INVESTIGATION AND MITIGATION OF POWER QUALITY PROBLEM USING UNIFIED POWER QUALITY CONDITIONER

(Case Study: Fincha Sugar Factory)

Lamesa Fila Gugsa

A Thesis Summited to

The Department of Electrical Power and Control Engineering

School of Electrical Engineering and Computing

Presented in Partial Fulfillment of the Requirements for the Degree of

Master's of Science in Electrical Power Engineering

Office of Post Graduate Studies

Adama Science and Technology University

September, 2022

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Declaration

I hereby declare that this Master Thesis entitled “investigation and mitigation of power quality problem using unified power quality conditioner **“**is my original work. That is, it has not been submitted for the award of any academic degree, diploma or certificate in any other university. All sources of materials that are used for this thesis have been duly acknowledged through citation.

Lamesa Fila Gugsa	______________	**September,2022**
Name of the student	Signature	Date

Recommendation

I, the advisor of this thesis, hereby certify that I have read the revised version of the thesis entitled “investigation and mitigation of power quality problem using unified power quality conditioner “” prepared under my guidance by Lamesa Fila Gugsa submitted in partial fulfillment of the requirements for the degree of Master’s of Science in power Engineering. Therefore, I recommend the submission of revised version of the thesis to the department following the applicable procedures.

____________________________ ___________________________ __________________

Advisor Signature Date

Approval Sheet

I, the advisor of the thesis entitled "investigation and mitigation of power quality problem using unified power quality conditioner" and developed by Lamesa Fila Gugsa, here by certify that the recommendation and suggestions made by the board of examiners are appropriately incorporated into the final version of the thesis.

____________________ ____________________ ________________

Advisor Signature Date

We, the undersigned, members of the Board of Examiners of the thesis by Lamesa Fila Gugsa have read and evaluated the thesis entitled "investigation and mitigation of power quality problem using unified power quality conditioner" and examined the candidate during open defense. This is, therefore, to certify that the thesis is accepted for partial fulfillment of the requirement of the degree of Master of Science in power Engineering.

Chairperson	Signature	Date
Internal Examiner	Signature	Date
Eternal Examiner	Signature	Date
Department Head	Signature	Date
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Acronyms

AC	Alternating Current
ANSI	American National Standard Institute
ASD	Adjustable Speed Drive
AV	Average
CFL	Compact Fluorescent Lamps
DC	Direct Current
DF	Distortion Factor
DPF	Displacement Power Factor
D-STATCOM	Distribution Static Compensator
DVR	Dynamic Voltage Restorer
FSF	Fincha Sugar Factory
GUI	Graphic User Interface
HVDC	High Voltage Direct Current
HVAC	Heating Ventilation and Air-Conditioning
I_s	Short Circuit Current
IEC	International Electro-technical Commission
IEEE	Institute of Electrical and Electronics Engineers
KHz	Kilo hertz
KVA	Kilo Volt Ampere
Ms	Millisecond
MVA	Mega Volt Ampere
NEMA	National Electrical Manufacturers Association
UPS	Uninterruptable Power Supply
PLC	Programmable Logic Controller
PQ	Power Quality
PSCAD	Power System Computer Aided Design software
PQ	Power Quality
PCC	Point of Common Coupling

PC	Personal Computer
PF	Power Factor
PFC	Power Factor Correction
PU	Per Unit
PPF	Passive Power Filter
RMS	Root Mean Square
SMPS	Switched mode power supplies
TDD	Total Demand Distortion
THD	Total Harmonic Distortion
THDI	Current Total Harmonic Distortion
THDv	Voltage Total Harmonic Distortion
TCRs	Thyristor Controlled Reactors)
UPQC	Unified power quality conditionar
VSCF	Variable Speed Constant Frequency
VFD	Variable Frequency Drives

Abstract

Now a days, power quality problems is one of the major problems for many industries. The poor power quality problems at distribution level can affects the operation and performance of sensitive and critical loads. This problems causes higher power losses, harmonics, sag and swells in the voltages and poor power factor..etc. This thesis focuses on the investigation of power quality problems and its mitigation using Unified power quality conditioner (UPQC) at Fincha Sugar Factor. UPQC is the only versatile devices which can mitigate several power quality problems related with distribution systems. A UPQC that combines the operation of a Distribution Static Compensator (D-STATICOM) and Dynamic Voltage Restorer (DVR) together with the shunt and series active control a devices.UPQC can solve the problems related to the voltage/current harmonics, voltage sag/swell and unbalance in distribution system. To evaluate the performance improvement in the system, a model of UPQC is developed in MATLAB/SIMULINK with atypical distribution at the load sides of Fincha Sugar Factory. Enhancements in power quality by UPQC are evaluated under maximum loads condition.. Proportional Integral (PI) controller is used to stabilize the DC link voltage and balance the active power between the shunt and series inverters and the Phase-Locked Loop (PLL) generated reference signals.

With the application of UPQC the system voltage and current harmonics are significantly reduced. The reactive power of the system is well compensated and thus system voltage is improved to nearly nominal value

Keywords: Power quality, UPQC, Series active power; shunt active power; harmonics, voltage sag/swell.

CHAPTER ONE
INTRODUCTION

1.1 Background

Power supply is a problem in developing countries including Ethiopia, both in terms of availability and quality. With the increasing of non-linear loads in electric power system, power quality distortion has become a serious issue in recent years. Sugar industries are among those industries affected by poor power quality. Power supply is a problem in developing countries including Ethiopia, both in terms of availability and quality. With the increasing of non-linear loads in electric power system, power quality distortion has become a serious issue in recent years. Sugar industries are among those industries affected by poor power quality. In Ethiopia Fincha Sugar Factory is one of the sugar factories which are affected by poor power quality. That means Fincha Sugar Factory experiences voltage variations problems caused by load variation, lightning strikes, switching of power lines and capacitor banks, system faults, and large motor start-ups. These power quality problem causes operation disturbance that require a long time to return to its normal operation and resume production. Therefore, a study of poor power quality is essential for the Sugar industries. Power quality problem study is the study of deviations in current and voltage waveforms from the ideal sine waves. Power quality is the combination of voltage quality and current quality. Thus, power quality is concerned with deviations of voltage and/or current from the ideal.(H. Akagi, Y. Kanazawa, A. Nabae,Tokyo,pp.1375-1386).At the distribution level, power quality can be a combination of voltage quality and current quality. From the marketing point of view, electricity is a product and the power quality is the index of the product quality (H. Fujita and H. Akagi, vol.13, no.2 March 1998).The prime objective of utility companies is to provide their consumers an uninterrupted sinusoidal voltage of constant amplitude. Unfortunately, this is becoming increasingly difficult to do so, because the size and number of nonlinear and poor power-factor loads such as adjustable speed drives, computers, power supplies, programmable logic controllers, furnaces, power converters, induction motors and traction drives are finding its applications at the industrial levels. These nonlinear loads draw nonlinear current and degrade electric power quality. The quality degradation leads to low power-factor, low efficiency, and overheating of transformers.(H. Fujita and H. Akagi, vol.13, no.2 March 1998). This thesis work is mainly concerned on power quality problems and it's mitigating in Fincha Sugar Factory.

1.2 Statement of the Problem

The main objectives of electric distribution is to provide their customers uninterrupted sinusoidal voltages of constant magnitude and frequency with sinusoidal balanced currents at the AC mains. However, now a days, distribution systems are facing severe power quality problems such as high reactive power burden, unbalanced loads and harmonics-rich load currents. In addition, Fincha Sugar Factory Utilities are not able to avoid the voltage sag, swell, surges, flicker, unbalance, and harmonics in the supply voltages across the consumer's loads ends. The effect of power quality problem at Fincha sugar factory such as: causing downtimes of several machines, failure of sensitive machine, increase maintenance cost and left labors without work as a result this affects the factory profit annually.

1.3 Significance of the Study

The output of this thesis work addresses the existing power quality problems and to increases the production output and its efficiency, performance of their equipment and saves the money they lost due to poor power quality which causes production loss, damage to sensitive electronic devices.

1.4 General and Specific Objective

1.4.1 General Objective

The main objective of this thesis work is to assess and investigate the power quality problems in Fincha Sugar Factory and based on the assessment to mitigate the problem

1.4.2 Specific objective

The specific objectives of this thesis are:

- Identify and examine the power quality problems that arise in Fincha Sugar Factory.
- Compare the level of those disturbances with acceptable values set by IEEE standards
- Identify the causes and adverse impacts of the PQ problems,
- Design the appropriate mitigation techniques to the existing PQ problems.

1.5 Scope of the study

This thesis work covers the power quality problems exceeding the IEEE standard and their mitigation techniques for Fincha Sugar Factory. Fincha sugar factory has its own Power generation plant to generate electric power from steam turbine generators; which is driven by steam comes from boilers. Additional the factory has its own substation which is step down 66 KV to 11KV which is found near to the factory. While this thesis is done all the factory turbines are out of the function. So this thesis done on investigation of power quality problems and its mitigation technic on the power come from the on grid substation which is found near to the factory. Most of times the quality of power generate and distribute to the factory is not good this causes of voltage sag; voltage swell; under voltage; over voltage; harmonics and other power quality problems. These power quality problems results in failure of machines; reduction of product; idle of workers which exposes the factory and the country for high cost (H. Fujita and H. Akagi, vol.13, no.2 March 1998). So, this thesis works on investigating power quality problems and proposed the solution for the problems at Fincha Sugar Factory.

1.6 Outline of the Thesis

The thesis is organized in to six chapters as the following:

Chapter one is introduction of the thesis.

Chapter two covers theoretical background and literature of the study topics focused on powerquality problems in general.

Chapter three shows methodology and data collection approach of the study have been also explained.

Chapter four presents a detailed description study area and data analyzing.

Chapter five covers results and discussion.

Finally, Conclusion and Recommendation have been made in Chapter Six.

CHAPTER TWO

THEORETICAL BACKGROUND AND REVIEW OF LITERATURE

2.1. Theoretical Background

The IEEE Standard Dictionary of Electrical and Electronics defines power quality as the concept of powering and grounding sensitive electronic equipment in a manner that is suitable to the operation of the equipment's. Power quality may also define as –the measure, analysis, and improvement of bus voltage, usually a load bus voltage to maintain that voltage to be a sinusoidal at rated voltage and frequency. Another definition of power quality reported in the literature is as follows: Power quality mainly deals with the interaction among the customers and the utility or it can be also said that it provides an interaction between the power system and the respective load. The ultimate goal of power system is the supply of electric energy to its customers. In the last 50 years or so, because of the extensive growth of industries electricity demand has tremendously increased which has led to establishment of many power generation and distribution grid. The demand for large amount of power for industrial and domestic use increased the burden on the generation. Electrical utilities working today are working as a subsystem of a large utility network that are tied together in order to form a complex grid. All these factors have put the power system under the requirement of a power quality (H. Fujita and H. Akagi, vol.13, no.2 March 1998).

Problem in power quality is usually referred to any electrical problem faced in the frequency, voltage or current deviation which leads to mal-operation of the customer's equipment. Often when we talk of quality of power we actually mean the quality of voltage because it is the voltage which is controlled most of the times. The term power quality can be related with reliability of the system by the electrical utilities. The most difficult thing is maintenance of the electrical power quality so that it will lie within the acceptable limits. There are many disadvantages of poor and low power quality. It may lead to higher power losses, abnormal and unusual behavior of electrical equipment, and interference with the nearby communication lines, poor voltage profile, harmonics, sag and swells in the voltage, poor and low distortion and displacement factor.(H. Fujita and H. Akagi, vol.13, no.2 March 1998).

In the recent era power electronic and electronic equipment are becoming more and more sensitive as compared to their counterparts few years back. The equipment which is very much susceptible to this variation or degradation of power quality is the sensitive loads. Pure sinusoidal voltage is required for its proper operation. Along with the increased sensitiveness of the equipment, the growing sensitiveness of companies towards the production loss on account of reduction in the margin of profit has also added to the burden on the quality of power. From ages electricity has been considered as a basic right in the domestic life and it will always be there. Due to this very reason even a small interruption in the supply leads to heavy complaints, even if no damages are related to it (N. Hingorani, Vol.32, Issue: 6, June 1995,pp 41-48). Tripping of the electrical equipment because of aggravations in the supply voltage is frequently portrayed by clients as "awful power quality". On the other hand utilities frequently see unsettling influences because of the end client equipment as the principle power quality issue. The trouble in evaluating power quality concerns is clarified by the way of interaction among the quality of power and the equipment. Modern electronic equipment is not only responsible for voltage unsettling influences; it additionally causes aggravations for different consumers. The main culprit behind this poor power quality is the use of power electronic devices that are mainly the equipment driven by converters and rectifiers like computer, speed drives etc. that acts as non-linear load. The increased use of power electronic devices has increased the tension on power system as it leads to generation of voltage and current harmonics and it also increases the reactive current. Nowadays, power electronic devices are used by the industries for many reasons like variable voltage, variable frequency and current control in order to get accurate controllability, better and higher efficiency, faster response and most importantly to make the devices compact in size. They have prompted an expansive development of voltage unsettling influences, albeit luckily not yet to a level where equipment gets to be sensitive. The fundamental problem here is the non-sinusoidal current of rectifiers and inverters that not only contain the fundamental component but also the harmonic components. The main problem arises because of the switching actions which these power electronics devices exhibit such as MOSFET, BJT, SCR, IGBT etc. Because of this switching action these devices acts as non-linear loads. The displacement and distortion factors also become poor as these devices draw leading/lagging and non-sinusoidal current from the supply, thereby resulting in injection of harmonics in the distribution systems. The harmonic current then starts flowing across the line and source impedance and this causes distortion of voltages, excessive power loss and voltage drop as the supply voltage gets distorted it leads to mal-operation of protection, control, and the metering equipment. So the necessity for maintenance of the power quality standards arises and to achieve a voltage that will be purely sinusoidal, the use of compensation technique is very much important. Many consumers are also there whose need of power quality is high than what provided by the electrical networks. So it’s very much essential to obtain a higher quality of electrical power.(N. Hingorani, Vol.32, Issue: 6, June 1995,pp 41-48).

Custom power devices and FACTS devices are used widely in order to overcome these problems and in order to assure a high and better power quality. Custom power devices refer to the power electronic controllers used in the distribution systems to get a higher level of power quality. They act as power conditioning equipment that helps in mitigating the distorted voltage and current. DVR, DSTATCOM, active filters etc. are utilized as a part of request to enhance the quality of voltage and current to a better standard.(H. Awad, M. H.J Bollen, 2003, vol.2, pp. 1129-1136).

Unified Power Quality Conditioner (UPQC) is a very effective step in improving these power quality problems. It is a combination of parallel-Active Power Filter and Series-Active power Filter. Both of these filters are associated through the same dc link. Parallel active filter is connected parallel with the load. It helps in compensating the harmonic current flowing through the load, compensates reactive power demand of the load and helps in maintenance of a constant dc link voltage. On the other hand, series active power filter is connected in series with the utility voltage by the help of series transformer and helps in maintenance of a sinusoidal the load voltage.(H. Awad, M. H.J Bollen, 2003, vol.2, pp. 1129-1136). So as a whole it helps in a simultaneous compensation of the delivered load voltage and source side currents. Power quality assessment procedure provides a general framework that contains all the possible elements that may be needed for power quality study. From a general purpose power quality assessment, all the major disturbances associated with the power system are investigated in this research. The investigation emphasizes only on the existing power quality problems. The power quality evaluation procedure followed in this thesis work includes the following general steps.

2.1.1. Identified Power Quality Problems

The specific power quality problems that need to be evaluated will be different from customer to customer. A review of the types of equipment used by the customer, process requirements and economic impacts of problems will lead to a list of problems that need to be studied. They can include possible problems with both the utility distribution system and the customer facilities (H. Awad, M. H.J 2003, vol.2, pp. 1129-1136) .The power quality problems have been present since the inception of electric power. However, recently the awareness of the customers toward the power quality problems has increased tremendously because of the following reasons: The customer‘s equipment have become much more sensitive to power quality problems than these have been earlier due to the use of digital control and power electronic converters, which are highly sensitive to the supply and other disturbances. The increased use of solid-state controllers in a number of equipment with other benefits such as decreasing the losses, increasing overall efficiency, and reducing the cost of production has resulted in the increased harmonic levels, distortion, notches, and other power quality problems. It is achieved, of course, with much more sophisticated control and increased sensitivity of the equipment toward power quality problems.

The quality of power has often been characterized as clean or dirty. Clean power refers to power that has sinusoidal voltage and current without any distortion and operates at the designed magnitude and frequency. Dirty power describes power that has a distorted sinusoidal voltage and current or operates outside the design limits of voltage, current, and/or frequency. Categories of dirty power quality sources include power system events, nonlinear loads, and poor wiring and grounding. (H. Awad, M. H.J Bollen, 2003, vol.2, pp. 1129-1136).Examples of dirty power quality sources include lightning, adjustable speed drives, and loose connections. The source of a power quality problem often causes a disturbance or power quality variation. The disturbance can then affect the operation of end-user equipment. This may seem confusing. To make sense of the confusing causes and effects of power quality problems, the power quality engineer breaks down a power quality problem into three parts: sources (initiating events), causes, and effects of power quality. The ability to define and understand the various types of power quality problems provides the necessary background needed to prevent and solve those problems. The power quality signature, or characteristic, of the disturbance identifies the type of power quality problem. The nature of the variation in the basic components of the sine Wave, i.e., voltage, current, and frequency, identifies the type of power quality problem.

Voltage sags are the most common type of power quality problems. However the IEEE Standard 1159-1995, classifies the power quality problem into the following major categories described as follows:

Figure: 2.1: power quality disturbances (H. Akagi, Y. Kanazawa, A. Nabae , Tokyo,.pp.1375-1386)

- Voltage Transient
- Impulsive transient
- Oscillatory transient
- Short duration voltage variation
- Interruption
- Sag
- Swell
- Long duration voltage variation
- Under voltage
- Over voltage
- Sustained interruption
- Waveform distortions

- DC offset
- Harmonics
- Inter harmonics
- Notching
- Noise
- Voltage unbalance
- Voltage Fluctuation
- Frequency deviation

(a)Transients

Transients are undesirable momentary changes in voltage and/or current signals in the power system. There are many causes due to which transients are produced in the power system. Some of them are: Arcing between the contacts of the switches, sudden switching of loads, poor or loose connections, and lightning strokes. These transients are categorized into impulsive and oscillatory transients (H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May/June 1984).

- Impulsive Transient

An impulsive transient is –a sudden, non-power frequency change in the steady state condition of voltage, current, or both, that is unidirectional in polarity.

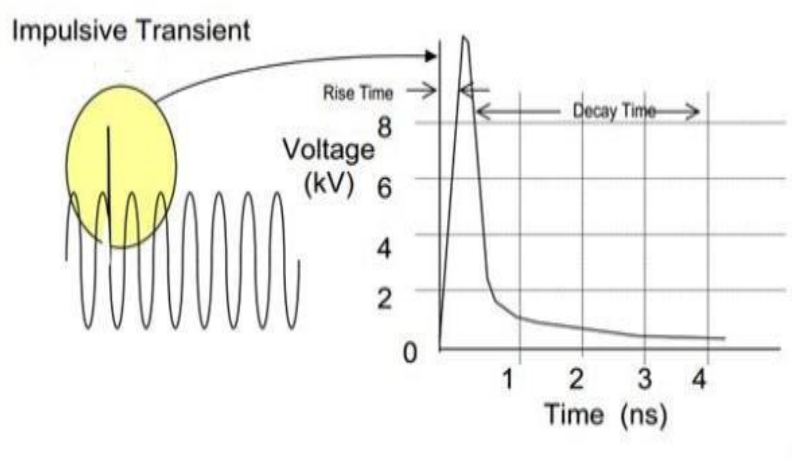


Figure 2.2. Impulsive Transient (H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May/June 1984).

Impulsive transients are normally characterized by their rise and decay times, which can also be revealed by their spectral content. Impulsive transients are generally caused by lightning strikes. An impulsive transient due to lightning strokes can occur because of a direct strike to a power line or from magnetic induction or capacitive coupling from strikes on adjacent lines.

- Oscillatory Transient

An oscillatory transient is a sudden, non-power frequency change in the steady state condition of voltage, current or both that includes both positive and negative polarity values. An oscillatory transient consists of a voltage or current whose instantaneous value changes polarity rapidly. It is described by its spectral content, duration, and magnitude. They are characterized by fluctuations in the measured quantity at very high frequencies. These can be further classified according to their frequency as high frequency transients (transients with a primary frequency component greater than 500 kHz and a typical duration measured in microseconds), medium frequency transients (transients with a primary frequency component between 5 and 500 kHz with duration measured in tens of microseconds.) or low frequency transients (transients with a primary frequency component less than 5 kHz and duration of from 0.3 to 50 ms), with the cause of the fault dependent upon the frequency. Due to the high frequency spectral contents of the oscillatory transients, they have Undesirable effects of electromagnetic interference and damage electrical and electronic equipment dueto the over voltage condition.

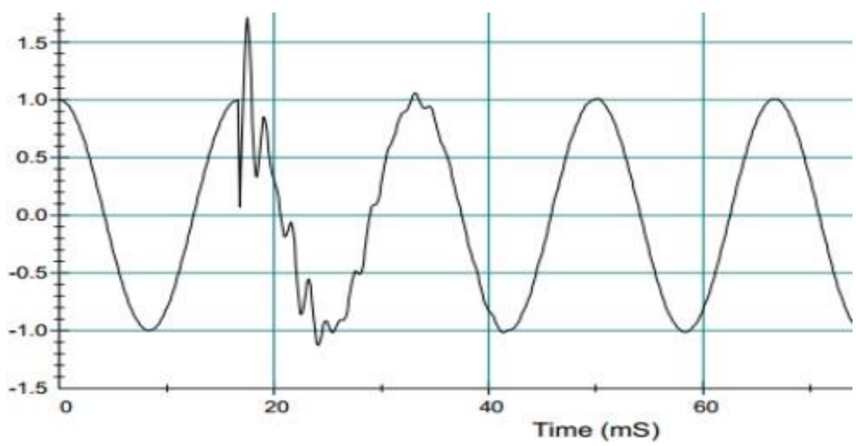


Figure 2.3.Oscillatory transient (H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May/June 1984).

(b) . Short-Duration Voltage Variation

These types of disturbance include root mean square (rms) voltage variations at power frequencies for a period of less than one minute. They are caused by faulty conditions, energizing of large loads which require high starting currents, or intermittent loose connectionsin the power wiring. Based on the type of fault, the short duration voltage variation may be classified into voltage sag (dip), voltage rise (swell), or interruption

Table: 2.1. The duration of voltage variation.

<table>
<tr><td></td><td colspan="2">Transient</td><td>Swell</td><td>High voltage</td></tr>
<tr><td>110 %</td><td colspan="3">Normal operating voltage</td><td></td></tr>
<tr><td>90%</td><td rowspan="4">Transient</td><td colspan="2">Voltage sag</td><td>Under voltage</td></tr>
<tr><td rowspan="3">10%</td><td colspan="2">Event duration</td><td>Sustained interruption</td></tr>
<tr><td>momentary</td><td>temporary</td><td></td></tr>
<tr><td>0.5cycle</td><td>0.3sec</td><td>1minute</td></tr>
</table>

- Voltage Sag

Voltage sags are referred to as voltage dips. IEEE defines voltage sags as a reductionin voltage for a short time. The duration of voltage sag is less than 1 minute but more than 8 milliseconds (0.5 cycles). The magnitude of the reduction is between 10 percent and 90 percent of the normal root mean square (rms) voltage at 50 Hz. The rms, or effective, value of a sine wave is the square root of the average of the squares of all the instantaneous values of a cycle and is equal to 0.707 ($1/\sqrt{2}$) times the peak value of the sine wave, as shown in Figure 2.4. A more detailed discussion of rms follows in the section on harmonics. Voltage sags differ from other voltage reduction, other voltage reduction disturbances often occur intermittently, like voltage flicker, while voltage sags occur once, for a short time. Figure 2.4 shows the voltage returning to normal after 0.12- second voltage sag. Utilities and end users can cause voltage sagson transmission and distribution systems. For example, a transformer failure can be the initiating event that causes a fault on the utility power system that result in voltage sag. These faults draw energy from the power system. Voltage sag occurs while the fault is on the utility's power system. As soon as a breaker or re-closer clears the fault, the voltage returns to normal. Transmission faults caused voltage sags that last about 6 cycles, or 0.10 second. Distribution faults last longer than transmission faults, while large motor loads can cause voltage sag on utility‘s and end user‘s power systems. Compared to other power quality problems affecting industrial and commercial end users, voltage sags occur most frequently. They reduce the energy being delivered to the end user and cause computers to fail, adjustable-speed drives to shut down, and motors to stall and overheat. Solutions to voltage sag problems include equipment that protects loads that are sensitive to voltage sags. Examples of these types of equipment include ferroresonnant, i.e., constant voltage transformers; dynamic voltage restorers (DVRs); superconducting energy storage devices; flywheels; written pole motor generator sets; and uninterruptible power supplies (UPS) (H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May/June 1984).

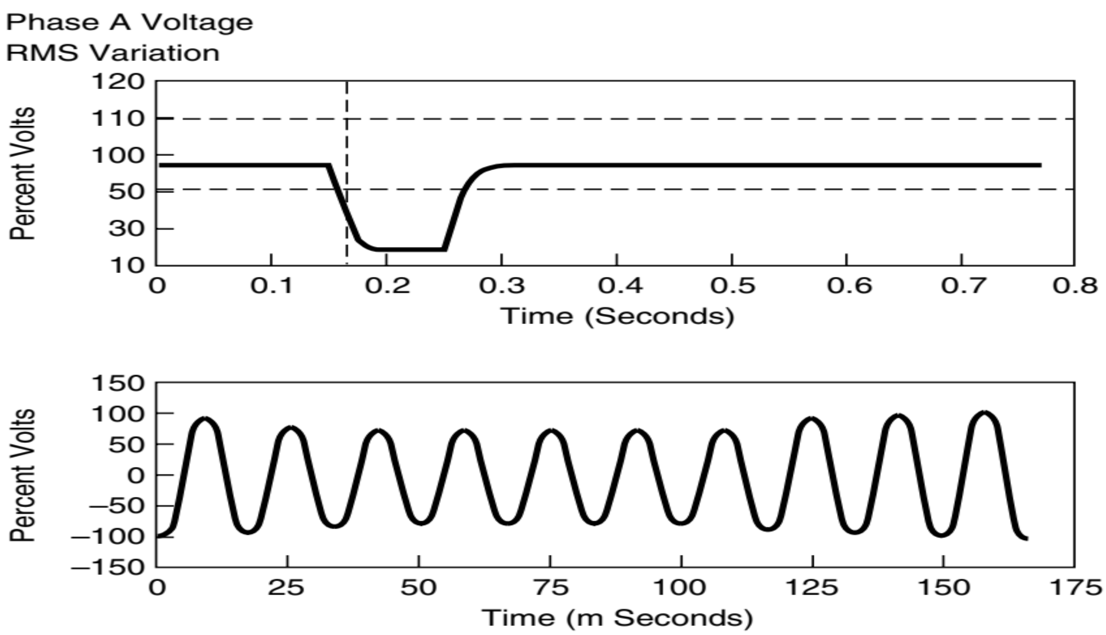


Figure.2.4. Voltage sag.(H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May 1984).

- Voltage Swell

Voltage swells, or momentary overvoltage‘s, are rms voltage variations that exceed 110 percent of the nominal voltage and last for less than 1 minute. Voltage swells occur less frequently than voltage sags. Single line to ground faults caused voltage swells. Examples of single-line to ground faults include lightning or a tree striking a live conductor. The increased energy from a voltage swell often overheats equipment and reduces its life. Figure 2.5 illustrates a typical voltage swell caused by a single-line to ground fault occurring in an adjacent phase .(H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May 1984).

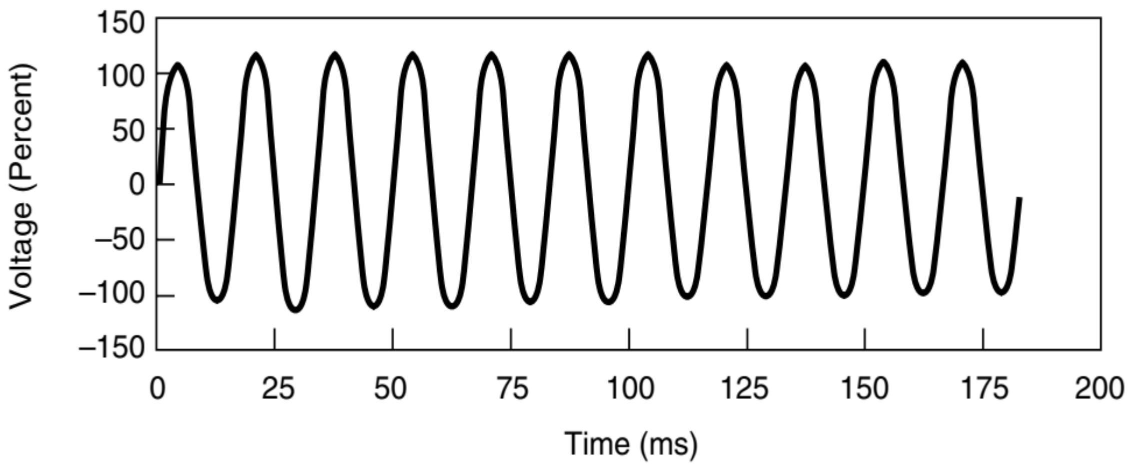


Figure 2.5. Voltage swells (H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May/June 1984).

- Interruption

Interruptions are a complete loss of voltage (a drop to less than 10 percent of nominal voltage) in one or more phases. IEEE Recommended Practice for Monitoring Electric Power Quality defines three types of interruptions. They are categorized by the time period that the interruptions occur: momentary, temporary, and long-duration interruptions. Momentary interruptions are the complete loss of voltage on one or more phase conductors for a time period between 0.5 cycles, or 8 milliseconds, and 3 seconds. A temporary, or short-duration, interruption is a drop of voltage below 10 percent of the nominal voltage for a time period between 3 seconds and 1 minute. Long-duration, or sustained, interruptions last longer than 1 minute. Figure 2.6 shows a momentary interruption. Loss of production in a business costs money. Any kind of interruption can result in loss of production in an office, retail market, or industrial factory. Not only does the loss of electrical service cause lost production, but the time required to restore electrical service also causes lost production. Some types of processes cannot –ride through‖ even short interruptions. –Ride through‖ is the capability of equipment to continue to operate during a power disturbance. For example, in a plastic injection molding plant, for a short interruption of

0.5 second it takes 6 hours to restore production. The common methods of reducing the impact of costly interruptions include on-site and off-site alternative sources of electrical supply. An end user may install on-site sources, such as battery-operated uninterruptible power supplies (UPS) or motor-generator sets, while a utility may provide an off-site source that includes two feeders with a high-speed switch that switches to the alternate feeder when one feeder fails.

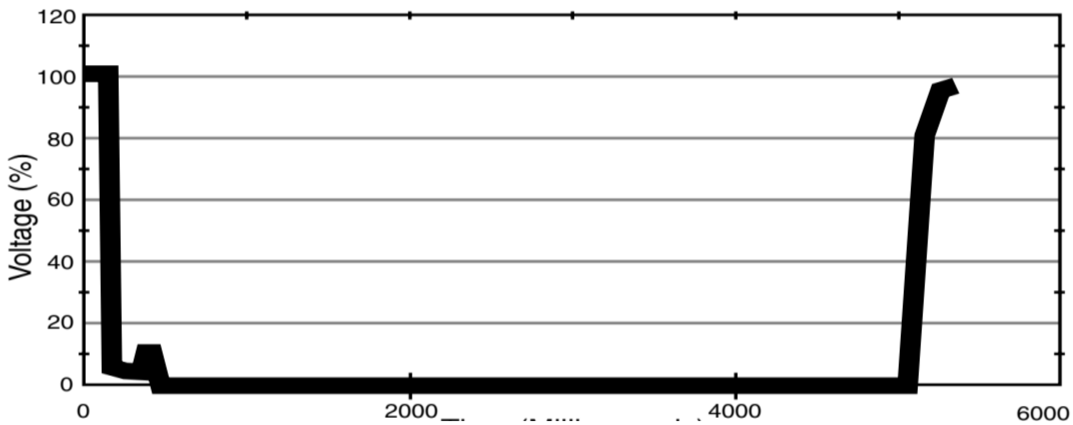


Figure 2.6. Momentary, temporary, and long-duration interruption plots.(H. Akagi, Y. Kanazawa, and A. Nabae, vol. IA-20, pp. 625-30, May/June 1984).

(c).Long Duration Voltage Variation

Long duration voltage variations encompass root-mean-square (rms) deviations at power frequencies for longer than 1 minute. They are usually not caused by system faults but system switching operations and load variations on the system. The long duration voltage variation may be either of an under voltage, over voltage or sustained interruption as discussed below.
(E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

- Overvoltage

Over voltages are close cousins to voltage swells, except they last longer. Like voltage swells, they are rms voltage variations that exceed 110 percent of the nominal voltage. Unlike swells, they last longer than a minute. Several types of initiating events cause overvoltage. The major cause of overvoltage is capacitor switching. This is because a capacitor is a charging device. When a capacitor is switched on, it adds voltage to the utility‘s system. Another cause of overvoltage is the dropping of load. Light load conditions in the evening also cause overvoltage on high voltage systems. Another common cause of overvoltage is the miss setting of voltage taps on transformers. Extended overvoltage shortens the life of lighting filaments and motors. Solutions to overvoltage include using inductors during light load conditions and correctly setting transformer taps.

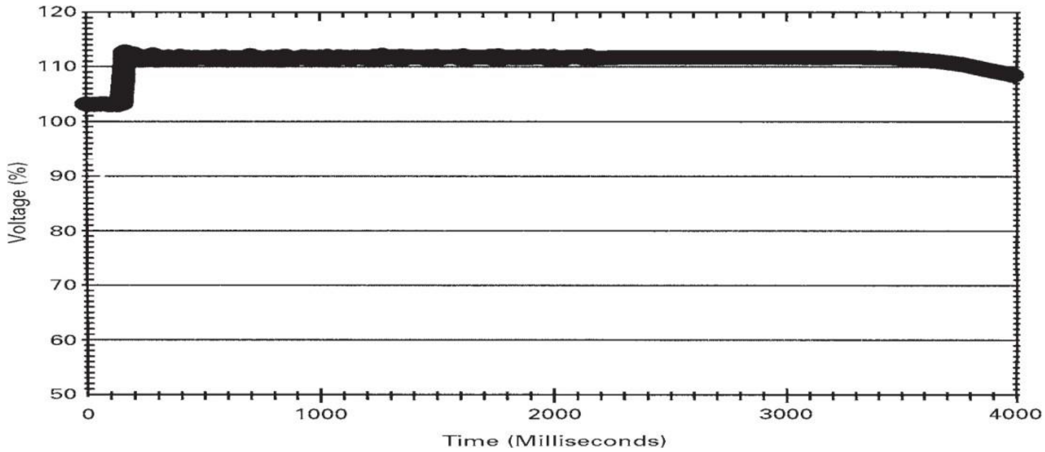


Figure 2.7. Shows a plot of overvoltage versus time (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

- Under voltage

Under voltage occurs when the voltage drops below 90 percent of the nominal voltage for more than 1 minute. They are sometimes referred to as brownouts, although this is an imprecise nontechnical term that should be avoided. They are recognized by end users when their lights dim and their motors slow down. Too much load on the utility‘s system, during very cold or hot weather, for example, or the loss of a major transmission line serving a region can cause under voltages. Overloading inside an end user‘s own distribution system can causes under voltages. Sometimes utilities deliberately cause under voltages to reduce the load during heavy load conditions. Reducing the voltage reduces the overall load, since load is voltage times current (kW = *V I*). Under voltages can cause sensitive computer equipment to read data incorrectly and motors to stall and operate inefficiently. Utilities can prevent under voltages by building more generation and transmission lines. Figure 2.8 shows a typical plot of under voltage versus time (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

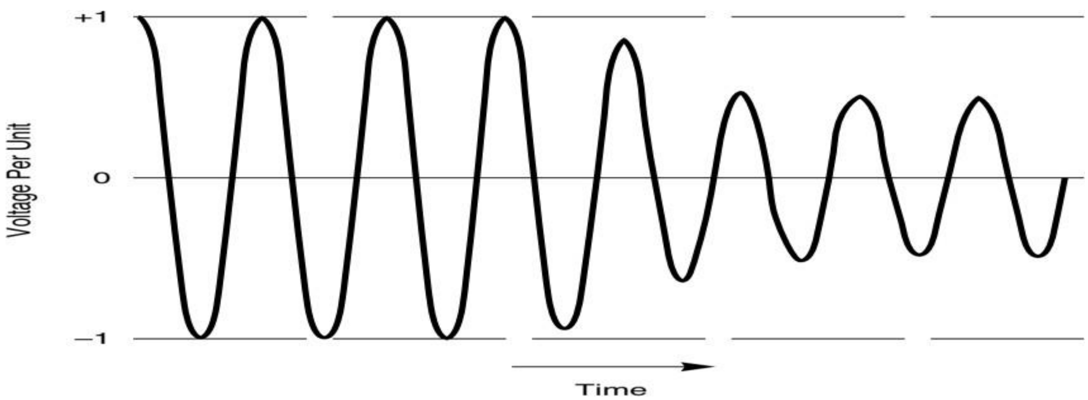


Figure 2.8. Under voltage plots (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, p p 697-703).

(d).Voltage Unbalance

Voltage unbalance or imbalance is the deviation of each phase from the average voltage of all three phases. Most equipment, especially motors, can tolerate a voltage unbalance of 2 percent. A voltage unbalance greater than 2 percent will cause motors and transformers to overheat. This is because a current unbalance in an induction device, like a motor or transformer, varies as the cube of the voltage unbalance applied to the terminals. Potential causes of voltage unbalance include capacitor banks not operating properly, single phasing of equipment, and connecting more single-phase loads on one phase than another. Installing monitors to measure the voltage unbalance provides the necessary data to analyze and eliminate the cause of the unbalance. Winding insulation life is reduced by one-half for each 10°C increase in operating temperature (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

(e).Voltage Fluctuation

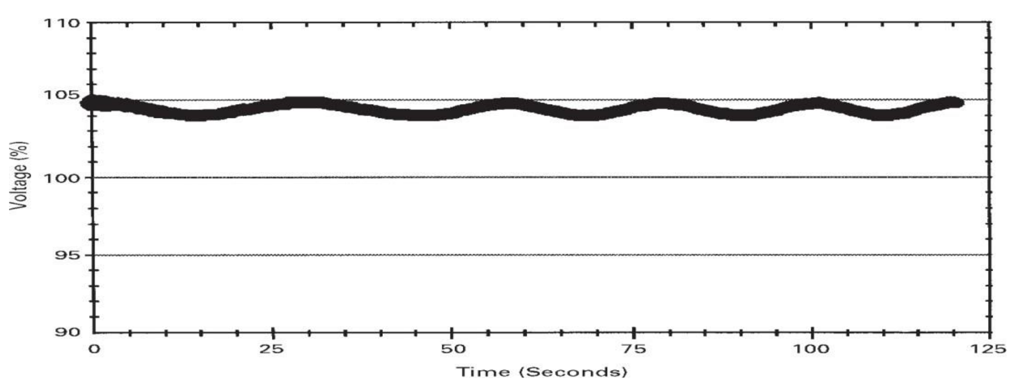


Figure.2.9.Voltage fluctuation (flicker) plots (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

Voltage fluctuations are rapid changes in voltage within the allowable limits of voltage magnitude of 0.95 to 1.05 of nominal voltage. Devices like electric arc furnaces and welders that have continuous, rapid changes in load current cause voltage fluctuations. Voltage fluctuations can cause incandescent and fluorescent lights to blink rapidly. This blinking of lights is often referred to as flicker. This change in light intensity occurs at frequencies of 6 to 8 Hz and is visible to the human eye. It can cause people to have headaches and become stressed and irritable. It can also cause sensitive equipment to malfunction. The solution to voltage fluctuations is a change in the frequency of the fluctuation. In the case of an arc furnace, this usually involves the use of costly but effective static VAR controllers (SVCs) that control the voltage fluctuation frequency by controlling the amount of reactive power being supplied to the arc furnace. Figure 2.9 shows voltage fluctuations that produce flicker

(f).Waveform Distortion

Waveform distortion is defined as any steady-state deviation of voltage or/and current waveform from an ideal sine wave of the power frequency. The waveform distortion is principally characterized by its spectral contents which are investigated using Fourier transform (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

The effect of the harmonic contents on the distortion of the sinusoidal waveform can be observed usually, the voltage waveform has negligible harmonics that it can be assumed to be pure sinusoidal at the fundamental frequency. In this case, if the current drawn by the load has harmonics, the active power of the load is consumed only at the fundamental component of the load current. The remaining harmonics generate a reactive power. There are five primary forms of waveform distortion of which one or more events occur in a distorted voltage or current waveform.

- DC-Offset

DC offset is the dc voltage or current component of the spectral contents in an AC voltage or current. This occurs mainly as the result of a geomagnetic disturbance or asymmetry of electronic power converters, such as half-wave rectification. Direct current in ac networks can have a detrimental effect by biasing transformer cores so they saturate in normal operation. This causes additional heating and loss of transformer life (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

- Harmonics

Harmonics is a growing problem for both electricity suppliers and users. A harmonics is defined as a sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency usually 50Hz or 60Hz. Distorted waveforms can be decomposed into a sum of the fundamental frequency and the harmonics. Harmonic distortion originates in the nonlinear characteristics of devices and loads on the power system [6].

Harmonics refers to both current and voltage harmonics. Harmonic voltages occur as a result of current harmonics, which are created by nonlinear electronic loads. These nonlinear loads will draw a distorted current waveform from the supply system. Loads like electric arc furnaces, discharge lighting (such as fluorescent lamps), magnetic cores, such as transformer and rotating machines that require third harmonic current to excite the iron, adjustable speed drives used in fans, blowers, pumps, and process drives can cause harmonic distortion. The effect of harmonics in the power system includes the corruption and loss of data, overheating or damage to sensitive equipment and overloading of capacitor banks.

High levels of harmonic distortion can cause such effects as increased transformer, capacitor, motor or generator heating, miss-operation of electronic equipment (which relies on voltage zero crossing detection or is sensitive to wave shape), incorrect readings on meters and miss-operation of protective relays. The likelihood of such ill effects occurring is greatly increased if a resonant condition occurs. Resonance occurs when a harmonic frequency produced by a non-linear load closely coincides with a power system natural frequency (E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

The high frequency harmonicsmay also cause interference to nearby telecommunication system.

Harmonics originate from the nonlinear characteristics of devices and loads that require currents other than a sinusoid on the power system. The most common of these loads are static power converters, although several other loads are also non-sinusoidal, such as the following.(E. H. Watanabe, R. M. Stephen, and M. Arcdes, vol.8, April 1993, pp 697-703).

Arc furnaces and other arc-discharge devices, such as fluorescent lamps

- Resistance welders (impedance of the joint between dissimilar metals is different for theflow of positive vs. negative current)

- Magnetic cores, such as transformer and rotating machines that require third harmoniccurrent to excite the iron
- Synchronous machines (winding pitch produces fifth and seventh harmonics)
- Adjustable speed drives used in fans, blowers, pumps, and process drives
- Solid-state switches that modulate the current-to-control heating, light intensity, etc.
- Switched-mode power supplies, used in instrumentation, PCs, televisions, etc.
- Static vary compensators
- Electronic phase controllers
- High-voltage DC transmission stations (rectifiers of AC to DC, and DC to AC invertors)
- Photovoltaic invertors converting DC to AC.

Using the Fourier series expansion, we can represent a distorted periodic wave shape by its fundamental and harmonics. It is also common to use a single quantity, the total harmonic distortion (THD), as a measure of the effective value of harmonic distortion. For characterizing harmonic currents in a consistent fashion, IEEE Standard 519-1992 defines another term, the total demand distortion (TDD). This term is the same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude at the instant of measurement (M.A.Chaudhari and Chandraprakash, Dec. 2012, pp 1-6).

The development of current distortion limits is to:

- ✓ Reduce the harmonic injection from each single consumer so that they will not cause unacceptable voltage distortion levels for normal system characteristics.
- ✓ Restrict the overall harmonic distortion of the system voltage supplied by the utility.
- Inter-harmonics

These are voltage and/or current components having frequency that are not integer multiples of the fundamental frequency. They can appear as discrete frequencies or as a wideband spectrum. Inter harmonics are generally the result of frequency conversion activities. The main sources of inter harmonics are static frequency converters, cyclic- converters, induction furnaces, and arcing devices. Power line carrier signals can also be considered as inter harmonics. Inter harmonic currents can excite resonances on the power system as the varying inter harmonic frequency becomes coincident with natural frequencies of the system. The higher frequency inters harmonic signals affect the power-line-carrier signaling. They can also induce visual flicker in fluorescent lamps and other arc lighting as well as in computer display devices.

- Notching

Notching is a periodic transient occurring within each cycle as a result of the phase-to-phase short circuit caused by the commutation process in AC–DC converters (Figure 2.10). Being periodic, this disturbance is characterized by the presence of the harmonic spectrum of the voltage waveform; in particular, notching mainly results in high-order harmonics. Most problems caused by notches are confined to a customer‘s own installation. In fact, the high frequency content of notches not under a utility‘s control is filtered ‘by the power transformer at the service entrance. Voltage notches are characterized by their depth and duration in combination with the point on the sine wave at which the notching starts. (M.A.Chaudhari and Chandraprakash, Dec. 2012, pp 1-6).

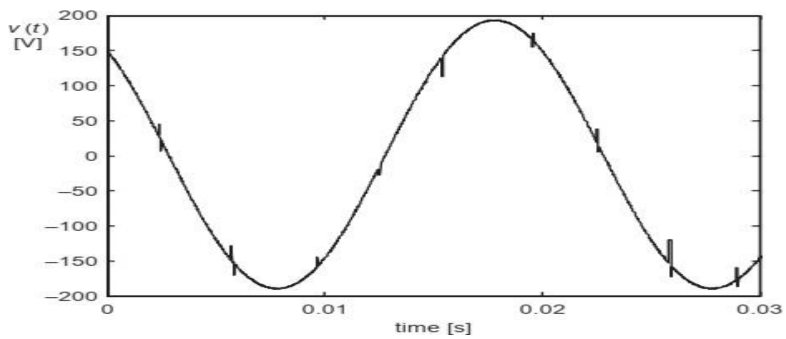


Figure 2.10.Notching (M.A.Chaudhari and Chandraprakash, Dec. 2012, pp 1-6).

- Noise

When you think of electrical noise, you may think of the audible crackling noise that emanates from high-voltage power lines, or you may imagine the low throbbing hum of an energized transformer. This type of noise can affect your life quality as much as your power quality. In fact, one man complained that the corona noise from a nearby 500-kV power line drowned out the babbling of a brook in his backyard. When power quality experts talk about electrical noise, they do not mean these audible noises. They mean the electrical noise that is caused by a low voltage, high-frequency (but lower than 200-Hz) signal superimposed on the 60-Hz fundamental waveform. This type of electrical noise may be transmitted through the air or wires. High-voltage lines, arcing from operating disconnect switches, startup of large motors, radio and TV stations, switched mode power supplies; loads with solid-state rectifiers, fluorescent lights, and power electronic devices can all cause this type of noise. Electrical noise adds hash on to the fundamental sine wave, as shown in Figure 2.11. Electrical noise can degrade telecommunication equipment, radio, and TV reception, and damage electronic equipment as well. There are two ways of solving the electrical noise problem. One solution is to eliminate the source of the electrical noise. Another way is to either stop or reduce the electrical noise from being transmitted. For example, the use of multiple conductors or installation of corona rings can reduce electrical noise from high-voltage lines. Grounding equipment and the service panel to a common point can eliminate electrical noise from ground loops. This prevents the ground wires from acting as a loop antenna and transmitting a humming type noise that interferes with communication signals. The electromagnetic interference (EMI) type of noise is reduced by shielding the sensitive equipment from the source of the electrical noise. Another way of protecting sensitive equipment from EMI is to simply move the source of the EMI far enough away so that the EMI becomes too weak to affect the sensitive equipment. (M. A. Chaudhari and Chandraprakash, Dec. 2012, pp 1-6).

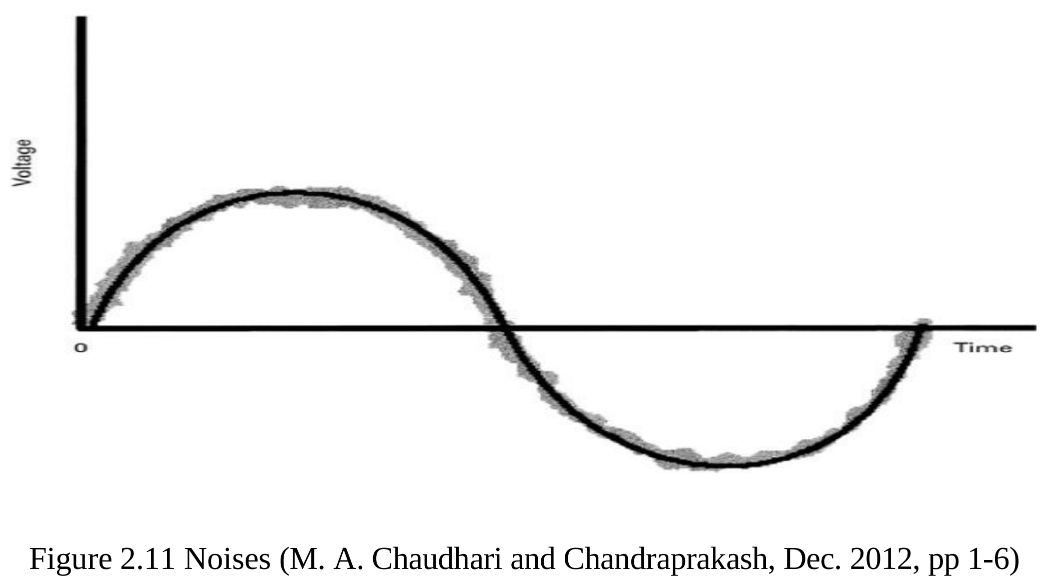


Figure 2.11 Noises (M. A. Chaudhari and Chandraprakash, Dec. 2012, pp 1-6)

(g).Voltage Fluctuation

A series of voltage changes or a continuous variation in the RMS voltage are denoted voltage fluctuations (Figure). If fluctuations occur within proper frequency ranges, they cause changes in the luminance of lamps, which can create the visual phenomenon called _flicker.' Above a certain threshold, the flicker becomes annoying, and annoyance grows very rapidly with the amplitude of the fluctuation. At certain repetition rates, even very small amplitudes can be annoying. The main sources of severe voltage fluctuations are industrial loads, which are particularly troublesome in the steelmaking industry, where there is significant use of arc furnaces, rolling mills and multiple-welder loads. In some cases, large fluctuating motor loads, such as mine winders, can also cause voltage fluctuation problems. Domestic loads with repeated switching, such as cooker hobs, electric showers, heat pumps and air conditioning, have the potential to cause local flicker, but the problem is contained by imposing statutory product design constraints in terms of the size and frequency of load switching. It should be noted that voltage fluctuations and inter-harmonics have an inherent relationship. In fact, the magnitude of a voltage waveform can fluctuate if it contains inter-harmonics, and conversely, the voltage fluctuation can cause the presence of inter-harmonics. Experience has shown that even a small amount of inter-harmonics can result in perceptible light flicker in incandescent and fluorescent lamps. In addition to flicker, an effect produced by voltage fluctuations is the braking or acceleration of motors connected directly to the system (M. A. Chaudhari and Chandraprakash, Dec. 2012, pp 1-6).

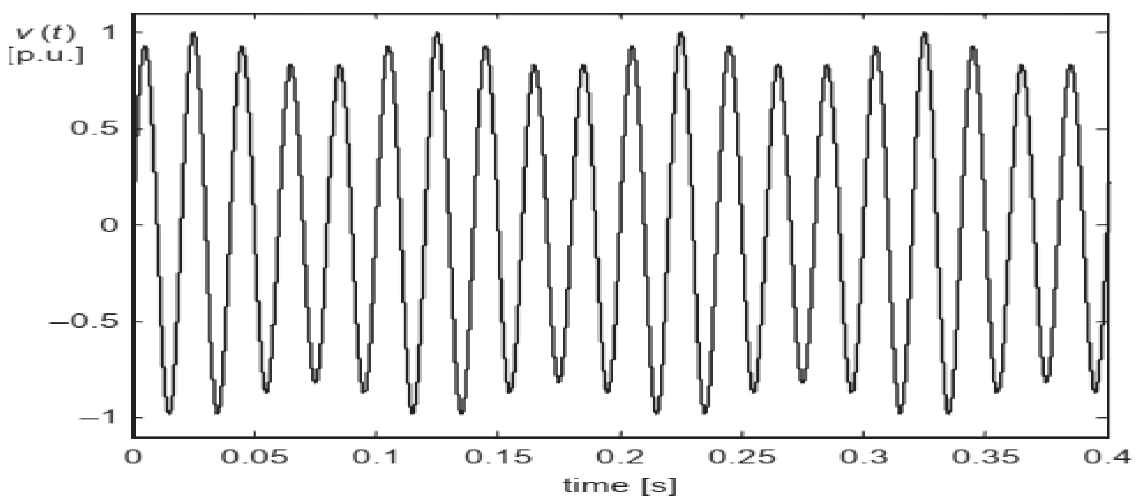


Figure 2.12. Voltage fluctuations (M. A. Chaudhari and Chandraprakash, Dec. 2012, pp 1-6.)

- Power Frequency Variations

A power frequency variation is a deviation of the frequency from the nominal value (equal to 50 or 60 Hz and denoted the power supply frequency, power system frequency or power frequency). A power frequency variation is linked directly to the variation in rotation speed of the generators supplying the electrical power system. There are slight variations in frequency due to imbalances between load and generation. Slight deviations in frequency can cause severe damage to generators and turbine shafts due to the large torque developed. In addition, cascading system separations can result with even slight deviations in frequency, since electric systems are closely connected and depend on synchronous operation. Actually, significant frequency variations are rare in modern interconnected power systems. (M. A. Chaudhari and Chandraprakash, Dec. 2012, pp 1-6).

2.1.2 Causes of Power Quality Problems.

There are a number of power quality problems in the present-day due to fast-changing electrical systems. The main causes of these power quality problems can be classified into natural and man-made in terms of current, voltage, frequency, and so on. The natural causes of poor power quality are mainly faults, lightning, weather conditions such as storms, equipment failure, and so on. However, the man-made causes are mainly related to loads or system operations. The causes related to the loads are nonlinear loads such as saturating transformers and other electrical machines, or loads with solid-state controllers such as vapor lamp-based lighting systems, ASDs, UPSs, arc furnaces, computer power supplies, and TVs. The causes of power quality problems related to system operations are switching of transformers, capacitors, feeders, and heavy loads. The natural causes result in power quality problems that are generally transient in nature, such as voltage sag (dip), voltage distortion, swell, and impulsive and oscillatory transients. However, the manmade causes result in both transient and steady-state types of power quality problems. Table 2.1 lists some of the power quality problems and their causes. However, one of the important power quality problems is the presence of harmonics, which may be because of several loads that behave in a nonlinear manner, ranging from classical ones such as transformers, electrical machines, and furnaces to new ones such as power converters in vapor lamps, switched-mode power supplies (SMPS), ASDs using AC–DC converters, cycle-converters, AC voltage controllers, HVDC transmission, static VAR compensators, and so on (Mehmet Ucar and Engin Ozdemir, Electric Power Systems Research 78 (2008) 58–73)

Table.2.2 .lists of the power quality problems and their causes(Chellali Benachaiba, Brahim Ferdi , Journal Vol. XIV, No. 1, 2008.F. A).

Problems	Category	Categorization	Causes	Effects
Transients	Impulsive	Peak rise time and duration	Lightning strikes, transformer energization, capacitor Switching	Power system resonance
	Oscillatory	Peak magnitude and frequency components	Line, capacitor, or load switching	System resonance
Short-duration voltage Variation	Sag	Magnitude, duration	Motor starting, single line to Ground faults.	Protection malfunction, loss of production
	Swell	Magnitude, duration	Capacitor switching, large load switching, faults	Protection malfunction stress on computers and home appliances
	Interruption	Duration	Temporary faults	Loss of production, malfunction of fire alarms
Long-duration voltage variation	Sustained Interruption	Duration	Faults	Loss of Production
	Under voltage	Magnitude, duration	Switching on loads, capacitor de-energization	Increments losses, heating
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energization	Damage to house hold appliances
Voltage Imbalance		Symmetrical Components	Single-phase load, single-phase	Heating of Motors
Waveform distortion	DC offset	Volts, amperes	Geomagnetic disturbance Rectification	Saturation in transformer
	Harmonics	THD, harmonics Spectrum	ASDs, nonlinear Loads	Increased losses, poor power factor
	Interharmonics	THD, harmonics Spectrum	ASDs, nonlinear Loads	Acoustic noise in power equipment

	Notching	THD,harmonics spectrum	Power electronic converters	Damage to capacitive Components
	Noise	THD, harmonics spectrum	Arc furnace , arc lamps, power converters	Capacitor overloading, disturbance to

		Appliance	
Voltage flicker	Frequency of occurrence, modulatingfrequency.	Arc furnace , arclamps	Human health, irritation, headache, migraine
Voltage fluctuations	Intermittent	Load change	Protection malfunction, light intensity changes
Power frequency Variation		Faults, disturbance in isolated customer-owned system and islanding	Damage to generator andturbine shafts

2.1.3 Loads That Cause Power Quality Problems

Most of the electrical loads have nonlinear behavior at the AC mains. As they draw harmonic currents of various types such as characteristic harmonics, non-characteristic harmonics, inter harmonics, sub harmonics, reactive power component of current, fluctuating current, unbalanced currents from the AC mains, these loads are known as nonlinear loads. Majority of rotating electric machines and magnetic devices such as transformers, reactors, chokes, magnetic ballasts, and so on behave as nonlinear loads due to saturation in their magnetic circuits, geometry such as presence of teeth and slots, winding distribution, air gap asymmetry, and so on. Many fluctuating loads such as furnaces, electric hammers, and frequently switching devices exhibit highly nonlinear behavior as electrical loads. Even non saturating electrical loads such as power capacitors behave as nonlinear loads at the AC mains and they create a number of power quality problems due to switching and resonance with magnetic components in the system and are overloaded due to harmonic currents caused by the presence of harmonic voltages in the supply system. Moreover, the solid-state control of AC power using diodes, thyristor, and other semiconductor switches is widely used to feed controlled power to electrical loads such as lighting devices with electronic ballasts, controlled heating elements, magnet power supplies, battery chargers, fans, computers, copiers, TVs, switched mode power supplies (SMPS) in computers and other equipment, furnaces electroplating, electrochemical processes, adjustable speed drives (ASDs) in electric traction, air-conditioning systems, pumps, wastewater treatment plants, elevators, conveyers, cranes, and so on. These AC loads consisting of solid-state converters draw non-sinusoidal currents from the AC mains and behave in a nonlinear manner and therefore they are also known as nonlinear loads. These nonlinear loads consisting of solid state converters draw harmonic currents and reactive power component of current from the AC mains. In three-phase systems, they could also cause unbalance and sometimes draw excessive neutral current, especially the distributed single- phase nonlinear loads on three-phase four-wire supply system. These solid-state converters may be AC–DC converters, AC voltage controllers, cyclo-converters, and so on. The injected harmonic currents, reactive power burden, unbalanced currents, and excessive neutral current caused by these nonlinear loads result in low system efficiency, poor power factor (PF), mal- operation of protection systems, AC capacitors overloading and nuisance tripping, noise and vibration in electrical machines, heating of the rotor bars due to negative sequence currents, de- rating of components of distribution system, user equipment, and so on. They also cause distortion in the supply voltage, disturbance to protective devices and other consumers, and interference in nearby communication networks and digital and analog control systems. (Mehmet Ucar and Engin Ozdemir, Electric Power Systems Research 78 (2008) 58–73). These nonlinear loads exhibit different behavior thereby causing different power quality problems, and they are therefore often classified according to their performance. Accordingly, the power quality improvement techniques for mitigating the power quality problems caused by nonlinear loads are also different to reduce the rating and cost of devices use for these purposes. One of the major and broad classifications of these nonlinear loads is based on their behavior either as current fed type or as voltage fed type or a combination of both. The current fed type of nonlinear loads with AC–DC converters having constant DC current used for field winding excitation, magnet power supplies, thyristor converter feeding DC motor drives, converter feeding current source inverter-fed AC motor drives, magnetic devices with saturation, and so ondraw the pre-specified kind of current pattern. Normally devices used for power quality improvements of such

current fed type nonlinear loads are connected in shunt with the loads to supply locally all their current components other than the fundamental active power component of load current. On the contrary, the voltage fed type of nonlinear loads having AC–DC converters feeding almost constant DC voltage loads such as battery chargers, AC–DC converters with large DC filter capacitor as front-end converters in SMPS, AC–DC converters in voltage source inverter feeding AC motor drives, and so on draw highly nonlinear and unpredictable current waveform rich in harmonics with high crest factor (CF)
However, even with sinusoidal applied voltage, they draw non-sinusoidal and increased current from the AC mains in addition to the fundamental active power component of current.

Some of these nonlinear loads are as follows: (Mehmet Ucar and Engin Ozdemir, Electric Power Systems Research 78 (2008) 58–73

- Fluorescent lighting and other vapor lamps with electronic ballasts
- Switched mode power supplies
- Computers, Xerox machines, medical equipment and television sets
- Printer, scanners, and fax machines
- High-frequency welding machines
- Fans with electronic regulators
- Microwave ovens and induction heating devices
- Variable frequency-based HVAC (heating ventilation and air-conditioning) systems
- Battery chargers and fuel cells
- Electric traction
- Arc furnaces
- Cyclone-converters
- Adjustable speed drives
- Static slip energy recovery schemes of wound rotor induction motors Wind and solar power generation
- Static VAR compensators (SVCs)
- HVDC transmission systems
- Magnet power supplies
- Plasma power supplies
- Static field excitation systems

These types of nonlinear loads draw harmonic currents and reactive power component of the current from the single-phase AC mains. Some of them have harmonic currents, reactive power component of the current, and unbalanced currents in the three-phase three-wire supply system. The single-phase distributed nonlinear loads also consist of harmonic currents, reactive power component of the current, and unbalanced currents and excessive neutral current in three-phase four-wire system. These increased currents in addition to the fundamental active power component of current cause increased losses, poor power factor, disturbances to other consumers, communication systems, protection systems, and many other electronics appliances, voltage distortion, voltage spikes, voltage notches, surges, dip, sag, swell in voltages, and so on. Owing to the ever-increasing use of such nonlinear loads in present-day distribution system for obvious reasons, the exhaustive study of these nonlinear loads becomes very relevant to find the proper remedy for mitigation of power quality problems caused by them in the supply system

Classification of Nonlinear Loads

The nonlinear loads can be classified based on the use of non-solid-state or solid-state devices, for example, the presence or absenceof power electronics converter in the circuits of nonlinear loads

(i) The use of converter types such as AC–DC converter type, AC voltage controllertype, and cyclo-converter type

(ii) Their nature as stiff current fed type or stiff voltage fed type or a combination of both

(iii) The number of phases such as two-wire single-phase, three-phase three-wire, andfour-wire three-phase systems.

(a).Non-Solid-State Device and Solid-State Device Type Nonlinear Loads.

The nonlinear loads may be classified based on whether they consist of solid-state devices or any other power converters or not. There are a number of electrical loads that are nonlinear in nature, but they do not involve any power converters. Similarly, there are only some nonlinear loads that consist of solid-state converters. (Mehmet Ucar and Engin Ozdemir, 78 (2008) 58–73). These nonlinear loads are further explained with examples.

- Non-Solid-State Device Type Nonlinear Loads.

As already mentioned, there are many electrical loads in nature that do not consist of any solid-state device or power electronics converter. However, they behave as nonlinear loads when they are connected to AC mains. Most of the electrical machines fall in this category of nonlinear loads. A number of physical phenomena in these electrical machines cause their behavior as nonlinear loads. Typically, the saturation in magnetic material of these machines and electromagnetic devices, skin and proximity effects in conductors, non-uniform air gap in rotating machines, effect of teeth and slotting, and so on result in harmonic currents under steady-state and transient conditions in the AC mains when they are connected to the AC supply system. Some practical examples of these types of nonlinear loads are various types of transformers operating at no load or light load conditions, magnetic ballasts of fluorescent lamps, and single-phase induction motors as they are usually designed with high level of no load current (due to high level of saturation) to reduce the cost and size of these motors. They draw harmonic currents and reactive power component of the current, and also cause excessive neutral current in the three-phase four-wire supply system due to such distributed single-phase nonlinear loads. (Mehmet Ucar and Engin Ozdemir,78 (2008) 58–73).

- Solid-State Device Type Nonlinear Loads

Many types of electrical equipment consist of different circuits of solid-state devices to process the AC power to suit specific application. They draw non-sinusoidal current from the AC mains and they behave as nonlinear loads. This non-sinusoidal current consists of harmonic currents and the reactive power component of the current along with the fundamental active power component of current. They use various AC–DC converters, AC voltage controllers, cyclo-converters, or a combination of all in their front-end converter. In the single-phase configuration, they draw harmonic currents and reactive power from the AC mains. Examples of single-phase nonlinear loads include both domestic and commercial equipment—among the home appliances are microwave oven, induction heaters, television sets, electronic ballasts-based lighting systems, domestic inverter, adjustable speed drive-based air conditioners, and AC voltage regulator-based fans, whereas the commercial and industrial equipment are computers, copiers, fax machines, Xerox machines, scanner, printers, small welding sets, and so on. In the three-phase, three-wire supply system, they may also draw unbalanced three-phase currents in addition to harmonic currents and reactive power. Some practical loads are three-phase adjustable speed drives, consisting of converter-fed DC motor drives, synchronous motor drives, induction motor drives, and other electric motors used in HVAC systems, wastewater treatment plants, large industrial fans, pumps, compressors, cranes, elevators, electrochemical process such as electroplating and electro-mining, and so on. In the three-phase four-wire supply system, there are many single-phase nonlinear loads connected to AC mains causing excessive neutral current. Distributed single-phase loads on all three phases such as electronic ballasts-based lighting systems, computer loads in high storied buildings, and all other single-phase loads cause burden on the AC mains of harmonic currents, reactive power component of currents, unbalanced currents, and excessive neutral current. .(Mehmet Ucar and Engin Ozdemir,78 (2008) 58–73)

(b).Converter-Based Nonlinear Loads

There are various types of converters used in electrical equipment's that behave as nonlinear loads. These nonlinear loads mainly consist of AC–DC converters, AC voltage controllers, cyclo-converters, or a combination of all. These are classified on the basis of these converters, but are not confined to them.

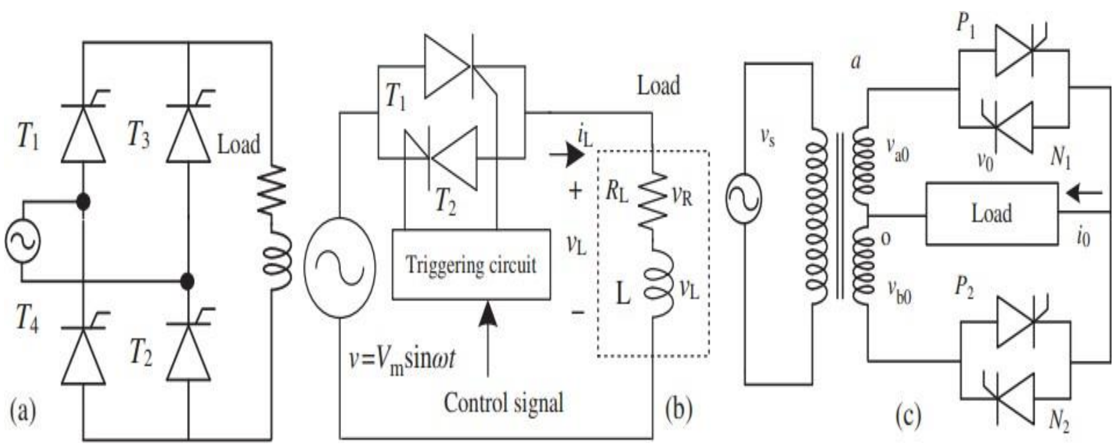


Figure 2.13. Various types of current fed nonlinear loads. (Mehmet Ucar and Engin Ozdemir, 78 (2008) 58–73)

- AC–DC converter-Based Type Nonlinear Loads

A large number of loads use AC–DC converters as front-end converters ranging from few watts to megawatt rating. These converters are developed in many circuit configurations such as single-phase and three-phase, uncontrolled, semi-controlled, and fully controlled, and half-wave, full-wave, and bridge converter circuits to suit the requirements of specific application.

Depending upon the types of filters used for filtering the rectified DC, their behavior varies in a number of ways at the AC mains. Some of the examples of such nonlinear loads include microwave ovens, SMPS, computers, fax machines, battery chargers, HVDC transmission systems, electric traction, adjustable speed drives, and so on. In some cases they draw current with excessive harmonic contents with high crest factor. However, in many cases they draw current with moderate harmonic contents and reactive power with low crest factor, even less than the sine wave. They exhibit poor power factor at the AC mains generally due to harmonics only, but with reactive power as well. (Mehmet Ucar and Engin Ozdemir, 78 (2008) 58–73).

- AC Controllers-Based Nonlinear Loads

Some nonlinear loads use AC voltage controllers for the control of AC RMS voltage across the electrical loads to control the physical process. They draw the harmonic currents along with the reactive power and cause poor power factor. In single-phase distributed loads on three-phase supply systems, they also cause excessive harmonic currents. Some of the examples of such nonlinear loads include AC voltage regulator in fans, lighting controllers, heating controllers, soft starters, speed controllers, and energy saving controllers of three-phase induction motors operating under light load conditions in a number of applications such as hack saw, electric hammers, wood-cutting machines, and so on. They are also used in static VAR compensators (SVCs) in TCRs (thyristor controlled reactors) and so on.(Mehmet Ucar and Engin Ozdemir, 78 (2008) 58–73).

- Cyclo-converter-Based Nonlinear Load

In many applications, cyclo-converters are used to convert AC voltage of a fixed frequency to variable voltage at a variable frequency or vice versa. These cyclo-converters-based nonlinear loads draw harmonic currents not only at higher order harmonics but also at sub harmonics and reactive power and exhibit a very poor power factor at the AC mains. Some of the examples of such nonlinear loads include cyclo-converter fed large-rating synchronous motor drives in cement mills, ore crushing plants, large-rating squirrel cage induction motors, slip energy recovery scheme of wound rotor induction motor drives, VSCF (variable speed constant frequency) generating systems, and so on.

(c).Nature-Based Classification

Most of the nonlinear loads behave as either stiff current fed type or as stiff voltage fed type, or a combination of both. The stiff current fed loads normally consist of AC–DC converters with constant DC current load and a predetermined harmonic pattern in the AC mains with reactive power burden. The voltage stiff loads consist of generally AC–DC converters with a large DC capacitor at the DC bus to provide ideal DC voltage source for the remaining process of solid-state conversion and draw peaky current from the AC mains with high crest factor. Since the analysis of the behavior and remedy for mitigation of power quality problems of these types of loads depend reasonably on this classification, it becomes relevant and important to select a proper compensator.(Mehmet Ucar and Engin Ozdemir, 78 (2008) 58–73)Current Fed Type of Nonlinear Loads.The stiff current fed types of nonlinear loads generally have predetermined pattern of harmonics and sometimes they have reactive power burden on the AC mains. They have flat current waveform drawn from the AC mains with a low value of crest factor. They typically consist of AC–DC converters feeding DC motor drives, magnet power supplies, field excitation system of the alternators, controlled AC–DC converters used to derive DC current source for feeding current source inverter supplying large-rating AC motor drives, HVDC transmission systems,and so on.

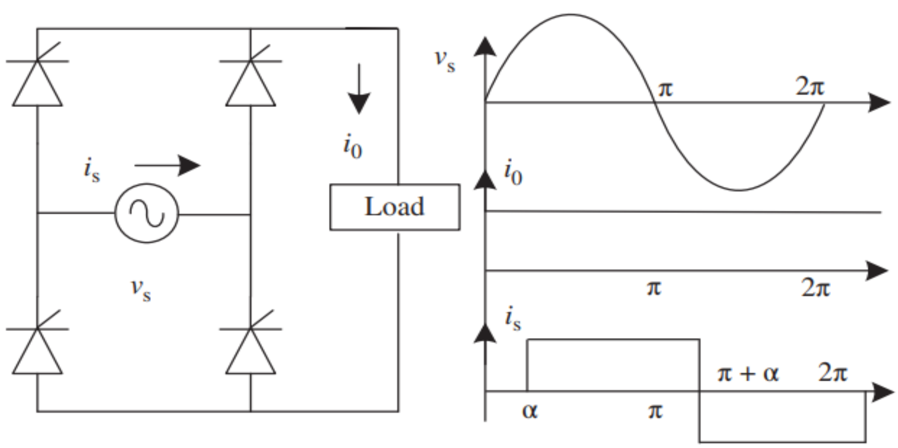
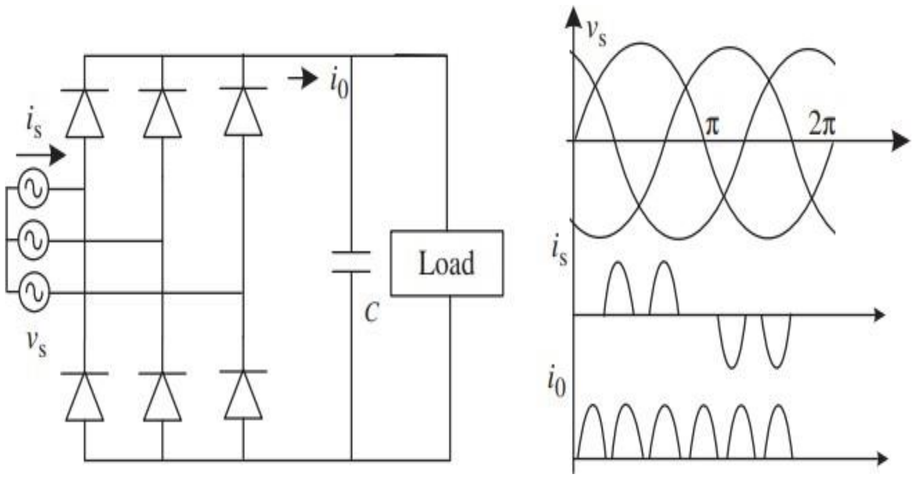


Figure 2.14. Shows such current fed type of nonlinear load. (Mehmet Ucar and Engin Ozdemir, 78 (2008) 58–73)

- Voltage Fed Type of Nonlinear Loads

The stiff voltage types of nonlinear loads behave as sink of harmonic currents. Typical example of such load is an AC–DC converter with a large DC capacitor at its DC bus to provide an ideal DC voltage source for the remaining process of solid-state conversion and it draws peaky current from the AC mains with high crest factor (as shown in Figure 2.15). They generally do not have reactive power requirement, but they have much greater number of harmonic currents drawn from the AC mains. Examples of such loads include SMPS, battery chargers, front-end converters of voltage source inverter fed AC motor drives, electronic ballasts, and most of the electronic appliances.(Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).



(

Figure 2.15. Voltage Fed Type of Nonlinear Loads. Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

Mix of Current Fed and Voltage Fed Types of Nonlinear Loads

The mixed nonlinear loads are combination of current fed and voltage fed types of loads. A group of nonlinear loads and a combination of linear and nonlinear loads fall under this category. Most of the electrical loads consisting of solid-state converters behave as these types of nonlinear loads.

(d) Supply System-Based Classification

This classification of nonlinear loads is based on the supply system having single-phase (two-wire) and three-phase (three-wire or four-wire) systems. There are many nonlinear loads such as domestic appliances that are fed from single-phase supply systems. Some three-phase nonlinear loads are without neutral conductor, such as ASDs (Adjustable Speed Drives), fed from a three-wire supply system. There are many nonlinear single-phase loads distributed on a four-wire, three-phase supply system, such as computers, commercial lighting, and so on.

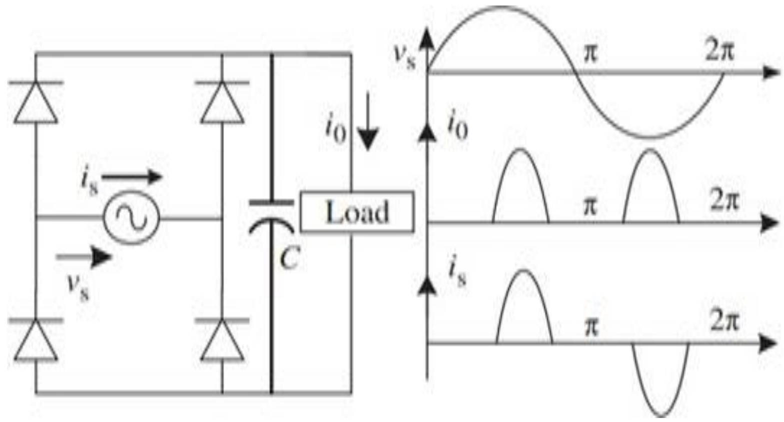


Figure 2.16. Shows such voltage fed type nonlinear load. .(Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

- Two-Wire Nonlinear Loads

There are a very large number of single-phase nonlinear loads supplied by the two-wire single-phase AC mains. All these loads consisting of single-phase diode rectifiers, semi-converters, and thyristor converters behave as nonlinear loads. They draw harmonic currents and sometimes also the reactive power from the AC mains. Typical examples of such loads are power supplies, electronic fan regulators, electronic ballasts, computers, television sets, and traction. Figure 2.16 shows such voltage fed type nonlinear load.

- Three-Wire Nonlinear Loads

Three-phase, three-wire nonlinear loads inject harmonic currents, and sometimes they draw reactive power from the AC mains and sometimes they also have unbalanced currents. These nonlinear loads are in large numbers and consume major amount of electric power. Typical examples are ASDs using DC and AC motors, HVDC transmission systems, and wind power conversion. .(Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

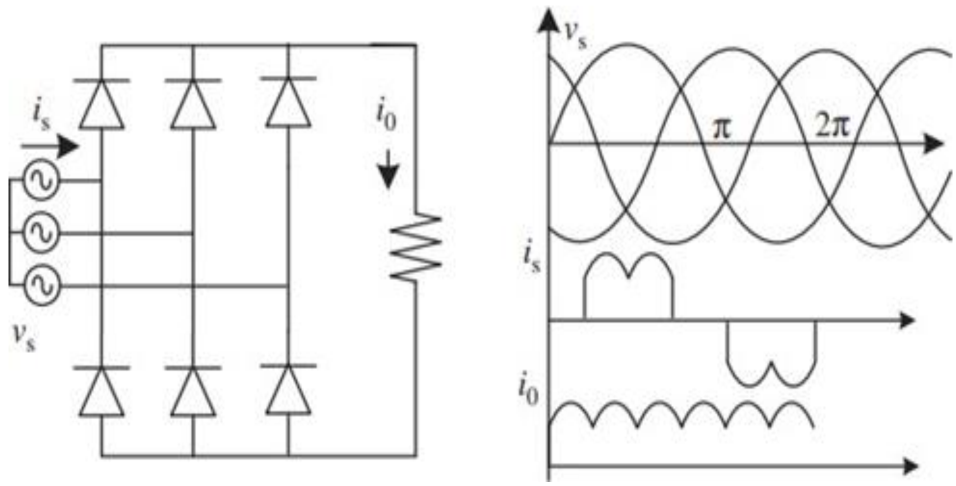


Figure 2.17. Shows such current fed type nonlinear load. .(Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

Four-Wire Nonlinear Loads

A large number of single-phase nonlinear loads may be supplied from the three-phase AC mains with the neutral conductor. Apart from harmonic currents, reactive power, and unbalanced currents, they also cause excessive neutral current due to harmonic currents and unbalancing of these loads on three phases. Typical examples are computer loads and electronic ballasts-based vapor lighting systems. Besides, they cause voltage distortion and voltage imbalance at the PCC and some potential at the neutral terminal. Figure 2.18 shows such current fed type nonlinear load.

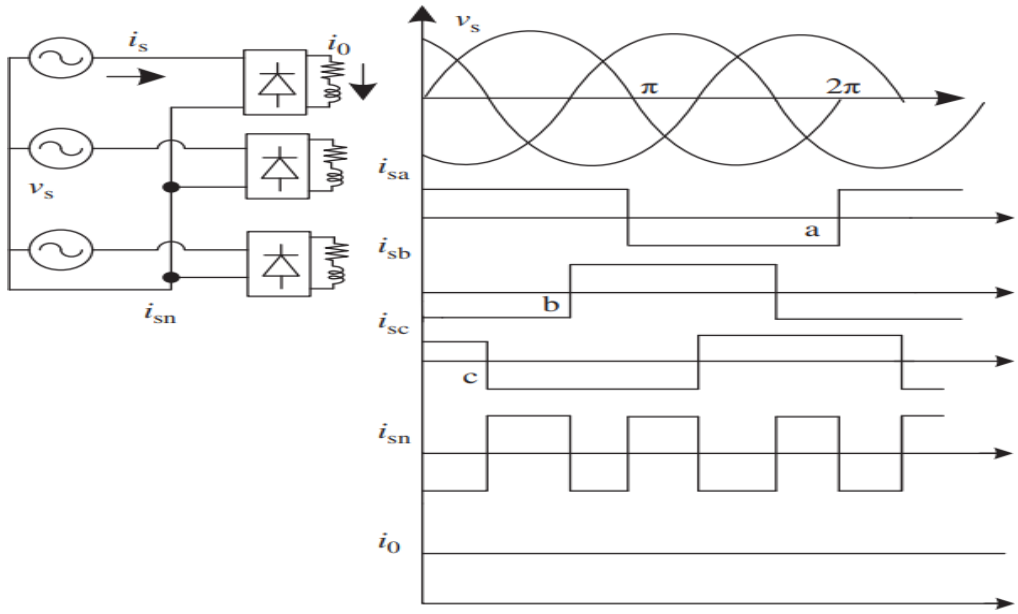


Figure 2.18. Shows such current fed type nonlinear load. (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

2.1.4 Power Quality Problems Caused by Nonlinear Loads

The nonlinear loads cause a number of power quality problems in the distribution system. They inject harmonic currents into the AC mains. These harmonic currents increase the rms value of supply current, increase losses, cause poor utilization and heating of components of the distribution system, and also cause distortion and notching in voltage waveforms at the point of common coupling due to voltage drop in the source impedance. Some of the effects are as follows (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

- Increased rms value of the supply current
- Increased losses
- Poor power factor
- Poor utilization of distribution system
- Heating of components of distribution system
- De-rating of the distribution system
- Distortion in voltage waveform at the point of common coupling, which indirectly affectsmany types of equipment
- Disturbance to the nearby consumers

- Interference in communication system
- Mal-operation of protection systems such as relays
- Interference in controllers of many other types of equipment
- Capacitor bank failure due to overload, resonance, harmonic amplification, and nuisancefuse operation.

2.1.5. Effects of PQ Problems on Sugar industries.

- **Effects of PQ on rotary machineries.**

Sugar industries cover a very wide range of products. Today‘s sugar industries machines are high technology machines. They include tens of sensors, driver controlled ac and dc electrical machines, communications cards, CPU units, touchscreens, Ethernet cards and encoders. This equipment’s operate at different voltage values. If any interruption, at the machines occurs for any reason, it can take up to 4 h for the machinery park to return to the acceptable performance values. Thus, any short-term or long- term interruption means a direct manufacturing loss. These machines which are sensitive to sinusoidal form of electrical power can shut down if a voltage drop, voltage sag and voltage fluctuations occur. These machines include special encoders used for position determination and interruptions without any reason can lead to the breakdown of this device (values approximately $500) and its replacement means at least 2hr of interruption. Voltage sags can result in excess current drawings, which cause the engines operating at approximately 6kW to draw higher currents, leading to the break-down of electronic cards driving such engines. Such cards cost approximately $2500 and their replacement may take minimum 2hr. High current and voltage harmonics and the other distortions can cause such machines to stop. Harmonics shorten the life of all electrical and electronic equipment’s in the machines. They cause break-downs, resulting in repair costs and manufacturing losses. They also shorten the depreciation periods of the machines, leading to increasing costs and thus losses.
(Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).Modern industrial processes are based on a large number of electronic devices such as programmable logic controllers and adjustable speed drives. The electronic devices are very sensitive to disturbances. Thus, industrial loads become less tolerant to power quality problems such as voltage sags, voltage swells, voltage flicker/imbalance, negative sequence current, reactive power, transients, frequency variation and harmonics

(a).Effect on Variable Speed Drives

Variable speed drives (VSD) use an electronic converter to produce a variable frequency motor drive voltage from the fixed supply frequency. They are used extensively in industrial processing, materials handling and building management. During sag, the amount of energy supplied by the electrical system is reduced and may be below that required by the process, resulting in loss of control. Since motor-controlled processes rarely operate in isolation, this can result in loss of synchronization with other parts of the process and uncoordinated shut down.

The problems of voltage sags applied to variable speed drives are:

- It is not possible to supply sufficient voltage to the motor (loss of torque, slowdown);
- The control circuits supplied directly by the network cannot function;
- There is overcurrent when voltage recovers (the drive filter capacitor is recharged);
- There is overcurrent and unbalanced current in the event of voltage sags on a single phase;
- There is loss of control of DC drives functioning as inverters (regenerative braking).

B. Effects on AC Contactors, Relays and Circuit Breakers

Contactors, relays and circuit breakers are made for all operation in a different range of coil voltage and contact ratings. Nowadays, most of the places, the contactor function has been replaced by power-electronics devices such as GTOs and IGBTs. Control relay functions have been replaced by PLCs using digital logic. Whether electromagnetic or solid state, the devices are impacted by line-voltage sags and Interruptions.

C. Effect on Personal Computers

The malfunction of Personal Computers (PCs) incorporated in a real-time system because of voltage disturbances effect more badly than the malfunction of the PC used offline. The modes of personal computer malfunction under line voltage sag occur as in DC filter capacitor voltage of the power supply doesn’t go with time. The software problems create the problems that include; Lockup, interruption, (blue screen), No response to any command from the keyboard and Blocking of the operating system. Automatic restarting of the system, or a permanent black screen, making a manual restart necessary, can identify hardware mis operation(Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

D. Product Damage

Sometimes PQ problems in manufacturing processes can result in product damage. Occasionally, the damage can be directly observed and the damaged product discarded or recycled. Product damage can be costly if the damage is delicate and the effects take some time to surface. Service or product losses due to a power disturbance need to be known in quantifying PQ costs. The number of units of service or product losses and the cost per unit of service or product loss/repair are key elements in determining the total cost of a power disturbance (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

E. Decreased Equipment Life

Many systems that experience disturbances, both detected and undetected, have resulted in decreased equipment life. High-energy, fast-rise-time transients can cause outright circuit board failure, even for systems protected by transient suppressors, or can cause degradation over time such that burnout is only delayed. Harmonic distortion and phase unbalance can combine to overstress motors and transformers, shortening their useful lifetimes, and consequently increasing production costs. Hence, equipment lifetime affected by PQ disturbances can show up as direct and hidden costs. (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

2.1.6. Solutions to Power Quality Problems

The mitigation of power quality problems can be achieved in two ways. It can be done from either customer side or utility side. First approach used is load conditioning and the other is line conditioning. Load conditioning ensures that the equipment is less sensitive to power disturbances. They are based on PWM converters and connected in shunt or in series to low and medium voltage distribution system. Series active power filters operate in conjunction with shunt passive filters in order to compensate load current harmonics. Series active power filters operates as a controllable voltage source whereas shunt active power filters operate as a controllable current source. Both of these schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. However, with the restructuring of power sector, the line conditioning systems or utility side solutions will play a vital role in improving the inherent supply quality. Some of the effective and economic measures can be identified as following: (Srinivas Bhaskar Karanki, Mahesh K. Mishra,B. Kalyan Kumar,, no. 4, October 2010).

- **Lightening and Surge Arresters**

Arresters are designed for lightening protection of transformers, but are not sufficient for limiting voltage fluctuations to protect sensitive electronic control circuits.

- **Thyristor Based Static Switches**

The static switch is a device for switching a new element into the circuit when the voltage support is needed. It has a dynamic response time of about one cycle. It can be used in the alternate power line applications. To correct quickly for voltage spikes, sags or interruptions, the static switch can be used to switch one or more of devices such as filter, capacitor, alternate power line, energy storage systems etc.

- **Energy Storage Systems**

Storage systems can be used to protect sensitive equipment from shutdowns caused by voltage sags or momentary interruptions. Energy is fed to the system to compensate for the energy that would be lost by the voltage sag or interruption. The systems used are usually DC storage systems such as batteries, UPS, super conducting magnet energy storage (SMES), storage capacitors or even fly wheels driving DC generators. The output of these devices can be supplied to the system through an inverter on a momentary basis.

- **Electronic Tap Changing Transformer**

A voltage-regulating transformer with an electronic load tap changer can be used with a single line from the utility. It can regulate the voltage drops up to 50% and requires a stiff system (short circuit power to load ratio of 10:1 or better).

- **Harmonic Filters**

Filters are used where effective reduction or elimination of certain harmonics is required. If possible, it is always preferable to use a 12-pulse or higher transformer connection, rather than a filter. Usually, multiple filters are needed, each tuned to a separate harmonic. Each filter causes a parallel resonance as well as a series resonance, and each filter slightly changes the resonances of other filters.

2.1.7 Custom Power Devices

For improving the system performance for distribution system and with the growing development of the power semiconductor technology, the concepts of custom power were introduced to distribution systems. The concept describes the value-added power that electric utilities will offer their customers in the future, focusing on the quality of power flow and reliability. Due to this increasing demand and the rapid development of the high-power semiconductor technology, the custom power solutions are taking place rapidly. In a custom power system customer receives specified power quality from a utility or a service provider or at-the-fence equipment installed by the customer in coordination with the utility, which includes an acceptable combination of the following features.(Srinivas Bhaskar Karanki, Mahesh K. Mishra,B. Kalyan Kumar,, no. 4, October 2010).

• No (or rare) power interruptions

• Magnitude and duration of voltage reductions within specified limits.

• Low harmonic voltage. • Low phase unbalance.

This can be done on the basis of an individual, large customer, industry or a supply for a high-tech community on a wide area basis.

❖ **Need of Custom Power**

The increased use of automated equipment, like adjustable speed drives, programmable logic controllers, switching power supplies, arc furnaces, electronic fluorescent lamp ballasts, automated production lines are far more vulnerable to disturbances than were the previous generation equipment and less automated production and information systems.

Even though the power generation in most advanced country is fairly reliable, the distribution is not always so. It is however not only reliability that the consumers want these days, quality too is very important for them. With the deregulation of the electric power energy market, the awareness regarding the quality of power is increasing day by day among customers. Power quality is an issue that is becoming increasingly important to electricity consumers at all levels of usage. (Srinivas Bhaskar Karanki, Mahesh K. Mishra,B. Kalyan Kumar,, no. 4, October 2010).

In the several processes such as semiconductor manufacturing or food processing plants, a batch of product can be ruined by a voltage dip of very short duration. Even short dips are sufficient to cause contactors on motor drives to drop out. There are other loads which are very sensitive such as hospitals, processing plants, air traffic control and numerous other data processing and service providers that require clean and uninterrupted power. Thus, in this scenario in which customers increasingly demand power quality, the term power quality attains increased significance. The factors mentioned point out the problems faced by the industry and awareness of consumers about quality of power due to which it has increasingly become important to provide the consumers with the reliable as well as superior power quality. Thus, the development of custom power has gained so much of widespread attention nowadays.

❖ Types of Custom Power Devices

There are many types of Custom Power devices. Some of these devices include Active Power Filters (APF), Surge Arresters (SA). Battery Energy Storage Systems (BESS), Super conducting Magnetic Energy Systems (SMES), Static Electronic Tap Changers (SETC), Solid State Fault Current Limiter (SSFCL), Solid-State Transfer Switches (SSTS), Static VAR Compensator (SVC), Distribution Series Capacitors (DSC), Dynamic Voltage Restorer (DVR), Distribution Static synchronous Compensators (DSTATCOM) and Uninterruptible Power Supplies (UPS) , Unified power quality conditioner(UPQC).

The classification of custom power devices can be done into two major categories, one is network configuring type and the other is compensating type. The network configuring type devices changes the configuration of the power system network for power quality enhancement. SSCL (Solid State Current Limiter), SSCB (Solid State Circuit Breaker) and SSTS (Solid State Transfer Switch) are the most representative in this category.

The compensating type devices are used for active filtering; load balancing, power factor correction and voltage regulation. The family of compensating devices includes DSTATCOM (Distribution Static compensator), DVR (Dynamic voltage restorer) and Unified power quality conditioner (UPQC). DSTATCOM is connected in shunt with the power system while DVR is a series connected device that injects a rapid series voltage to compensate the supply voltage. UPQC is the combination of DSTATCOM and DVR. It injects series voltage and shunt currents to the system.

Though there are many different methods to mitigate voltage sags and swells, but the use of a custom power device is considered to be the most efficient method to serve for different purposes. The term Custom Power pertains to the use of power electronic controllers in a distribution system to deal with various power quality problems. It makes sure that customers get pre-specified quality and reliability of power supply that may include a single or the combination of the specifications like no power interruptions, low phase unbalance, low harmonic distortion in load voltage, low flicker at the load voltage, acceptance of fluctuations, magnitude and duration of overvoltage and under voltages within specified limits and poor factor loads without significant effect on the terminal voltage.(Srinivas Bhaskar Karanki, Mahesh K. Mishra,B. Kalyan Kumar,, no. 4, October 2010).

- **Solid State Current Limiter**

The most widely used solution for limitation of the fault currents is to use a transformer with a split secondary winding (or a three windings transformer) and current limiting reactors. The basic configuration of Solid-State Current Limiter is shown in Figure 2.1. However, the usage of fault current limiting reactors with powerful motor loads has a negative impact on the stability of motors, for example when short-term voltage sags occur. It would be worthwhile to directly control transients, resulting from faults, at primary circuits, thus alleviating effects of the faults.

Series fault current limiters used to limit the fault current by disconnecting solid-state switch and increasing the impedance. However, such scheme has a disadvantage: the system should be operating in continuous mode, and malfunction of the static switch could lead to interruption of power supply for the customer. Parallel fault current limiters are activated only at the moment of fault and have the following functions:

- ✓ limit the peak fault current
- ✓ decrease the motors feeding into the fault
- ✓ Shunt the consumer switches while disconnecting

- **Solid State Transfer Switch**

The SSTS can be used very effectively to protect sensitive loads against voltage sags, swells and other electrical disturbances. The SSTS provides continuous high-quality power supply to sensitive loads by transferring, within a time scale of milliseconds, the load from a faulted bus to a healthy one. The basic configuration of this device consists of two three-phase solid-state switches, one for the main feeder another for the backup feeder. These switches have an arrangement of back-to-back connected thyristors, Each time a fault condition is detected in the main feeder, the control system swaps the firing signals to the thyristors in both switches, i.e., Switch 1 in the main feeder is deactivated and Switch 2 in the backup feeder is activated. The control system measures the peak value of the voltage waveform at every half cycle and checks whether or not it is within a pre specified range. If it is outside limits, an abnormal condition is detected and the firing signals to the thyristors are changed to transfer the load to the healthy feeder. (Srinivas Bhaskar Karanki, Mahesh K. Mishra,B. Kalyan Kumar,, no. 4, October 2010).

The success of the SSTS is mainly due to its rather low cost compared with other solutions. A requirement is that a secondary in-feed, independent from the main source (e.g. a feeder to another substation), must be available. Therefore, this solution is particularly attractive for installations that already have mechanical transfer systems, where upgrading to a static system does not require major changes in the layout of the distribution system. Formerly available only for low voltages, SSTS systems are now advertised for higher voltages and load ratings, which make them suitable for high-power industrial applications. Transfer-time estimation of a SSTS is not a straightforward process due to its dependence on commutation between the thyristor switches in each phase. The commutation is determined by the system parameters and the component characteristics. To offer ride-through capability, the load must be transferred within the shortest possible time.(Srinivas Bhaskar Karanki, Mahesh K. Mishra,B. Kalyan Kumar,, no. 4, October 2010).

- **Active Power Filters**

The increasing use of power electronics-based loads (adjustable speed drives, switch mode power supplies, etc.) to improve system efficiency and controllability is increasing the concern for harmonic distortion levels in end use facilities and on the overall power system. The application of passive tuned filters creates new system resonances which are dependent on specific system conditions. Passive filters often need to be significantly overrated to account for possible harmonic absorption from the power system. Passive filter ratings must coordinate with reactive power requirements of the loads and it is often difficult to design the filters to avoid leading power factor operation for some load conditions.

Active filters have the advantage of being able to compensate for harmonics without fundamental frequency reactive power concerns. Currently they are based on PWM converters and connect to low and medium voltage distribution system in shunt or in series. Series active power filters must operate in conjunction with shunt passive filters in order to compensate load current harmonics. Shunt active power filters operate as a controllable current source and series active power filters operates as a controllable voltage source. Both schemes are implemented preferable with voltage source PWM inverters, with a dc bus having a reactive element such as a capacitor. Active power filters can perform one or more of the functions required to compensate power systems and improving power quality. The rating of the active power can be less than a conquerable passive filter for the same nonlinear load and the active filter will not introduce system resonances that can move a harmonic problem from one frequency to another. (Srinivas Bhaskar Karanki, Mahesh K. Mishra,B. Kalyan Kumar,, no. 4, October 2010).

- **Distribution Static Compensator (DSTATCOM)**

The purpose of the DSTATCOM is to cancel load harmonics fed to the supply. The coupling of DSTATCOM is three phases, in parallel to network and load. It works as current sources, connected in parallel with the nonlinear load, generating the harmonic currents the load requires also balance them in addition to providing reactive power. In order to compensate undesirable components of the load current the DSTATCOM injects currents into the point of common coupling. With an appropriated control strategy, it is also possible to correct power factor and unbalanced loads. This principle is applicable to any type of load considered a harmonic source.

Its advantage is that it of carries only the compensation current plus a small amount of active fundamental current supplied to compensate for system losses. Shunt Active Power Filter in current control mode is also called as (DSTATCOM. A. Banerji, S. K. Biswas, B. Singh, Vol.2, No.3, September 2012, pp 285-296).

- **Dynamic Voltage Restorer (DVR):**

DVR injects a voltage component in series with the supply voltage, thus compensating voltage sags and swells on the load side. Control response is on the order of 3msec, ensuring a secure voltage supply under transient network conditions. Voltage injection of arbitrary phase with respect to the load current implies active power transfer capability. This active power is transferred via the dc link, and is supplied either by a diode bridge connected to the ac network, a shunt connected PWM converter or by an energy storage device. It works as a harmonic isolator to prevent the harmonics in the source voltage reaching the load in addition to balancing the voltages and providing voltage regulation. (Rosli Omar, Nasrudin Abd Rahim, Marizan sulaiman " IEEE journal on Power Electronics Drives and Energy System).

- **Unified Power Quality Conditioner (UPQC)**

The best protection for sensitive loads from sources with inadequate quality, is shunt series connection i.e. unified power quality conditioner (UPQC) .Recent research efforts have been made towards utilizing unified power quality conditioner (UPQC) to solve almost all power quality problems for example voltage sag, voltage swell, voltage outage and over correction of power factor and unacceptable levels of harmonics in the current and voltage

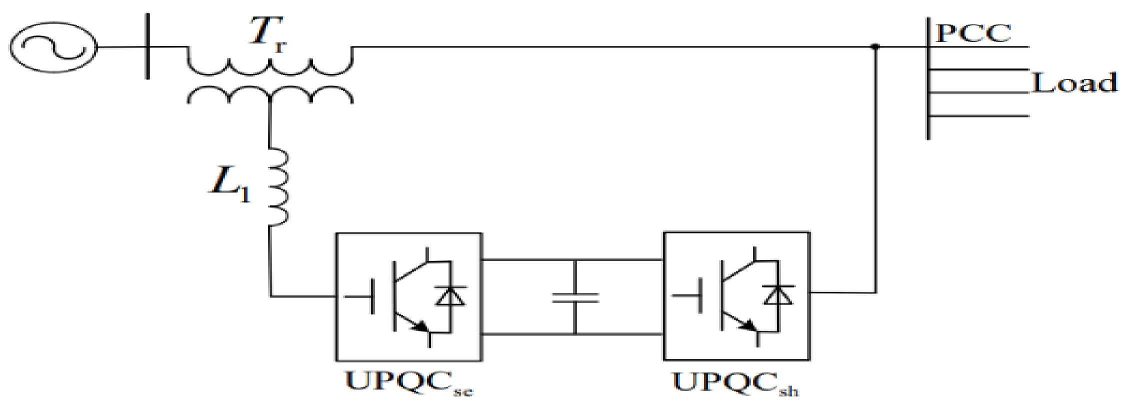


Figure.2.19. The basic configuration of UPQC . (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011)

The main purpose of a UPQC is to compensate for supply voltage flicker/imbalance, reactive power, negative-sequence current, and harmonics. In other words, the UPQC has the capability of improving power quality at the point of installation on power distribution systems or industrial power systems. The UPQC, therefore, is expected as one of the most powerful solutions to large capacity sensitive loads to voltage flicker/imbalance.

Unified Power Quality Conditioner (UPQC) for non-linear and a voltage sensitive load has following facilities:

- It eliminates the harmonics in the supply current, thus improves utility current quality for nonlinear loads.
- UPQC provides the VAR requirement of the load, so that the supply voltage and current are always in phase, therefore, no additional power factor correction equipment is necessary.
- UPQC maintains load end voltage at the rated value even in the presence of supply voltage sag.
- The voltage injected by UPQC to maintain the load end voltage at the desired value is taken from the same dc link, thus no additional dc link voltage support is required for the series compensator.

The UPQC consists of two three phase inverters connected in cascade in such a manner that Inverter I is connected in series with the supply voltage through a transformer inverter II is connected in parallel with the load. The main purpose of the shunt compensator is to compensate for the reactive power demanded by the load, to eliminate the harmonics and to regulate the common dc link voltage. The series compensator is operated in PWM voltage-controlled mode. It injects voltage in quadrature advance to the supply voltage (current) such that the load end voltage is always maintained at the desired value. The two inverters operate in a coordinated manner.

There are three principle elements to the custom power concept; these are:

- The Dynamic Voltage Restorer (DVR), it provides series compensation by voltage injection for power system sag and swell.
- The Distribution Static Compensator (D-STATCOM), it provides continuously variable shunt compensation by current injection for eliminating voltage fluctuations and obtaining correct power factor in three-phase systems. An ideal application of it is to prevent disturbing loads from polluting the rest of the distribution system.
- Unified Power Quality Conditioner (UPQC), it provides series and shunt compensation i.e. inject voltage in sag and swell condition and inject current for elimination of voltage fluctuations, correct power factor, avoid pollution to rest of the distribution system.

The proper selection of necessary custom power strategies in addition to accurate system modeling and appropriate protection devices will increase the power quality.(Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

2.1.8. Superiority of UPQC over Other Devices

Each of Custom Power devices has its own benefits and limitations. The UPQC is expected to be one of the most powerful solutions to large capacity loads sensitive to supply voltage and load current disturbances /imbalance. The most effective type of these devices is considered to be the Unified Power Quality Conditioner (UPQC). There are numerous reasons why the UPQC is preferred over the others. UPQC is much flexible than any single inverter-based device. It can simultaneously correct for the unbalance and distortion in the source voltage and load current whereas all other devices either correct current or voltage distortion. Therefore, the purpose of two devices is served by UPQC only. (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011)

Basically UPQC (Unified Power Quality conditioner) is a equipment which is used for compensate for voltage distortion and voltage unbalance in a power system so that the voltage at load side is completely balance and sinusoidal & perfectly regulated and also it is used to compensate for load current harmonics so that the current at the source side is perfectly sinusoidal and free from distortions and harmonics. UPQC is a combination of a Shunt Active power filter and Series Active power filter. Here Shunt Active power filter (APF) is used to compensate for load current harmonics and make the source current completely sinusoidal and free from harmonics and distortions. Shunt APF is connected parallel to transmission line. Here Series APF is used to mitigate for voltage distortions and unbalance which is present in supply side and make the voltage at load side perfectly balanced, regulated and sinusoidal. Series APF is connected in series with transmission line. UPQC consists of two voltage source inverters connected back to back through a DC link capacitor in a single phase, three phase-three wire, three phase-four wire configuration. The inverter in shunt APF is controlled as a variable current source inverter and in series APF is controlled as a variable voltage source inverter. Earlier passive filters where also used for compensation of harmonics and voltage distortion but due to their many disadvantages they are not used nowadays. (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011)

2.1.9. Basic Configuration of UPQC

UPQC mainly consists of:-

Table: 2.3. Active Filter Solutions to Power Quality Problems

Active filter connection	Load on AC Supply	AC Supply on load
Series	• Current harmonic Filtering. • Reactive current Compensation. • Current unbalance. • Voltage flicker. • Voltage unbalance.	• Voltages sag / swell. • Voltage unbalance. • Voltage distortion. • Voltage interruption. • Voltage notching. • Voltage flicker
Shunt	• Current harmonic Filtering. • Reactive current Compensation. • Current unbalance. • Voltage flicker	

Series APF: - In a transmission line series APF is generally connected in series. It is connected to the transmission line with the transformer. Series APF is a voltage source inverter connected in series with transmission line. It is used to compensate or mitigate the problems which come due to voltage distortions and voltage unbalances. The series APF injects a compensating voltage so that load voltage will be perfectly balanced and regulated. Controlling of series inverter is done by PWM (pulse width modulation) techniques. Here we used Hysteresis band PWM techniques as it implementation is easy. Also its response is fast. Its details are explained in subsequent sections.

Shunt APF: - In a transmission line shunt APF is generally connected in parallel. Shunt APF is used to compensate for distortions & harmonics which are produced due to current. Due to non-linear load there is harmonics in load current, so to keep source current completely sinusoidal and distortion free we uses Shunt APF. Shunt APF injects compensating current so that the source current is completely sinusoidal and free from distortions. Controlling of Shunt APF is done by hysteresis band PWM techniques. In hysteresis band PWM techniques output current follows the reference and current and is within the fixed hysteresis band.

Series Transformer:- The necessary voltage which is generated by series APF so that the voltage at load side is perfectly balanced and regulated i.e. Sinusoidal is injected into the transmission line with the help of these transformers. The series transformer turns ratio should be suitable so that injected voltage is suitable such that it injects a compensating voltage which will completely make the load side voltage balanced and also it reduces the current flowing through series inverter.

Low Pass Filter: - Low pass filter is used at the output of series inverter so that the high frequency voltage components are removed which is produced due to switching of Voltage source inverter

High pass filter: - High pass filter is used at output of shunt inverter so that the ripples which are produced due to currents switching are absorbed.

DC link capacitor: - The two voltage source inverter are connected back to back through a DC capacitor. DC capacitor is provides a DC voltage for working of both the inverter. The DC capacitor also provides a real power difference between source and load during the transient period and also acts as a energy storage elements. During steady state real power supplied by source should be equal to the sum real power demand of load & a small amount of power which compensates for active filter. DC capacitor voltage should be equal to reference value but due to disturbance in real power balance between source and load due to change in load conditions the DC capacitor value is changed from reference value.

Power quality is a set of electrical boundaries that allows a piece of equipment to function in its intended manner without significant loss of performance. In other words power quality problem is any power problem manifested in voltage, current, or frequency deviations that result in failure or mal-operation of customer equipment. IEEE Standard 1159 defines power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment‖ . (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

Now-a-days the customers use large number of devices at their installations that consist of power electronics. The residential customers use different domestic appliances such as televisions, video cassette recorders, microwave ovens, personal computers, heating ventilation air conditioning equipment, dishwashers, dryers etc. The business and office equipment include workstations, personal computers, copiers, printers, lighting etc. On the other hand, the industrial customers use programmable logic controllers (PLC), automation and data processors, variable speed drives, soft starters, inverters, computerized numerical control tools and so on. Presently, many customers use compact fluorescent lamps (CFL) for lighting their installations. Many of these devices are quite sensitive to power quality disturbances. Manufacturers of electrical and electronic equipment and end users of electric power are challenging utilities to upgrade the quality of their electric power supplies. Utilities on the other hand are forcing end-users to mitigate the quality of electric current they draw. The issue of power quality has reached up to making national regulations in some countries. The following are some of the works done before on power quality problems and mitigation techniques. (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

2.2. Review of Other Related Works

Shazly A. Mohammed, Abdel-Moamen M.A. and B. Hasanin. Did analysis, modeling and simulation of Dynamic Voltage Restorer (DVR) for compensation of voltage quality disturbances. Accordingly, DVR provides the most commercial way to mitigate voltage sag by injecting voltage as well as power in to the system. Finally they found DVR handled both three phase balanced and unbalanced solutions without any difficulties. They injected appropriate voltage component to correct rapidly any disturbances in the supply voltage to keep the load voltage balanced and constant at the nominal value.(Prakash sundaram1, Shimi S.L. Dr.S.Chatterji).Published a paper 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, and 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 found shunt harmonic filters are economical way of mitigating harmonics.Hussein Mohamed El-Eissawi Fathi,, investigates and mitigates the power quality problems in nuclear installations. Normally electrical power is supplied to the installations via two sources and each source is designed to carry the full load. The assessment of power quality was performed at the nuclear installations for both sources at different operating conditions. In both sources there were several disturbances, which exceeded the thresholds of the power quality standards defined by IEEE Std. 1159 - 1995. Effective and economic mitigation techniques were suggested to the power quality problems occurred.

M. Davudi, S. Torabzad, B. Ojaghi has presented a paper on Analysis of Harmonics and Harmonic Mitigation Methods in Distribution Systems, using Electromagnetic Transient Analysis Program (ETAP).

Muhammad Yasir, proposes generic evaluation approach for estimating the financial impact of voltage sag events on customer operations. The proposed technique is based on the event tree method. Using this approach, it is possible to consider the impacts of operational failure of various sensitive equipment involved in the customer operations on the financial losses expected from voltage sag events. A methodology, based on the developed approach, is also proposed for analyzing the effectiveness and practical viability of various voltage sag mitigation solution. A quantitative case study is conducted in the thesis to illustrate the applicability of the proposed approach.

Shady A. El-Kashlan and Hussein El-Desouki Saied published a paper on power quality assessment via coordinated voltage control in distributed power generation. On their paper, they presented the advantages of active approach in distribution network operation. Their study focused on a voltage quality problem and introduced the coordinated voltage control technique to increase the share of distribution generation in distribution networks and to supply the customers with the required power quality.

Michella Weverink published a paper on Mitigation of Voltage Sags in Industrial Power Plants with Medium Voltage DC Distribution System. His study focus on how to mitigate the voltage sags in industry.

Alexandre Nassif, , presents an evaluation of the relative severity of the harmonic currents from power electronic-based home appliances and the impact of the discrepancy of the harmonic current phase angles. An investigation is carried out on the common filter topologies, and the most cost-effective topologies for mitigating harmonics are identified. As many of the larger harmonic loads also generate inter harmonics, inter harmonics have 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 81 million annually (0.65%of GDP) under a typical scenario (300 hours of planned outages) of imposing power interruptions such as those experienced during 2001. Also the impact due to unplanned outages can be as high as US$ 47 million (0.38%of GDP) in a typical year having 100 hours of unplanned outages. This is a significant economic loss especially in comparison to the 4.5 %to 5%average GDP growth that has taken place in Sri Lanka during the last few years. The economic losses due to planned and unplanned power interruptions can also be expressed in other forms. One commonly used measure is the economic loss (in US$) per unit of supply (kWh); identified as the cost of unserved energy. These findings emphasize the importance of reducing both planned and unplanned interruption.

CHAPTER THREE

RESEARCH METHODOLOGY

3.1. Research Approach

The research methodologies follows literature review, interview with company electrical personnel, collection of data from down time log-book, collection of data by using power quality analyzer FLUKE345 plus and collection of data from SCADA were included. By comparing the existing PQ problems to IEEE Standard 1159-1995 and finding the solution for the problems. MATLAB/SIMULINK software modeling and simulation of power quality problems have been carried out for the modeled networks & based on the above steps the Conclusion and Recommendation has been made in this thesis work. Shortly the following diagram shows the methodology that has been followed in this thesis work.

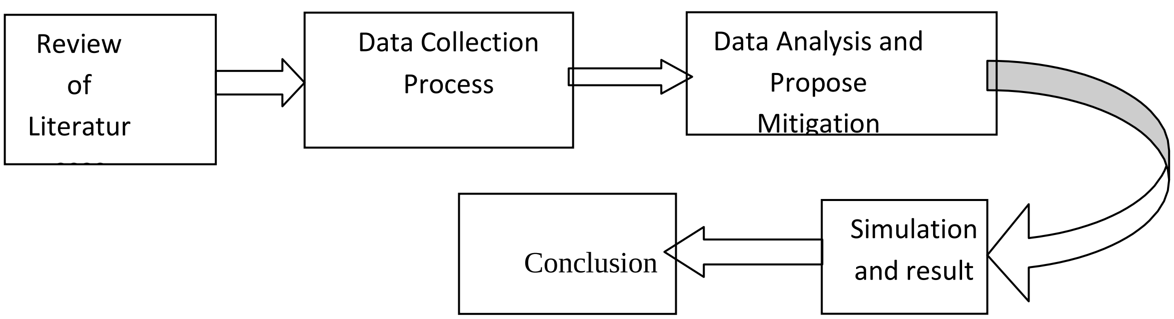


Figure 3.1 Methodology Diagram

3.2. Review of Literatures

This thesis work was done by reviewing different books and the related paper those help me to understand about the power quality problems and its mitigation ways. In other words power quality problem is any power problem manifested in voltage,current, or frequency deviations that result in failure or mal-operation of customer equipment. IEEE Standard 1159 define power quality as the concept of powering and grounding sensitive equipment in a manner that is suitable for the operation of that equipment. Thespecific power quality problems that need to be evaluated will be different from customer to customer. A review of the types of equipment used by the customer, process requirements and economic impacts of problems will lead to a list of problems that need to bestudied. They can include possible problems with both the utility distribution system and the customer facilities.

There are a number of power quality problems in the present-day fast-changing electrical systems. The main causes of these power quality problems can be classified into natural and man-made in terms of current, voltage, frequency, and so on. The natural causes of poor power quality are mainly faults, lightning, weather conditions such as storms, equipment failure, and so on. However, the man-made causes are mainly related to loads or system operations. The nonlinear loads cause a number of power quality problems in the distribution system. They inject harmonic currents into the AC mains. These harmonic currents increase the rms value of supply current, increase losses, cause poor utilization and heating of components of the distribution system, and also cause distortion and notching in voltage waveforms at the point of common coupling due to voltage drop in the source impedance. Some of the effects are as follows:

3.3. Data Collection Processes

3.3.1. Instrument Used For Data Collection

The data collection process has been done by referring power generation logbook, the factory downtime logbook, using power quality analyzer (FLUKE 345) meters and data from SCADA. The data got from power generation log book describes the bill of the factory: that means how much power is generated and how much the factory consumed the powers. The factory downtime logbook describes the duration how much the factory is work and how much the factory is stopped in 24 hrs. The device has the ability to measure High speed voltage quality parameter, RMS voltage quality parameters, Power quality parameters, 3-Phase quality parameters, Harmonic quality parameters and distortion factors simultaneously. The FLUKE 345 is a low cost, class 1 (IEC1036) high technology portable analyzer for both single phase and three phase systems, manufactured by ELCONTROL ENERGY and supplied complete with three 1000A clip-on CTs. voltage leads and all accessories in strong carry case.

Figure 3.2. FLUKE 345. Instrument

To identify the power quality problems and to see their compatibility with the IEE-1159 standard measurements of electrical quantities have been done. For the analysis of power quality problems of the factory power distribution network measurements are carried out the selected sites. Hence measurements of power quality parameters are taken at the two mark distribution boards by using FLUKE 345power quality analyzer.

Flexible and easy to use

The FLUKE 345 measures a wide range of electrical parameters and can be used for many applications in today's modern electrical environment. Measuring mode is selected by a simple turn of the rotary switch and the large color display presents data in a clear, easy-to-understand way. By default the display will show the most common measurements, in very large format. If more detailed views are required they are available with the press of a single key (up to six measurements at once).

Inrush current

Diagnose equipment start-ups with the inrush current mode. A current trigger level is set prior to recording. Once the level has been exceeded, the meter will begin capture. Recordings from 3 seconds to 300 seconds may be captured, and up to 1000 inrush events may be stored in the instruments memory. Screen captures and data logging any measurement can be stored in memory for later viewing, or downloaded to a PC. Simply press 'SAVE' to capture the active screen to memory – up to 50 screen shots can be saved for quick and simple documentation. Additionally, over 150,000 individual measurements can be logged for later review on the display or on a PC using Power Log software

Analysis and reporting software

Designed to quickly view recorded data, the included Power Log software displays all recorded parameters on interactive trends. Generate professional reports with the 'Report Writer' function, or copy and paste images into report document manually.

• Easy-to-use tabbed window format allows quick data evaluation.

• One-step downloads and display capability

• Waveform, harmonics, and trend download • Simple data export to other applications

Fluke 345 used to measures the following electrical parameters

- Current measurement (dc, dc rms, ac rms)
- Voltage measurement (dc, dc rms, ac rms)
- Harmonics
- THD (Total Harmonic)
- Watts measurement (single- and three-phase) (dc, dc rms, ac rms)
- VA measurement (single- and three-phase) (dc, dc rms, ac rms)
- VAR measurement (single- and three-phase)
- Power factor (single- and three-phase)
- Displacement power factor

3.3.2. Unplanned Down Time Data from Quality Control

Power quality monitoring on the system network was done based on methods described above and these power quality disturbances data from down time logbook recorded are used as indication and justification of the study problem. Voltage sags and swells are detected by their symptoms such as lights flickering, excessive equipment heating, and malfunctions of computers, programmable logic controllers and stoppage of motors. Voltage sags and swells give severe impacts to the industrial customer's equipment. The severe power quality disturbances that cause stoppage of sugar machine was voltage sag as seemed to occur most frequently as compared to other power quality disturbances. Therefore, voltage sag is one of the prime factors due to which the factory suffers huge loss because of downtime, rejects, idle workers and equipment damage**.** When equipment is not operating due to unscheduled downtime, productive drops and process Constance suffers or failed, which in turn leads to product waste. The losses include the cost of idle labor starting from the moment of interruption and ending when normal process activity resumes, and process restart cost.

Table 3.1.Unplanned downtime recorded for three years

months	2019		2020		2021	
	Hrs	No.of events	Hrs	No.of events	Hrs	No.of events
Oct.	15	6	10.5	5	15	6
Nov.	9.4	5	8.5	3	7.8	5
Dec.	6.5	5	7.9	5	3	3
Jan	5.4	3	4.3	3	6.4	4
Feb.	6.5	4	8.7	3	6.9	4
March.	4.6	3	5.4	5	7.5	6
Appr.	6.4	3	6.2	4	4 .8	5
May.	8.3	6	8.4	2	8.2	7
June	18	7	11	10	12.8	8
Total	73.7	42	70.9	40	69.3	49

From table 3.1.shows that for instant in 2020 unplanned down time was 70.9 hrs.' The production capacity of the factory in 24 hrs is 11,000 tone white sugar. So;within 70.9 the factory produces 77900 tone white sugar. So, the factory losses 77900 tons of white sugar per year due to under voltage and over voltage. To minimized this losses the problems of under voltage and over voltage of power quality problems should be solved by installing an appropriate devices on power distribution sides. UPQC is one of the most power full devices to solve the problems that caused due to voltage sag and voltage swells. The work of this work investigating power quality problems and its mitigation using UPQC at the distribution sides at cane preparation plant of fincha sugar factory.

3.3.3 Data Collected from Secondary Transformer

Measurement-1

The first measurement was taken at PCC at low side of the step down transformer that supply power for cane preparation plant and the measurement results of voltage; active power, apparent power, table reactive power, power factor, line to ground voltage, line currents and harmonic distortion of the voltage and currents are depicted in the following.

Table 3.2: voltage data from transformer

Sr.no	Frequency	Reference voltage	Instantaneous phase voltage			%voltage sag		
	Hz	V	V1	V2	V3	V1%	V2%	V3%
1	50	230	230	229	230	100	99.6	100
2	49.9	230	226	225	225	97.8	97.8	97.8
3	50	230	170	171	170	74	74.3	74
4	50	230	222.5	223	222	96.7	96.5	96.5
5	50.1	230	225	226	225	97.2	97.8	97.2
6	49.9	230	225	226	225	98.2	97.8	97.2
7	50	230	227.5	228.	228	98.6	99.1	99.1
8	50	230	222	223	222	96	96.5	96.5
9	50	230	228	227	227.5	99.1	98.7	98.6
10	50	230	229	228	228	99.5	99.1	99.1

The table 3.2 shows the voltage values level and distortion value of each phase taken from the transformer of the feeder of cane preparation plant; the measurement on individual phases. The measurement result at the end was showed that the voltage sag was about 26%. This point is at which the factory operation was disturbed. The duration of voltage distortion was occurred for 0.22ms that runs from 0.03 to 0.3ms. This unbalance of voltage distortion was made fluctuation of the operation in which the motors were over heated and not function. Again the measurement taken at the terminal of the motors indicates the voltage unbalance is beyond the standard. So to prevent such type of problems voltage compensation should be necessary .The objective of this thesis work is to avoid such problems by installing Unified power quality conditioner (UPQC)

Measurement; 2

Table 3.3.; Active power; reactive power; current and power factor Data from transformers

Active power(P) (KVA)			System current(A)			Reactive power(Q) (KVAR)			P.F
P1	P2	P3	A1	A2	A3	Q1	Q2	Q3	0.8
75	75	74.5	402.6	407.9	402.6	53.3	53.3	52.9	0.81
74.5	74.5	74	407	408.8	406	52.9	52.9	52.5	0.81
74	75	74.5	440.7	441	440.9	52.3	53.3	52.6	0.8
76	76	76	421.7	420.7	422.6	54	54	54	0.81
75.5	75	75	414.3	409.7	411.5	53.6	53.3	53.3	0.8
74.5	74.5	74	408.8	407	406	52.6	52.9	52.5	0.81
74	75	74	401.6	406.1	400.7	52.5	53.3	52.5	0.8
76	75	76	422.6	417.1	422.6	54	53.3	54	0.81
73.5	74	74	398	402.5	401.6	52.2	52.5	52.5	0.81
74	74	74	398.9	400.7	400.7	52.5	52.5	52.5	0.8

The table 3.3. Shows the value of current level, per phase and unbalances value between the phases for different readings. On the table for phase A as shows on no-3 the system of current value due to voltage sag is 440.65A, which is greater than the system current operational values value 402.57 A .This result is occurs due to voltage sag in the utility side. This over current causes system over load; motors over heat and sometimes burn out of motors. There for to avoid the problem that caused due to the distortion of current , the appropriate value of current compensation should be needed. The objective this research is to solve such type of the problems by installing the appropriate UPQC which compensate the values of current.

As the data taken from the transformer implies the average power factor of the three phases is low, 0.81. The factory has been penalized by Ethiopian Electric Utility (EEU) for the low power factor. Therefore the power factor should be also be corrected so that the efficient use of power is ensured and also for factory to escape from penalty.

Summary

As the data collection form the factory indicated that the factory losses high amount of the money per year due to power quality problems .That means the factory has no power quality mitigation at the distribution side for controlling of the quality of power, due to this the voltage sag; voltage swell; under voltage; over voltage; harmonic’s and other power quality problems that occurs at source side affect the operation of the factory. To minimize the factory cost additional power quality improvement should be installed in the factory in the distribution side. There for this investigation of those problems as the above data’s and proposed mitigation of power quality problems as the following conditions

CHAPTER FOUR
DESCRIPTION OF STUDY AREA AND DATA ANALYSIS

4.1. Description of the Study Area

Fincha Sugar Factory is one of the largest sugar factories in Ethiopia**.** It founds in Oromia Regional State, Horo Gudurru Wellega Zone,Abay Chrome District in Fincha Rift Valley around 350KM from the capital, Addis Ababa. The area was conducted by Bulkers Agricultural international Ltd.of Britain since 1978 while the project work had started in 1989. The finance needed to construct the factory was secured from the Africa development bank and Africa development fund; governments of Australian and Spain and domestic bank of the nation. Fincha River which is generating hydroelectric power and then made reach the rift valley to water the sugar plantation field of Fincha sugary factory; finally goes to Nile River as a tributary. The factory command area is 67,098 hectares.

The factory started production in1998 and till jully,2013 the average annual design production capacity of Fincha sugar factory is 1100 tons of sugar and it had the capacity of producing 8,000 ltrs ethanol. The factory has carried out expansion projects both on its sugarcane plantation field and its sugar mill. It has come up with a plant of 1,200 TCC design capacity and capable of annually producing tons of sugar and 20,000 ltrs ethanol. The factory agricultural expansion project has been carried out around the areas known as East bank, Nashie and also on the idle areas found on the western side of the river. The factory, therefore in near future will bring its total sugarcane plantation land which had been only 12,170 hectares close to 21,000hectares.the cultivation land expansion job has enable led the factory to the expand its cane covered land to more than 19,000 hectares till 2016.the factory needs 31 Megawatt electric powers .In Ethiopia Fincha Sugar Factory is one of the sugar factories which are affected by poor power quality that means Fincha Sugar Factory experiences voltage variations problems caused by load variation, lightning strikes, switching of power lines and capacitor banks, system faults, and large motor start-ups. These power quality problem causes operation disturbance that require a long time to return to its normal operation and resume production. Therefore, a study of poor power quality is essential for the Sugar industries. Power quality problem study is the study of deviations in current and voltage waveforms from the ideal sine waves. Power quality is the combination of voltage quality and current quality. Thus, power quality is concerned with deviations of voltage and/or current from the ideal (H.Akagi, vol.9, no.3, 1994).At the distribution level, power quality can be a combination of voltage quality and current quality. From the marketing point of view, electricity is a product and the power quality is the index of the product quality .The prime objective of utility companies is to provide their consumers an uninterrupted sinusoidal voltage of constant amplitude. Unfortunately, this is becoming increasingly difficult to do so, because the size and number of nonlinear and poor power-factor loads such as adjustable speed drives, computers, power supplies, programmable logic controllers, furnaces, power converters, induction motors and traction drives are finding its applications at the industrial levels. These nonlinear loads draw nonlinear current and degrade electric power quality. The quality degradation leads to low power-factor, low efficiency, and overheating of transformers (H.Akagi, vol.9, no.3, 1994). This thesis work is mainly concerned on power quality problems and it's mitigating in Fincha Sugar Factory.

Figure 4.1 Study area Fincha sugar factory

4.1.1. Parts of the Factory

Fincha sugar factory has different plants. These plants includes cane crushing plant; dewatering plants; steam generation plants (boilers);power house plants; treatment plants; boiling houses ;ethanol plants and work shop.

- **Cane crushing and Fiber Preparation plant;**

This plant is the first part of the factory in which cane from the field enters the factory. In this plant crushing process take place or cane changes into fibrous form. After the crushing processes takes place the fib roused parts go to mill for further processes.

The factory has 2 lines of cane crushing and Fiberizing plants lines. These are existing (old) crushing line and expansion crushing line. The existing crushing line has the capacity of Cushing is 46000 tons and the new crushing line has the capacity crushing is 64000 tons per day.

Figure: 4.2. Cane crushing and Fiber Preparation plan

- **Dewatering Mills plant**

Fincha sugar factory has two dewatering mill .these are Existing(old) Dewatering and new(expansion)dewatering mill .Existing(old) Dewatering has four mill sets and two processing stages. The four mills are first mill; second mill; third mill and fourth mills .in the first mill and in the second mill the mixing of fiberized cane and warm water is occurred. In the third mill and fourth mill squeezing processes (extracting of juice from fiberized is occurred). This process is called Dewatering .After the Dewatering processes is completed in dewatering mill plant the extracted juice go to boiling houses for further processing in order to produce the final product of white sugar. In another way the fiber separated from the juice is go to boiler to serve as a fuel.

Figure: 4.3. Dewatering mill plant

- **Boilers (steam generation plant):**

Boilers are used to convert liquid water to steam by heating processes. In this process chemical energy changed to thermal energy or steam energy**.** In Fincha sugar factory there are two steam generation plants. These are existing and expansion steam generation plants. Each has two boilers its capacity. The capacity of existing steam generation plant per boiler is 65 tones per hour and the capacity of expansion steam generation plant per boiler is 110 tones per hour. Used to generate steam by heating water get from treatment plants and fiberized fuel from dewatering mill .so, the boiler in put raw materials are fuel and treated water to convert water to steam. Steam and ashes are the output .the output steam from the boiler is used as input for steam turbine generators to produce electricity.

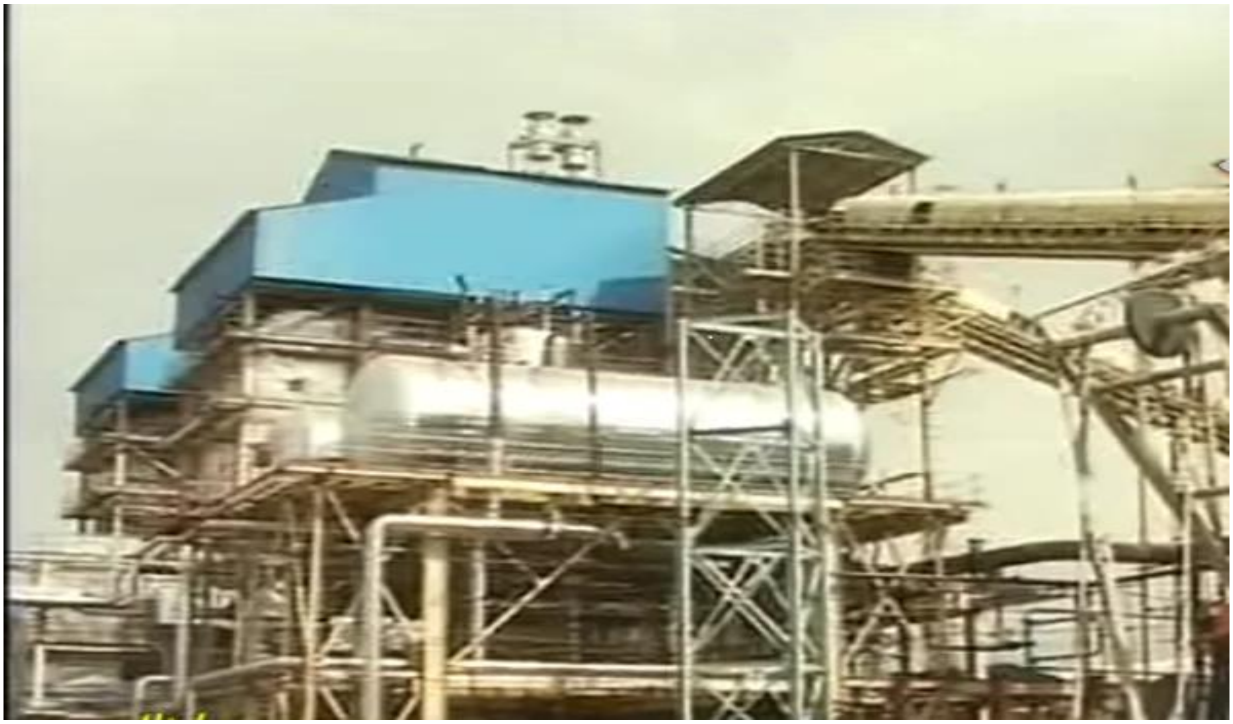


Figure: 4.4. Steam generation plant (boiler)

- **Power house (steam power generation plant)**

Power generation plant use to generate electric power from steam turbine generators which is driven steam comes from boilers. In Fincha sugar factory there are two power generation plants. These are existing and expansion power generation plants. Each of them consists of two turbines unities. The two existing steam turbine generators generate 3.5MW each, and the two expansion steam turbine generators generate 12MW each. The total capacity of power generation from existing and expansion of Fincha sugar factory is 31MW, however the expansion STG is not on the operations as this time duet long maintenance case. Also the factory has a line that synchronous with grid to export the grid while excess power is generate and to import the power from the grid while the power generate is minimal. So, many times the quality of power generate and distribute to the factory is not good this causes of voltage sag; voltage swell; under voltage; over voltage; harmonics and other power quality problems. The power quality problems results in failure of machines; reduction of product; idle of workers these are exposes the factory and the country to high cost. So; this thesis works on investigating power quality problems and proposed the solution for the problems.

Figure 4.5.Power plant switchgear 11kv bus bar

In this research, the case study area is chosen at Fincha Sugar Factory. It has seven feeders are connected with Switchgear 11kV bus bar, which are supply power for factory. This research is emphasized on 1250KVA transformer side in which the power quality problem occurs due to factory loads such as knife and fib rising mill loads. The single line diagram of case study area is shown as the following diagram.

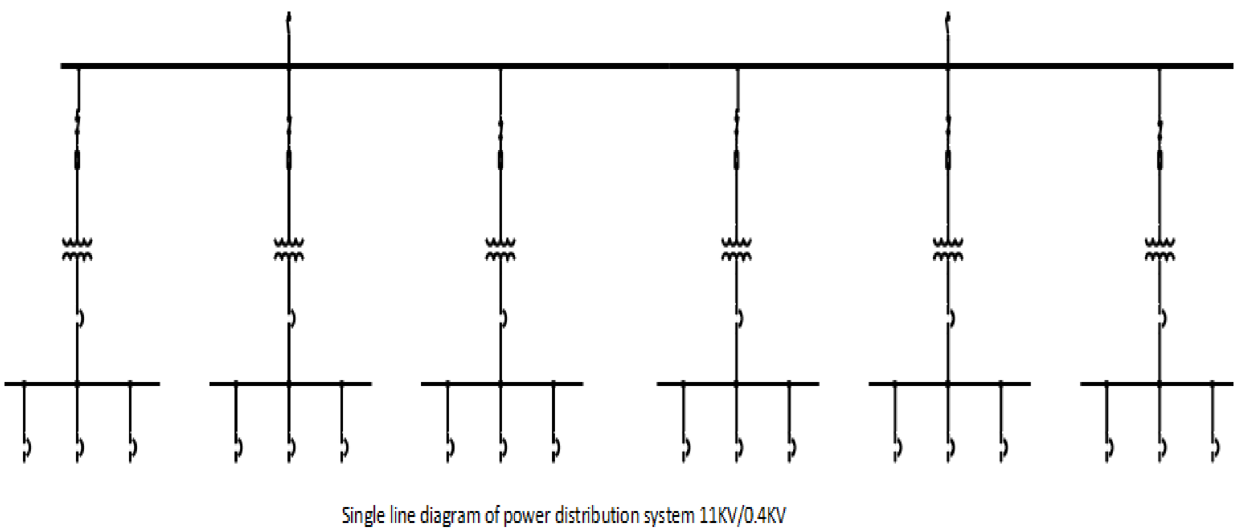


Figure (a) single line diagram of power distribution system 11kv/0.4kv

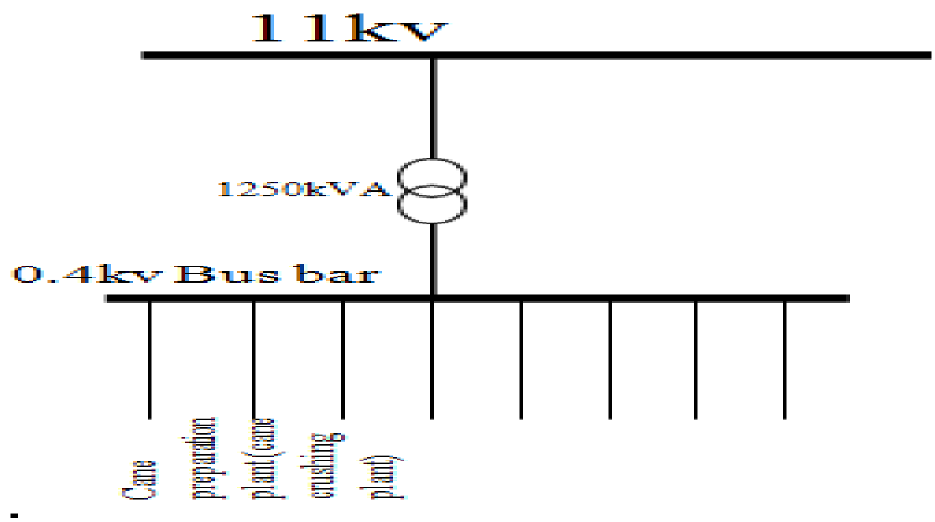


Figure (b) Single Line Diagram of cane preparation plant power distribution system

Figure: 4.6. (a and b) Single Line Diagram power distribution system

4.2. Data Analysis

4.2.1 Wave form distortion data Analysis

The PCC is the location where another customer can be served from the system. The standard allows for the same procedure to be applied by the customer at other locations within a facility but different current limit values could apply in these cases. The waveform distortion is principally characterized by its spectral contents which are investigated using Fourier transform. IEEE Standard 519-1992 defines, the total demand distortion (TDD). This term is the same as the total harmonic distortion except that the distortion is expressed as a percent of some rated load current rather than as a percent of the fundamental current magnitude at the instant of measurement.

$$THD_U=\frac{\sqrt{\sum_{h=2}^{\infty} I_{(h)}^{2}}}{I_L}*100 \tag{4.1}$$

Whereas:

I_h is the harmonic currents,

I_L is the rated load-current.

Table 4.1 Harmonic current limits for individual end users from IEEE standard 159-1992

$V \leq 69KV$						
Isc/I_L	h<11	11<h<17	17<h<23	23<h<35	35<h	TDD
<20	4	2	1.5	0.3	0.3	5
20-50	7	3.5	2.5	0.5	0.5	8
50-100	10	4.5	4	1.5	0.7	12
100-1000	12	5.5	5	2	1	15
>1000	15	7	6	2.5	1.4	20

A procedure to determine the short-circuit ratio is as follow

Whereas: I_{SC} - Short circuit current at the point of common coupling.

I_L - Maximum demand loads current (fundamental frequency component) at the point of common coupling.

$$I_L = \frac{P}{\sqrt{3 * PF * KV}} \tag{4.2}$$

$$I_{sc} = \frac{U20}{\sqrt{3ZT}} \tag{4.3}$$

$$\text{Short circuit ratio} = \frac{Isc}{IL} \tag{4.4}$$

Whereas:

U_{20} - Nominal voltage with the secondary side of transformer open

Isc - Short circuit current of the transformer

%Z-Percentage transformer impedance

P - Load demand

PF - Power Factor

The tables of individual harmonic component limits apply to the odd harmonic components. Even harmonic components are limited to 25% of the limits in the tables. Current distortion which results in a dc offset is not allowed. The total Demand Distortion (TDD) as defined previously;

$$TDD = \sum_{h=2}^{hmax} \frac{Ih2}{IL} \tag{4.5}$$

Whereas:

Ih - Magnitude of individual harmonic components (RMS, amps) h - Harmonic order

I_L - Maximum demand load current (RMS amperes) defined above

I_L is the fundamental component of the maximum demand load currents. All power generation equipment is limited to these values of current distortion regardless of actual Isc/I_L .TDD is total demand distortion(uses maximum load current as the base, rather than the fundamental current),which is identical with THD.

Table 4.2: Harmonic voltage limits, IEEE standard 519-1992

	Maximum individual	Maximum THD
Utility bus voltage	Harmonic component (%)	(%)
<69kv	3.0	5.0
69kv -137.9kv	1.5	2.5
138kv	1	1.5

IEEE Standard for Shunt Power Capacitors (IEEE Standard 18-1992) specifies the following continuous capacitor ratings

- 135 percent of nameplate kVAr
- 110 percent of rated RMS voltage (including harmonics but excluding transients)
- 180 percent of rated RMS current (including fundamental and harmonic current)
- 120 percent of peak voltage (including harmonics

Voltage Sag and swell in the utility voltage

Along with changing the voltage level of the network, 20% or higher increases voltage unbalance.

The percentage of voltage sag and voltage swell are monitored continuously as given below

$$\%Unbalance = \frac{V2*100}{V1} \qquad (4.6)$$

Where: V1 and V2 respectively are the positive and negative sequence voltage.

If the system has mostly single phase loads, then minor voltage unbalance

% voltage sag =(nominal RMS –Measured RMS *100)/(Nominal RMS value) (4.7)

%voltage swell= (measured RMS-nominal RMS *100)/(Nominal RMS value) (4.8)

With the application of various mitigation schemes, the voltages are tried to be kept within the acceptable

Limits of ± 0.05 per unit (pu)

Voltage Rise at End User Bus

The voltage rise from placing capacitors on an inductive circuit is a two-edge‘s word from the power quality standpoint. If the voltage is low, then the capacitors provide an increase to bring the voltage back into tolerable limits. However, if the capacitors are left energized when the load is turned off, the voltage can rise too high, resulting in a sustained overvoltage. The voltage rise by the end user from the installation of capacitors is approximated by the following equation. (Matin Kesler, Angin Ozadmir, vol.58, no.9, sep 2011).

$$\%\Delta V=(kVArcap*ZT(\%))/kVAT \qquad (4.9)$$

Whereas:

%ΔV - Percentage rise in voltage

kVArcap- Capacitor bank rating

kVAT - Step down transformer rating

ZT (%) - Step down transformer impedance, %

This formula assumes that the transformer is the bulk of the total impedance of the power system up to the point at which the capacitor is applied.

Voltage root mean square and current mean square

$$Vrms = Vm*0.7071 \qquad (4.10)$$

Where:

Vrms- voltage root mean square

Vm-peak voltage

$$Irms = Im/\sqrt{2} = Im*0.7071 \qquad (4.11)$$

Where:

Irms-current root mean mean square

Im-peak current

4.2.2 Modeling and Designing of UPQC

- **Mathematical modeling**

Unified Power Quality Conditioner (UPQC) is one of the major custom power solutions, which is capable of mitigating the effect of supply voltage sags at the load end or at the point of common coupling(PCC) in distribution system .the performance of the designed UPQC is evaluated by using the MATHLAB/SIMULINK program

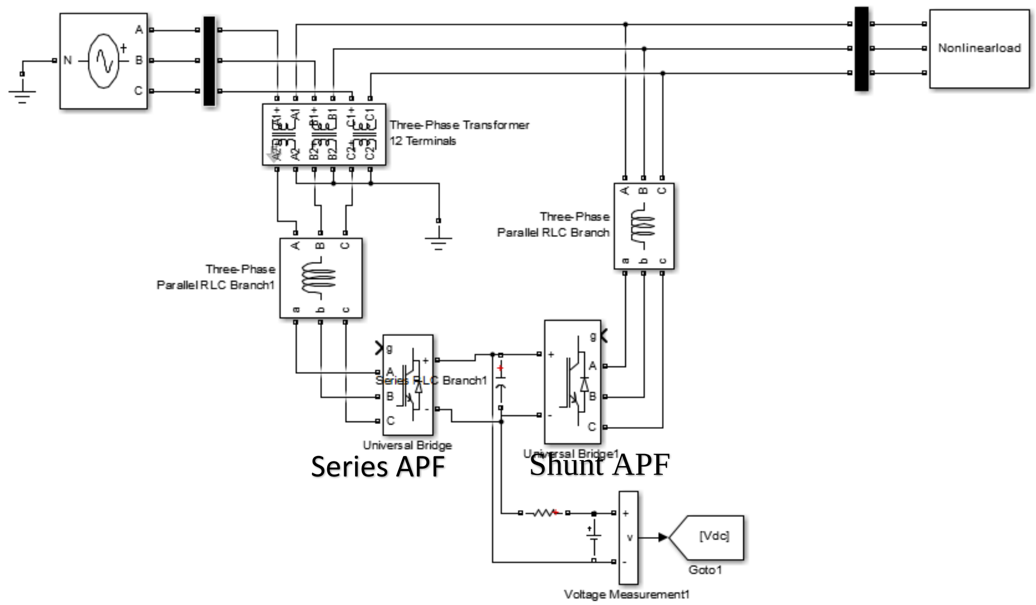


Figure: 4.7. Power distribution system modeling with UPQC

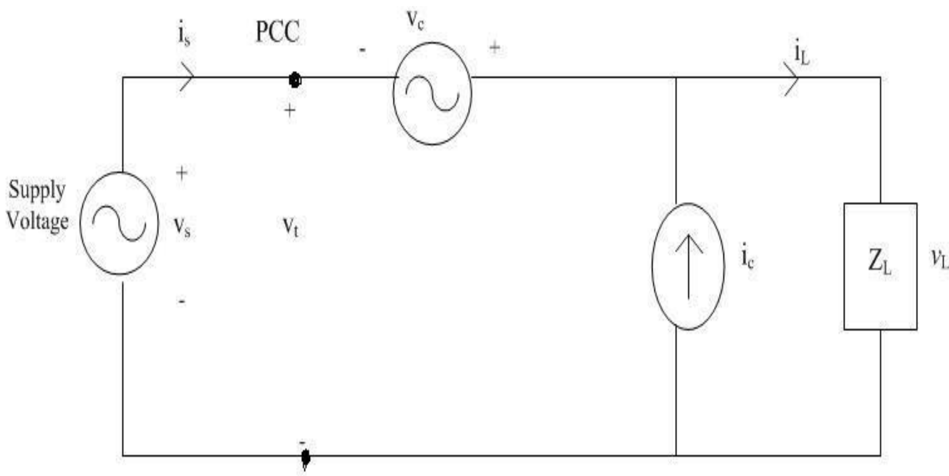


Figure: 4.8.single line diagram of Power distribution system with UPQC

Consider the voltage at source, at the point of common coupling and voltage across load are denoted byVS, VCC and Vl. respectively. The source and load currents are denoted by Is and Il respectively. The voltage injected by series active power filter is denoted by Vsr., whereas the current injected by shunt active power filter is denoted by Ish. Assuming the load voltage, Vl, as a reference and suppose the lagging power factor of the load is cosΦl.

Vl = Vl at an angle 0 degree (4.12)

Il = Il at an angle – Φl (4.13)

Vcc = Vl (1+K) at angle of 0 degree (4.14)

Where factor 'K' represents the fluctuations in source voltage and is defined as

$$K = (Vcc - Vl) / Vl \quad (4.15)$$

The voltage injected by series active power filter is,

$$Vsr = Vl - Vcc = -K\ Vl \quad (4.16)$$

Assuming the UPQC to be lossless, the active power demanded by the load is equal to the active power input at point of common coupling. Thus it provides nearly a unity power factor source current, therefore, for a given load condition the input active power at point of common coupling can be expressed as

$$Pcc = Pl \quad (4.17)$$

$$Vcc = Vl^{*}\ Il^{*}Cos\Phi l \quad (4.18)$$

$$Vl = (1+K)^{*}\ Is = Vl^{*}\ Il^{*}Cos\Phi l \quad (4.19)$$

$$Is = Il / (1+K) * Cos\ \Phi l \quad (4.20)$$

The above equation suggests that the source current IS depends on the factor K, since Φl and Il are load characteristics and are constant for a particular type of load. The complex power absorbed by the series active power filter can be expressed as,

$$SSr = VSr^{*}\ Is \quad (4.21)$$

$$Psr = Vs^{*}Is^{*}Cos\Phi s = -K^{*}Vl^{*}Is^{*}Cos\Phi s \quad (4.22)$$

$$QSr = VSr * Is * Sin\Phi s \quad (4.23)$$

ΦS = 0 since unified power quality conditioner is maintaining unity power factor

$$Psr=Vsr^{*}Is= -K^{*}Vl^{*}Is \quad (4.24)$$

$$QSr \approx 0 \quad (4.25)$$

The complex power absorbed by the shunt active power filter can be expressed as,

$$SSh = Vl^{*}ISh \quad (4.26)$$

The current provided by the shunt active power filter, is equal to the difference between the input source current and the load current, which includes the load harmonics current and the reactive current.

Therefore

$$ISh = Is - Il \quad (4.27)$$

Whereas

ISh = Is at an angle 00 - Il at an angle – Φl

$$ISh = Is - (\ Il^{*}\ Cos\Phi l - j^{*}\ Il * Sin\Phi l\ )$$

$ISh = (Is – Il^* Cos\Phi l) + j^* Il * Sin\Phi l$

$$PSh = Vl^*ISh^*Cos\Phi Sh \quad (4.28)$$

$= Vl^* ((Is –Il)^*Cos\Phi l))$

The reactive power from the source flows to the load during the normal working condition when unified power quality conditioner is not connected in the circuit. While during the operating condition of UPQC, the shunt active power filter is put into the operation, the reactive power required by the load is now provided by the shunt active power filter. From equation (4.4), if K is less than zero (this condition is possible during the voltage sag at the source end), then the voltage at point of common coupling (Vcc) must have lesser value than the load voltage (Vl), then from equation (4.13), the series active power filter supplies the active power (Psr) to the load and from equation (9), Is will be more than the normal rated current. Thus it is concluded that the required active power is taken from the source itself by taking more current so as to maintain the power balance in the network and to keep the dc link voltage at acceptable range. Again from equation (4.4), if K is greater than zero(this condition is possible during the voltage swell at the source end), then the value of Vcc is greater than the Vl and the active power (Psr) is absorbed from the source. If K = 0, then there is no exchange of power takes place through the UPQC, which is the normal working condition of the distribution system.

➢ Design of Unified Power Quality Conditioner (UPQC)

The mathematical design of the UPQC is the designing of two voltage source converter (VSC) connected back to back. The design of UPQC is the design of series VSr and shunt VSh which is shown in Fig.4.2. The parameters of the VSC should be designed deliberately for better performance. The critical parameters that should be taken into consideration while designing UPQC are DC link voltage (Vdc), DC link capacitor (*C*dc), shunt interfacing inductance (Lf), series interfacing inductance (Lse),series capacitor (Cse) and the switching frequency (fsw).

The design procedure of UPQC

Design Calculation of UPQC Parameter

1. Calculation of UPQC Parameters for design
2. Voltage sag calculation to know the compensation values
3. Calculate the peak values of voltage and currents for UPQC.
4. Choose standard components for the UPQC and verify their performance to assure that

capacitor components will operate within IEEE-18 recommended limits

Table 4.3: Input Parameters for Designing of UPQC

No	Parameters	Values	Unit
1	Modulation index(m)	0.85 to 1	-
2	Line Voltage, VLL	400	V
3	Phase voltage	230	V
4	Variation of energy during dynamics(k1)	10%	-
5	Overloading factor, α	1.2	
6	DC bus recovered time, t	30	Ms
7	Current Ripple, I crpp	15%	-
8	Switching frequency , fs	20	KHz

From data collection for phase voltage Vl=230v;Vcc=170;Ps=75000w

Vl = 230 v at an angle 0 degree

Il = Il at an angle – Φl

Vcc = Vl (1+K) at angle of 0 degree

Where factor 'K' represents the fluctuations in source voltage and is defined as

$$K = \frac{Vcc - Vl}{Vl} = \frac{170-230}{230} = -0.26$$

The voltage injected by series active power filter is,

Vsr = Vl – Vcc = –K Vl

=0.26*230 = -60v

Assuming the UPQC to be lossless, the active power demanded by the load is equal to the active power input at point of common coupling. Thus it provides nearly a unity power factor source current, therefore, for a given load condition the input active power at point of common coupling can be expressed as

Pcc = Pl

Pcc = Vl* Il*CosΦl

Vl * (1+K)* Is = Vl* Il*CosΦl

$$Is = \frac{Il * \text{Cos}\Phi l}{1+K}$$

$Il = \frac{PL}{Vl * \cos \Phi l} = \frac{75KW}{230*0.81}$

$=402.57A$

Now $Is = \frac{402.57*0.81}{1-0.26} = 440.65A$

The above equation suggests that the source current IS depends on the factor K, since Φl and Il are load characteristics and are constant for a particular type of load. The complex power absorbed by the series active power filter can be expressed as,

SSr = VSr* Is = 60 *440.65

= 26.44KVA

Psr = Vs*Is*CosΦs = –K*Vl*Is*CosΦs

QSr = VSr * Is * SinΦs

ΦS = 0 since unified power quality conditioner is maintaining unity power factor

Psr=Vsr*Is= –K*Vl*Is

= 60*440.65= 26439VA

= 26.44KVA

QSr ≈ 0

The complex power absorbed by the shunt active power filter can be expressed as,

SSh = Vl*ISh

The current provided by the shunt active power filter, is equal to the difference between the input source current and the load current, which includes the load harmonics current and the reactive current.

Therefore

ISh = Is – Il

Whereas

ISh = Is at an angle 00 - Il at an angle – Φl

ISh = Is – (Il* CosΦl – j* Il * SinΦl)

ISh = (Is – Il* CosΦl) + j* Il * SinΦl ;

= (440.65 – 402.65*0.81) + j*402.57* Sin(35.9)

= 114.57 + j235.9 A

PSh = Vl*ISh*CosΦSh

= Vl* ((Is –Il)*CosΦl))

= 230*(440.65 – 402.57)*0.81

= 7094 W = 7.094KW

DC capacitor voltage:

The value of the common link DC bus voltage of back to back connected VSIs of the UPQC depends on the instantaneous energy available to the UPQC

For a VSI the DC link voltage is defined as

$$Vdc = \frac{2\sqrt{2}.vll}{\sqrt{3}.m} \qquad (4.25)$$

Where:

VLL -is the line voltage of the grid

m- Is the depth of modulation?

VLL- is the ac line out voltage of UPQC.

According to IEE the modulation index of the industries should be between 0.85 - 1 in normal condition.

Considering modulation index as 1 and for line to line voltage (VLL =400 V),

$$Vdc = \frac{2\sqrt{2}.vll}{\sqrt{3}.m} = 2\sqrt{2}*400* \frac{2\sqrt{2}*400}{\sqrt{3}*1}$$

$$= 677.69V$$

The Vdc obtained is 677.69 V and is selected as 700 V.

DC bus capacitor:

The value of dc capacitor (Cdc) of back to back connected VSIs of the UPQC depends on the change of DC voltage during increase and decrease of the load. Using the principle of energy conservation, the equation for Cdc is as follow.

$$1/2Cdc[V^2dc-V^2_{dc1}]=3Vrms(\alpha I)t \qquad (5.33)$$

Where: Vdc- is the reference dc voltage

Vdc1- is the minimum voltage level of dc bus,

α -is the overloading factor?

Vrms- is the phase voltage,

I -is the phase current, and

t -is the time by which the dc bus voltage is to be recovered.

Considering the minimum voltage level of dc bus, Vdc1=690 V, Vdc=700 V, Vrms=400/sqrt (3) =239.60 V, I=25.40 A, t=350μs, α=1.2,

$$1/2Cdc[V^2dc-V^2_{dc1}]=3V(\alpha I)t$$

$$Cdc = \frac{6V(\alpha I)t}{[V2dc-V2dc1]}$$

$$= \frac{6*239.6*1.2*25.4*350}{(700)2-(690)2}$$

$$=2340\mu F$$

The calculated value of Cdc is 2340μF.Hence Cdc is selected as 3000 μF.

Selection of AC Inductor for phase leg:

An empirical formula has been selected for various values of the interfacing inductance (Lf) of a shunt and series VSC. It depends on the current ripple peak to peak(Irip) , switching frequency(fsw) , dc bus voltage (Vdc) .In normal condition the reactive inductance (Xf) value can be evaluated as follows,

$$Xf = 2*\pi*fsw*Lf \tag{5.34}$$

$$Xf = \frac{Vdc}{Irip}$$

$$Lf = \frac{Vdc}{2*\pi*\alpha*fsw*Icr(p-p)};$$

$$Icr(p-p) = \frac{Vout*\left(1-\frac{Vout}{Vin}\right)}{Lf*Fsw}$$

Where:Lf= inductance

Fsw= Switching frequency

α- is the overload factor?

Considering, Icr,p-p=2.5%, fs=10 KHz, m=1,Vdc=700 V, α=1.2,

$$Lf= \frac{Vdc}{2*\pi*\alpha*fs*Icr(p-p)} \tag{5.35}$$

$$= \frac{700}{2*\pi*1.2*50*10*0.025} = 7.407mH$$

The Lf value is calculated to be 7.407 mH. A round-off value of Lf of 8 mH is selected in this work.

Estimation of Switch (IGBT)

This could be selected on the basis of DC link voltage Vdc; Irip and the peak source current (Ispeak). The voltage rating of switch (IGBT) is the sum of DC link voltage and 10% of Vdc .

The voltage switch rating Vsw and current switch rating Isw can be evaluated as,

Vsw = Vdc+10% of Vdc

= 700+70 = 770 KHz

Isw =1.25*(Irip+Ispeak)

= 1.25*(0.025+25.4)

= 31.78A

The first order high-pass filter tuned at half of the switching frequency is applicable to filter out the harmonics of the voltage at PCC. The time constant of the filter is one tenth of the fundamental time period (*T*), which can be evaluated as the RseCse << T/10, where Rse and Cse are the ripple filter resistance and its capacitance respectively.

Estimation of the Interfacing Inductor

The interfacing inductor Lse has been designed based on the switching frequency of the series VSC and it can be estimated as follows,

$$Lse = \frac{Vdc}{\sqrt{3}*4*fsw*Irip}$$

$$= \frac{700}{\sqrt{3}*4*10*0.025} = 0.404$$

Ripple Filter:

A low-pass first-order filter at half the switching frequency is used to filter the high-witching frequency noise from the injected voltage of series APF. Considering a low impedance of 8.1Ω for the harmonic voltage at half the switching frequency 20 KHz /2 =10 KHz, the ripple filter capacitor is designed as Cf =5µF. A series resistance (Rf) of 7 Ω is included in series with the capacitor (Cf).The impedance is found to be 638Ω at fundamental frequency, which is sufficiently large, and, hence, the ripple filter draws negligible fundamental current.

CHAPTER FIVE

RESULTS AND DISCUSSIONS

5.1. Simulation Results of Power Distribution System without UPQC.

The output results are getting from the design calculation of UPQC by using the above equations and that is tabulated in the following Table

Table 5:1 Output Parameters for Simulation of both power system without UPQC and with UPQC model

Parameters	Values
Source Voltage	11kV
Distribution Voltage	VLL= 400V or 230V per phase
System Frequency	50Hz
D-STATCOM, Filter Inductance, Lf	8mH
DC Link Voltage of Shunt inverter, V	700v
DC Link Capacitor, Cdc	3000μF
DVR, Filter Inductance, L f	70.585mH
Turn ratio of Transformer	3:5
Impedance	638Ώ
Capacity of Transformer	0.5MVA

The case study area of the factory power distribution system source voltage 11kV is connected with 11kV/0.4kV step down transformer. The outgoing of the step down transformer distributes the voltage for the cane crushing plant. The systems have non-linear load. The modeling of the power system and its simulation without UPQC are shown in Fig. 5.1.-5.2. According to the simulation result, the voltage sag and current harmonic distortion of the power system was occurred. Additional the modeling of the power system and its simulation with UPQC compensation are shown in Fig. 5.3 – 5.7 as the following.

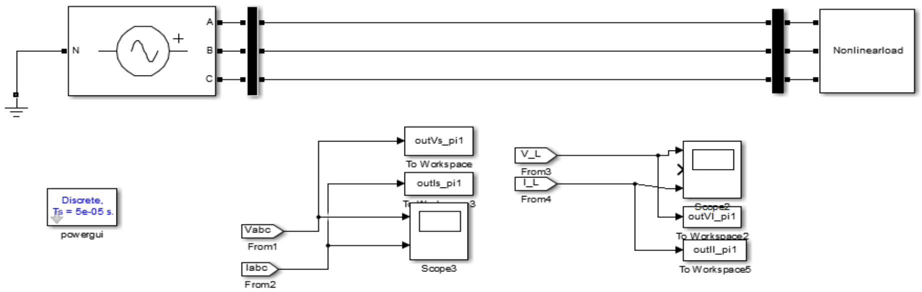


Figure: 5.1.Simulation of power distribution system without UPQC

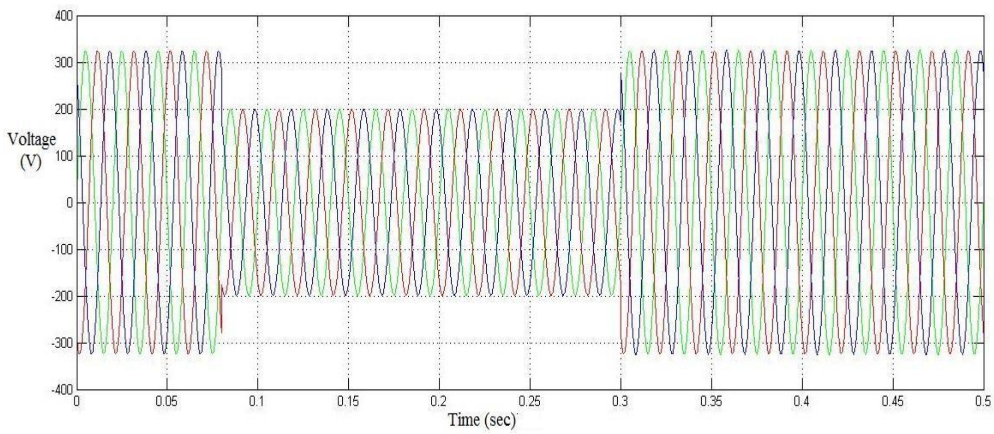


Figure.5.2. simulation result of system Source voltage without UPQC during sag

As given in Figure.5.2. It is the source voltage during sag. Sag time interval is 0.08 sec to 0.3 sec. The sag is due to voltage unbalance that may be caused due to faults.

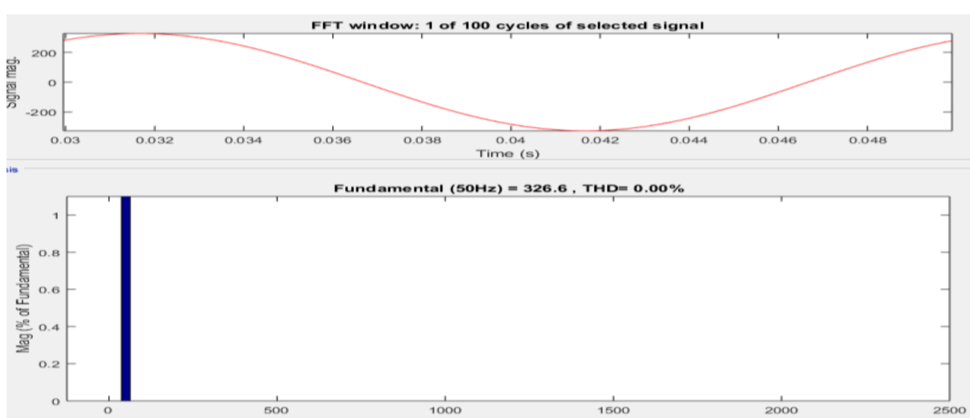


Figure.5.3.Simulation of source voltage and its harmonics without UPQC

From the simulation results, the source voltage is sinusoidal shape there is no harmonic distortion even though voltage sag is occurs.

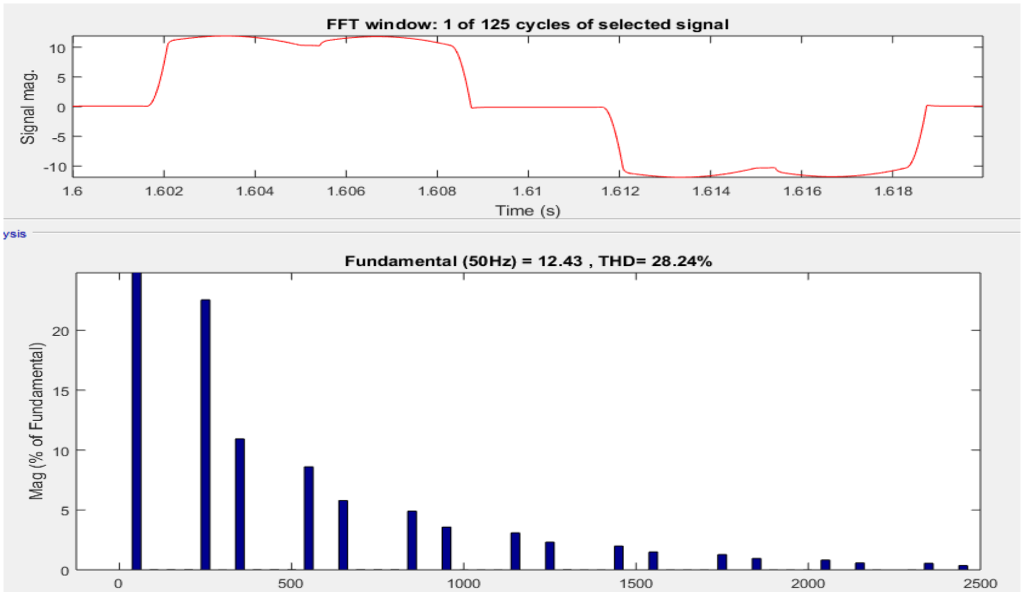


Figure5.4.Simulation of source current distortion and its harmonics without UPQC

From the simulation results, the source current harmonic distortion due to voltage sag is 28.24% the source current distortion is poor such as 45% and power factor is also poor, about 0.81p.u due to the sag of source voltage.

5.2. Simulation Results of Power Distribution System with UPQC

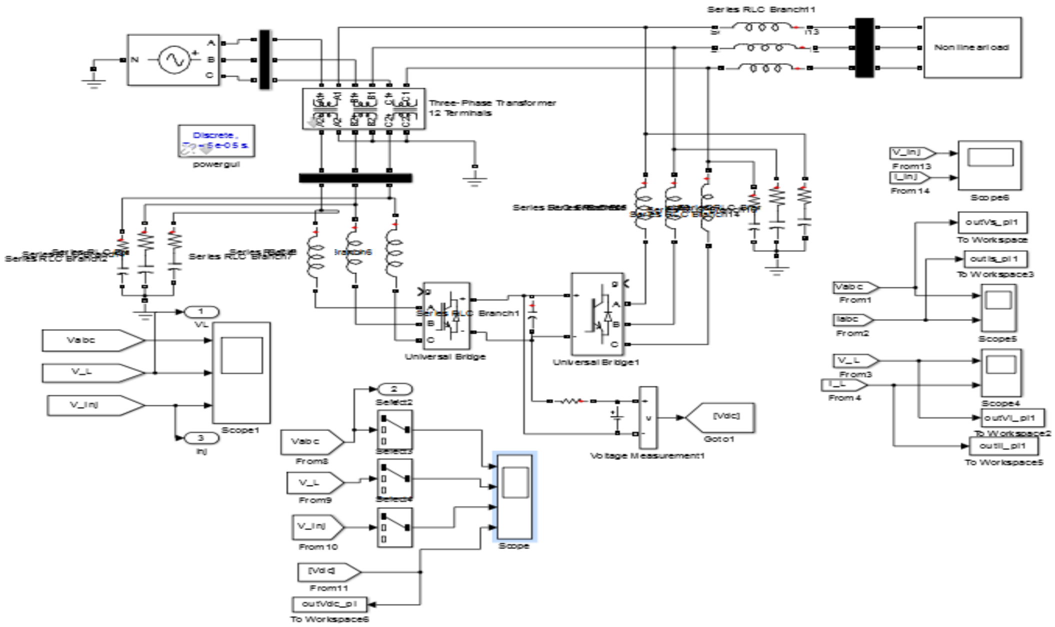


Figure: 5.5. Simulation of Power system with UPQC for compensation of voltage sag and current Harmonic

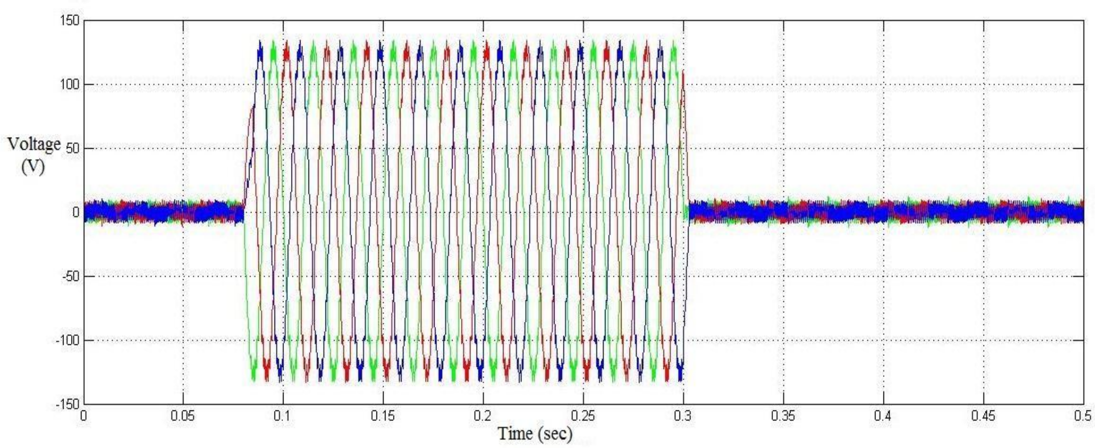


Figure.5.6.The compensating voltage injected by UPQC .

The injected voltage time interval is 0.08 sec to 0.3 sec. By injecting voltage in this time interval the load side voltage is made completely balanced and sinusoidal.

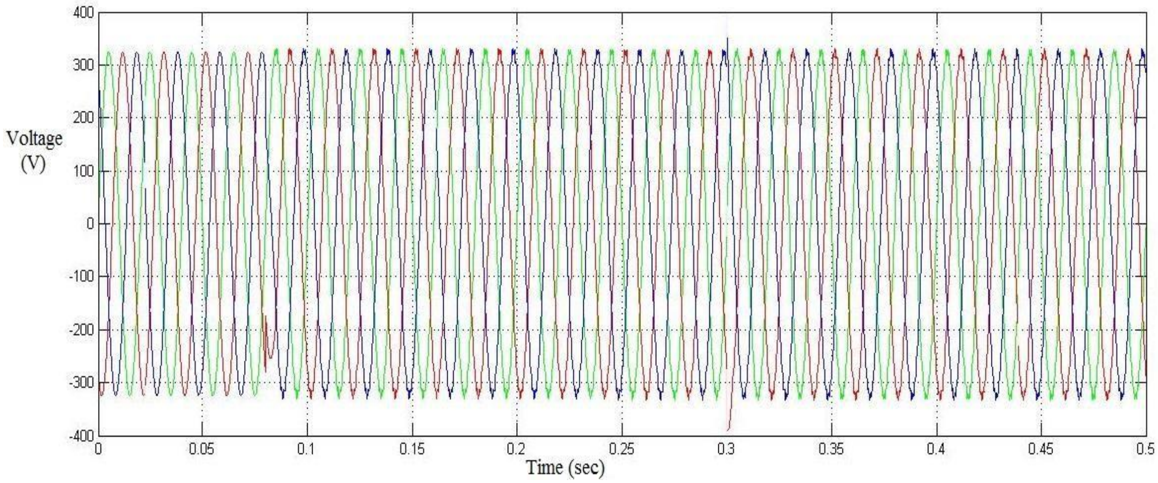


Figure.5.7. Load voltage with UPQC

The Figure shows the load voltage of UPQC that is completely sinusoidal and perfectly balanced. The sag at time interval 0.08 sec to 0.3 sec is removed by the help of UPQC. The load voltage becomes free from all unbalance which was caused due voltage dip.

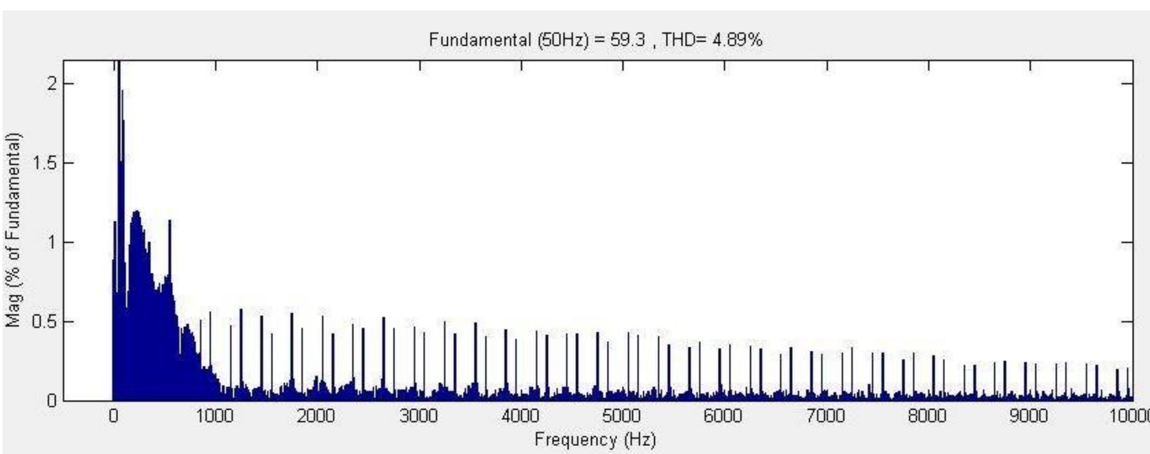


Figure.5.8.THD of source current after using UPQC

The figure shows the THD of current voltage is shown. The THD in source current is 4.89% after use of UPQC which is not beyond IEEE standard 5%. So we come to know that after applying UPQC the harmonic contents in current is reduced.

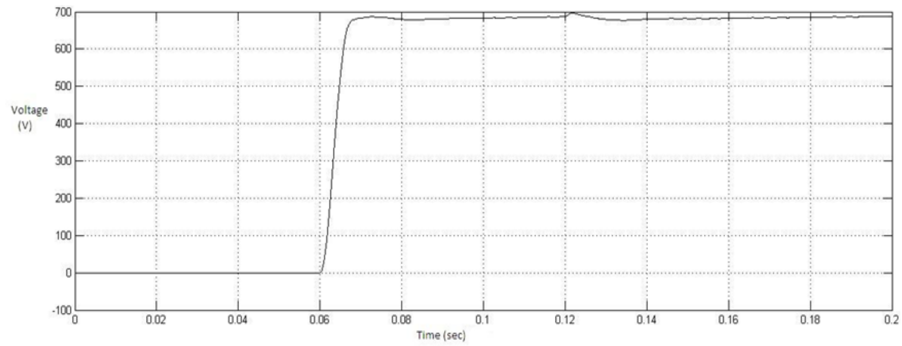


Figure.5.9. Capacitor Voltage

In Figuere.5.9 capacitor voltage is given. After 0.06 sec capacitor voltage rises and become constant. Because after that series APF starts operating; and DC capacitor always tries to follow reference DC voltage which is 700 V.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATION

6.1 Conclusions

Unified quality conditioner was studied and investigated in this thesis for power quality enrichment. UPQC is a type of advance hybrid filter which uses series APF for removal of voltage related problems like voltage dip/rise, fluctuation, imbalance and shunt APF for removal of harmonics concerning with current problems. What types of problems are there in power quality was studied and discussed. UPQC system is developed and discussed in detail.

The Simulink models of power system without UPQC and with UPQC are developed.

The simulation is done and voltage sag is eliminated and voltage drawn from source is completely sinusoidal. The THD of source voltage is within the limit that is 5%.

6.2. Recommendation

The UPQC model can be enhanced and enriched to terminate the power quality problems in a power osystem. The various ways for doing that:-

- UPQC model can be established for the non-linear load and unstable voltage.
- We can connect wind turbines, solar energy system that is renewable source of energy to UPQC to get improved power in consumer ends during serious conditions.
- The prototype of this UPQC model can be established in laboratory.
- UPQC model can be established for three phase four wire system for the non-linear load and unstable voltage.
- Here the UPQC model developed was right shunt UPQC, further we can develop model for left shunt UPQC.

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