed for all VFDs, some of the VFD panels' earth found to mingle with the lighting transformer neutral, so disconnected and dedicated earthing provided for all LCL filters in the Centrifuge Panels using 25sq.mm Cu cable, and earth pit provided for the VFD panels and the previously provided VFD panel earth bus bar isolated from existing earth pit and diverted to the dedicated earth pit.

Then harmonics measurements on the Transformer side after the above modifications with all centrifugal VFD in off mode and after that in on mode. As per above measurements, we notice no difference in 2nd, 3rd & 19th harmonics level with or without Centrifuge drives and comply with IEEE519 standard.

CHAPTER FIVE

Conclution and Recommendations

5.1 Conclusion

This thesis presents an overall harmonics-study for mitigation it in the White Nile Sugar Factory and demonstrates the importance of mitigation harmonics.

A comprehensive data bank of harmonics has been constructed from instrumentation and calculation from the side of mills and process house. The data has been collected for solving the problem of harmonics and to perform network harmonic analysis.

The VFDs and other nonlinear loads are dirty loads in the network because they generate harmonics. The effect of these harmonics is that they distort the network voltage. The normal solution for mitigation harmonics is a filter with reactors.

If your plant is suffering from any of the following

- Damage to sensitive electronic control systems
- Excessive heating and failure of transformers, motors, capacitors, lighting ballast capacitors or capacitor fuses.
- Erroneous operation of electronic control systems.
- Nuisance tripping of circuit breakers.
- Interference in communication systems.
- Excessive current in the neural conductor.

Then you could have a harmonic problem.

Harmonic problems must not be confused with transient disturbances. Harmonics are continuous, steady state disturbances whereas the transient disturbances are caused by 'spikes', surges, or impulses.

In recent years, the most widely used non-linear devices have been power diodes, thyristors and other power semiconductors. These devices were commonly found in rectifier circuits for UPS systems, variable speed AC and DC drives, switched mode power supplies, static converters, Thyristor control systems and diode bridges, so most of those devices are found in White Nile Sugar Factory.

Thyristor devices are usually referred to by their phase number, i.e. 2, 3, 6, 12 … etc which refer to the number of DC current pulses they produce each cycle. The most commonly used three phase thyristor converter of these is the 6 and 12 pulse devices.

Harmonic may be produced in output wave form of an A.C generator due to anon sinusoidal air gap flux distribution or to "tooth ripple "which is caused by the effect of the slots which has the windings.

Also in rectifiers the DC component of the wave must contain a large proportion of second harmonic. Iron cored coils are a source of harmonic generation in A.C circuits owing to the non linear character of B-H curve and hysterics loop, especially if saturation is occurs.

5.2 Recommendations

1. Passive harmonic filter is a serial combination of a capacitor and an inductance for which the tuning frequency corresponds to a harmonic voltage to be eliminated.
2. I recommend do furthering study on grounding in whole plant and improving the working of VFDs at other drives in the plant which will mitigate the harmonics effects.
3. I hope researchers study well the reasons of harmonics and find out the exact related problems and the optimum solutions.
4. It is very important to make different measurements after solution for various situations of the load to be sure that the steps are chosen accurately.
5. For further studies in these fields it is recommended to conduct more researches to study the relation between harmonics and power factor corrections.
6. A research is needed to develop by study all the related problems to choose the best mitigation.

References

[1] Dugan, Roger C.; Mark McGranaghan, Surya Santoso, H. Wayne Beaty (2003). Electrical Power Systems Quality. McGraw-Hill Companies, Inc... ISBN 0-07-138622-X.

[2] J. J. Paserba, “How FACTS Controllers Benefit AC Transmission Systems”, Power Engineering Society General Meeting, 2004. IEEE 6-10, Vol.2, Page(s):1257 – 1262, June 2004

[3] Benysek, Grzegorz, “Improvement in the Quality of Delivery of Electrical Energy using Power Electronics Systems” Series: Power Systems (2007) pp 9-16]

http://www.springer.com/978-1-84628-648-3

[4] Harmonics: The Effects on Power Quality and Transformers, Robert D. Henderson, ***Member,*** *IEEE,* and Patrick **J.** Rose

[5] Interaction Between 1500-kVA Supply Transformer and VFD, Load at an Industrial Plant, Mahesh M. Swamy, Member, IEEE, and Steven L. Rossiter,Asso AssociateMember,IEEE.

[6] IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems, IEEE Std 519-2014

[7]Harmonic Mitigation Techniques Applied to Power Distribution Networks, Hussein A. Kazem, Faculty of Engineering, Sohar University, P.O. Box 44, 311 Sohar, Oman

[8] Fundamental of electrical power quality assessment

Janusz Mindy kowski Gdynia Maritime University, Department of Ship Electrical Power Engineering, Gdynia, Poland

[9] Power System Harmonics Causes and Effects of Variable Frequency Drives Relative to the IEEE 519-1992 Standard, Bulletin No. 8803PD9402 August, 1994

[10] IEEE Recommended Practices and Requirements for Harmonic Control in
Electrical Power Systems, ANSI/IEEE Std. 519-1992.
[11] Hazards of Harmonics and Neutral Overloads, **Neil Rasmussen** 2011 Schneider Electric – Data Center Science Center.
[12] ETON 1 MEM; ‘Power Factor Capacitor’ Eaton Electric Limited, Redding’s Lane, Birming-UK, 2004 Catalogue.
[13] Power factor correction and harmonic filtering in electrical plants, ABB, ABB SACE, 2008.
[14] Power System Harmonic Mitigation for Water and Wastewater Treatment Plants, Louis Hapeshis, PE, Square D Engineering Services
[15] N.G.Hingorani, L. Gyugyi, Understanding FACTS, Concept and Technology of Flexible AC Transmission Systems, New York, Wiley, 2000. IEEE Trans. on Power Delivery, Vol. 12, No. 4, pp. 1717-1722, 1997.
[16] ICAR, IEC 871_831 EN 60831, 60831 "power factor correction" 2000, Italy
[17] Power Factor Correction Systems [Manual], ICAR.spa, Via Iso nzo, 10-20052, Monza (MI) Italy www.icar.com, sales@icar.com.

Appendix (A)

List of motors failed in process house up to end of 2^{nd} crop

Juice clarification &lime station (transformer 1)

Sr. No.	equipment	Rating in KW	Speed (rpm)	voltage	Method of starting
1	Defecated juice pump no. 3	250	1484	690	VFD
2	Juice Clarifier no. 1	5.5	1440	690	VFD
3	Juice Clarifier no. 2	5.5	1440	690	VFD
4	Mud bin screw conveyer	7.5	1440	690	VFD
5	Flocculent Juice Clarifier	1.1	1400	400	DOL/VFD
6	Phosphate acid dosing pump	0.37	1390	400	DOL/VFD
7	Color precipitant dosing pump	0.18	1300	400	DOL/VFD
8	Juice Clarifier no. 3	5.5	1440	690	VFD
9	Mud recirculation pump	15	1450	690	DOL
10	Juice Clarifier no. 4	5.5	1440	690	VFD

Evaporation &juice heating station (transformer 2)

Sr. No.	equipment	Rating in KW	Speed (rpm)	voltage	Method of starting
1	Evaporator C row	75	1482	690	S/D
2	Juice recirculation pump 4^{th}	37	1465	690	VFD
3	Juice recirculation pump 2^{th}	75	1482	690	S/D
4	4^{th} effects juice Rec. pump	37	1465	690	DOL
5	2^{th} effects juice Rec. pump	37	1465	690	DOL
6	4^{th} effects juice Rec. pump in A row	37	1465	690	DOL

Continuous centrifugal machine & vertical crystallizer station (transformer 5)

Sr. No.	equipment	Rating in KW	Speed (rpm)	voltage	Method of starting
1	C-1 mono vertical crystallizer	5.5	950	690	DOL
2	Liquidation pump	37	1465	690	DOL
3	C-2 mono vertical crystallizer	5.5	950	690	S/D
4	B magma pump	11	1450	690	DOL
5	Vertical crystallizer	9.3	960	690	VFD
6	Continuous pan Rec.XLR	7.5	1440	690	DOL
7	B masscuite transfer pump	37	1465	690	VFD
8	A1 molasses pump	11	1460	690	DOL
9	Vertical crystallizer	9.3	980	690	VFD
10	Vertical crystallizer	9.3	960	690	VFD

Batch centrifugal machine, sugar drying and bagging station (Transformer 6)

Sr. No.	equipment	Rating in KW	Speed (rpm)	voltage	Method of starting
1	Heavy molasses pump	18.5	1460	690	DOL
2	Batch machine no.4 phase -1	280	743	690	VFD
3	A masscuite transfer pump no.4 phase-2	37	1465	690	VFD
4	A masscuite transfer pump no.4 phase-2	37	1465	690	VFD

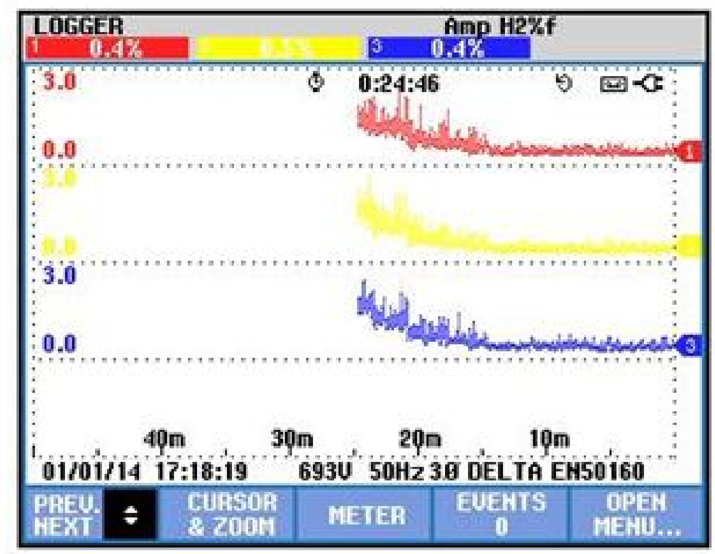
Batch centrifugal machine, sugar drying & bagging station (Transformer7)

Sr. No.	equipment	Rating in KW	Speed (rpm)	voltage	Method of starting
1	A masscuite transfer pump	37	1465	690	VFD
2	120 Ton mechanical circulator	90	1482	690	VFD
3	FBD Hot air blower	45	1470	690	S/D
4	A masscuite transfer pump	37	1465	690	VFD
5	FBD cold air blower	37	1465	690	VFD
6	Syrup transfer pump	18.5	1460	690	DOL/VFD
7	Receiving crystallizer	7.5	1440	690	DOL
8	Sugar grader	22	980	690	VFD
9	Seed pump	15	1450	690	VFD
10	I.D.Fan line-4	90	1482	690	S/D

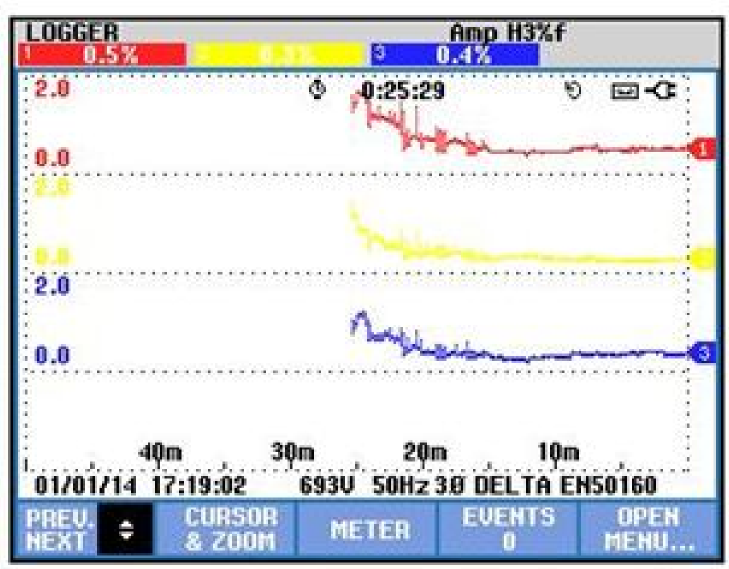
Appendix (B)

Harmonics reading in process house station-4 after filters installed and some modification done

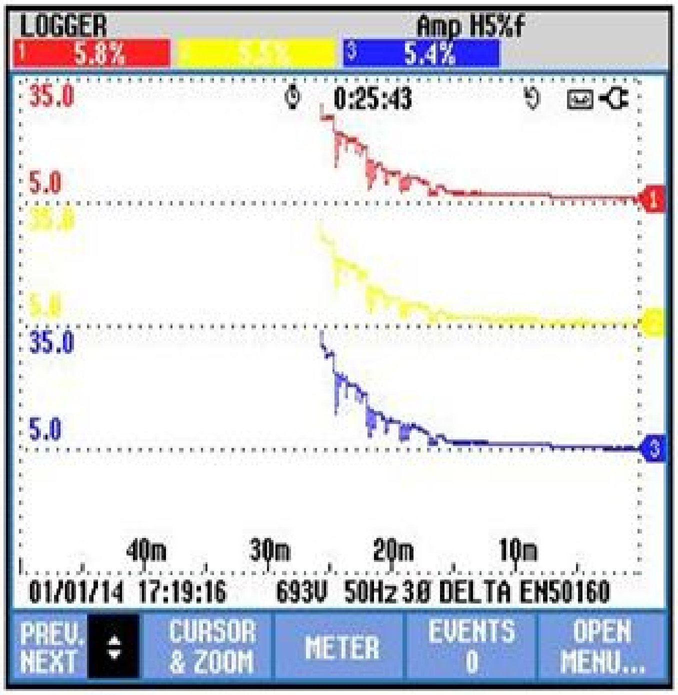
Second order Harmonic distortion:



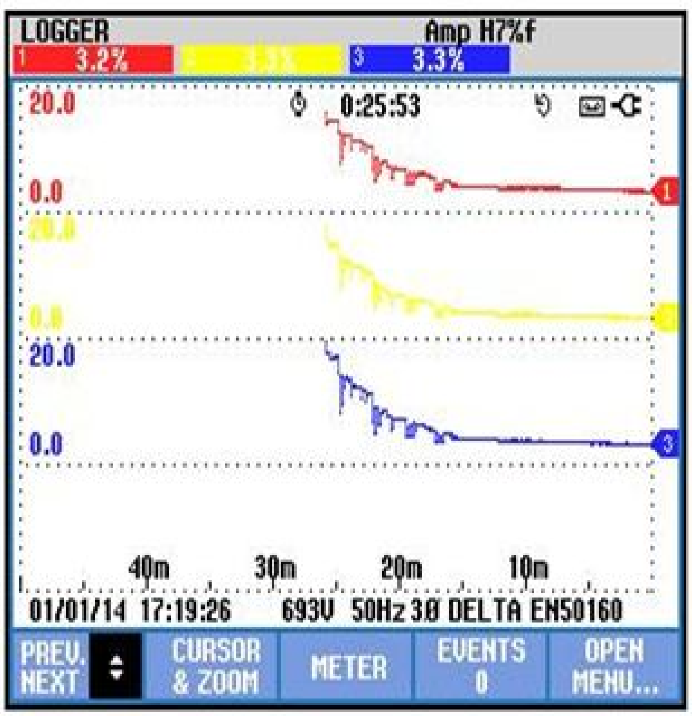
Third order harmonics:



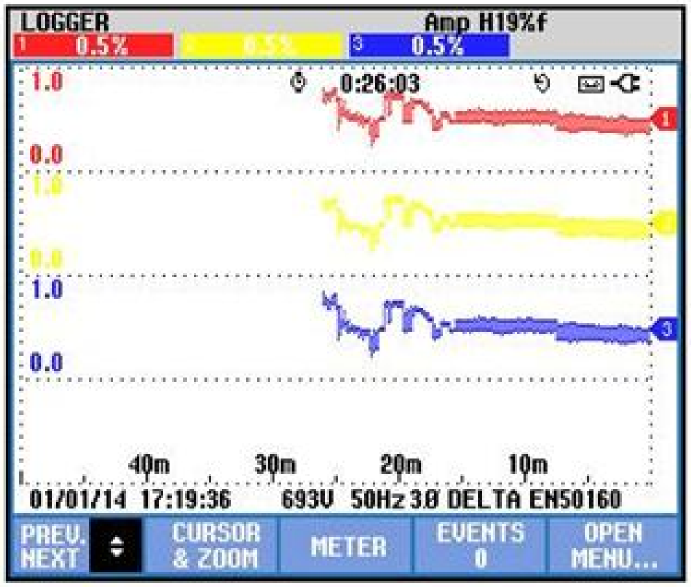
Fifth order Harmonics:



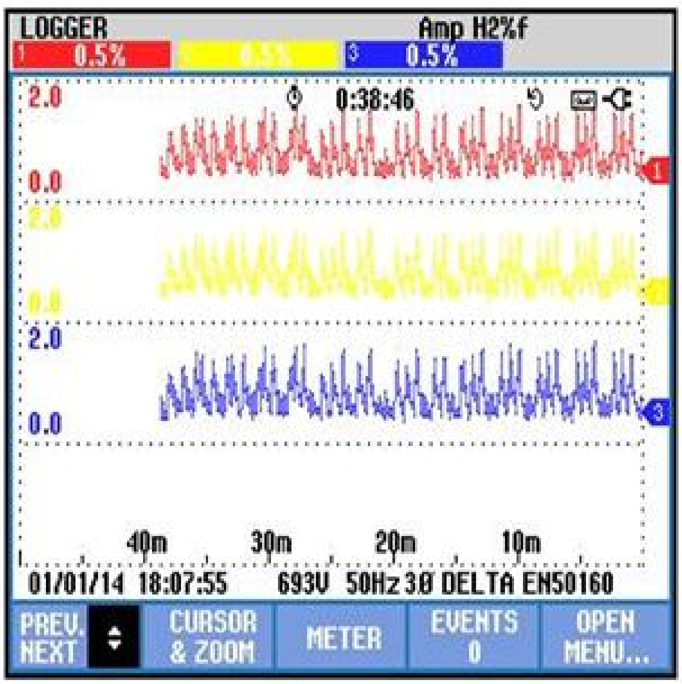
Seventh order Harmonics:



Nineteenth order harmonics:



Second order Harmonics:



d order Harmonics: