HAWASSA UNIVERSITY

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Department of Electrical and Computer Engineering

Harmonic Impact of Adama-II Wind Power Generation (150MW) on Distribution Network and Mitigation Using Harmonic Filters

By

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In

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We the under signed Board of examiners of the final open defense by Megersa Tesema Under the title of **Harmonic Impact of Adama-II Wind Power Generation (150MW) on Distribution Network and Mitigation Using Harmonic Filters** and recommend that it be accepted as fulfilling the thesis requirement for the degree of M.Sc in power system and energy Engineering.

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DECLARATION

I MegersaTesema, declare that this thesis is my own original work and that it has not been presented before and will not be presented to any other University for similar or any other degree award.

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CERTIFICATION

The thesis/project entitled, Study of **Mitigation of Harmonic Impact of Adama-II Wind Power Generation (150MW) on Distribution Network and Mitigation Using Harmonic Filters** submitted by Megersa Tesema to Hawassa University in partial fulfillment of the requirements for the degree of M.Sc. in Electrical Power & Energy Engineering is hereby recommended to be presented for final evaluation and examination.

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ABSTRACT

This paper presents the studies of the harmonic impact of a significantly medium scale Adama-II wind power generation of 150MW on distribution network system. This 150MW of Adam wind power generation-II is modeled in detail using the commercial grade MATLAB version 2018, which is validated through load flow studies conducted by MATAB software. This research investigates and mitigates the harmonic distortion levels in distribution networks. In this research Adama-II wind power has been selected. Measurements and calculations had been done considering the distribution transformers which supply power to customer. The Total Harmonic Distortion of Current (THDi) has been the main focus for the study and it is compared with the power quality standards stated on IEEE-519 and IEC-61000.Results of the research include the total harmonic distortion of voltage levels in study area network is above 50.6% in the distribution network. This value is high as compared to IEEE-519 and IEC-61000 standards (the standards in which appalling harmonic limits in power system and estimates the harmonic indices at the point of interfaces through mutual agreeable methods). One of the most economic and effective ways to mitigate harmonics in power systems is through the use of passive tuned harmonic filters. In this thesis a single-tuned, high pass, double tuned and C-type filters were designed as a mitigating technique and observed to reduce the harmonic distortion levels to acceptable values (the values of the convention agreement of harmonic magnitude in power system should be ≤ 3%). The current and voltage distortion caused by the non-linear loads is investigated with Primary data from the Adama wind-II wind power farm generation company. The simulation is verified the system output to observe the extent of the wave shapes of the existing system with and without the addition of designed filters.

***Key words: -** Distribution systems, frequency scan, harmonics, network resonance, medium scale Adama-II wind power generation, total demand distortion, voltage distortion, current distortion and total harmonic distortion.*

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LIST OF ABRIVATION

AC	Alternating Current
Ci	Cost initial
COE	Cost of energy
CFL	Compact Florescent Lamp
DC	Direct Current
DFT	Discrete Fourier Transform
DP	Distributive Power
EEPCo	Ethiopian Electric Power Corporate Organization
Egen	Annual Energy Generation
EMC	Electromagnetic Interface Capability
ER	Engineering Recommendation
LCOE	Least Cost of Energy
MVAb	Base Megavolt Ampere
PCC	Point of Common Coupling
S.C.R	Short Circuit Ratio
TCOST	Total Cost
TDD	Demand Total Harmonic Distortion
TMY	Typical Metrological Year
UK	United Kingdom
USA	United States of America
MATLAB	Matrix Laboratory
EV	Energy band gap
FFT	Fast Fourier Transform
Fu	Filter Utilization
HVdc	High Voltage Direct Current
IEC	International Electron Commission
IEEE	International Electrical Engineering
LV	Low voltage network
MV	Medium voltage network
ITHDi	Current Total Harmonic Distortion
Pf	Power Factor
PWM	Pulse Width Modulation
Res	Renewable Energy Sources
USD	United State Dollar
THD	Total Harmonic Distortion
VTHDv	Voltage Total harmonic. Distortion
WTGS	Wind Turbine generator

LIST OF SYMBOLS

A	Gain Total Cost
A_S	Gain of filter Size
Ib	Base Current
KVb	Base Kilo-Volt
Bf	Sustenance
C	Capacitance
Ft	Fuel Cost
H_h	Voltage Harmonic Order
I_h	Current Harmonic Order
Isc	Short circuit current
Gf	Conductance
Kcl	Loss Factor Capacitor
I_L	Current at the Customer Load
h	Harmonic Order
K	Shape of Parameter of Wei-bull
L	Network Inductance
Ltr	Transformer Inductance
M	Damped Arm Component
Mit	Fixed Maintenance Operation cost
n	Life time of Years
R	Resister
r	Annual discount
PA	Atmospheric Pressure
Rbc	Low Voltage Resister Terminal b to c
R_{CA}	High Voltage Resister Terminal c to a
Q	Quality of Filter
Rs	Cell internal Resistance
Pv	Equivalent Cost and Pressure Value
R_{AB}	High Voltage Resister Terminal a to b
Rab	Low Voltage Resister Terminal a to b
R_{BC}	High Resister Terminal b to c
ρ	Air Density
η	Efficiency
$\tilde{\alpha}$	Turn ratio of Transformer
δ	Frequency dilation
δ_m	Largest Expected Deviation
Xtr	Transformer reactance
Ysn	System admittance
Ur	Turbine rated Speed
S	Filter size
Uc	Turbine Cut-in Speed
Ut	Total Cost
Uu	Cost of Energy Loss per Kilowatt hour
Zs	System Impedance
Up	Turbine Cut-out Speed
Rca	Low Voltage Resister Terminal c to a
Rtr	Transformer Resistance
R_{CA}	High Voltage Resister Terminal c to a

CHAPTER ONE

1. INTRODUCTION

1.1 BACKGROUND

Power electronic-based Electrical Energy sources in the network such as: wind farm and any other micro grid system generate harmonics and injects into the existing power network. Distribution/transmission networks are often capacitor shunt compensated targeting voltage regulation and power factor compensation. The combination of overhead line inductances and shunt capacitors together with cable capacitances resonates at certain frequencies implying occurrence of network resonances. Then following these frequencies relatively higher impedance will appear across the network and which measured as peak values in the frequency scan of network impedance.

If injected harmonics comes close or align with any one of the frequencies, of the resonant modes, voltage magnitudes at the corresponding harmonic frequencies are going to be amplified resulting equipment damage or cause protective relay failure variations in resonant modes were also reported with changes in transmission and sub-transmission network loading conditions and short circuit levels. The harmonic impact of a medium-scale wind farm on the distribution network systems is reported in and. Harmonic amplification due to network resonance is a potential scenario to consider which limits wind power connectivity in distribution feeder. IEEE 519 Standard recommends that a general harmonic analysis procedure be adopted as part of the system planning process whenever known small scale harmonic sources exist on a system or significant dispersed generators are being proposed in a distribution network.

This study has been performed with the integration of specific local distribution, transmission, a wind farm developer, and a wind farm operator harmonic generation. The main focus is determining the harmonic distortion introduced into the power utility from medium scale wind farms are generate harmonics distortion at different operating level of the load demands under various operating condition.

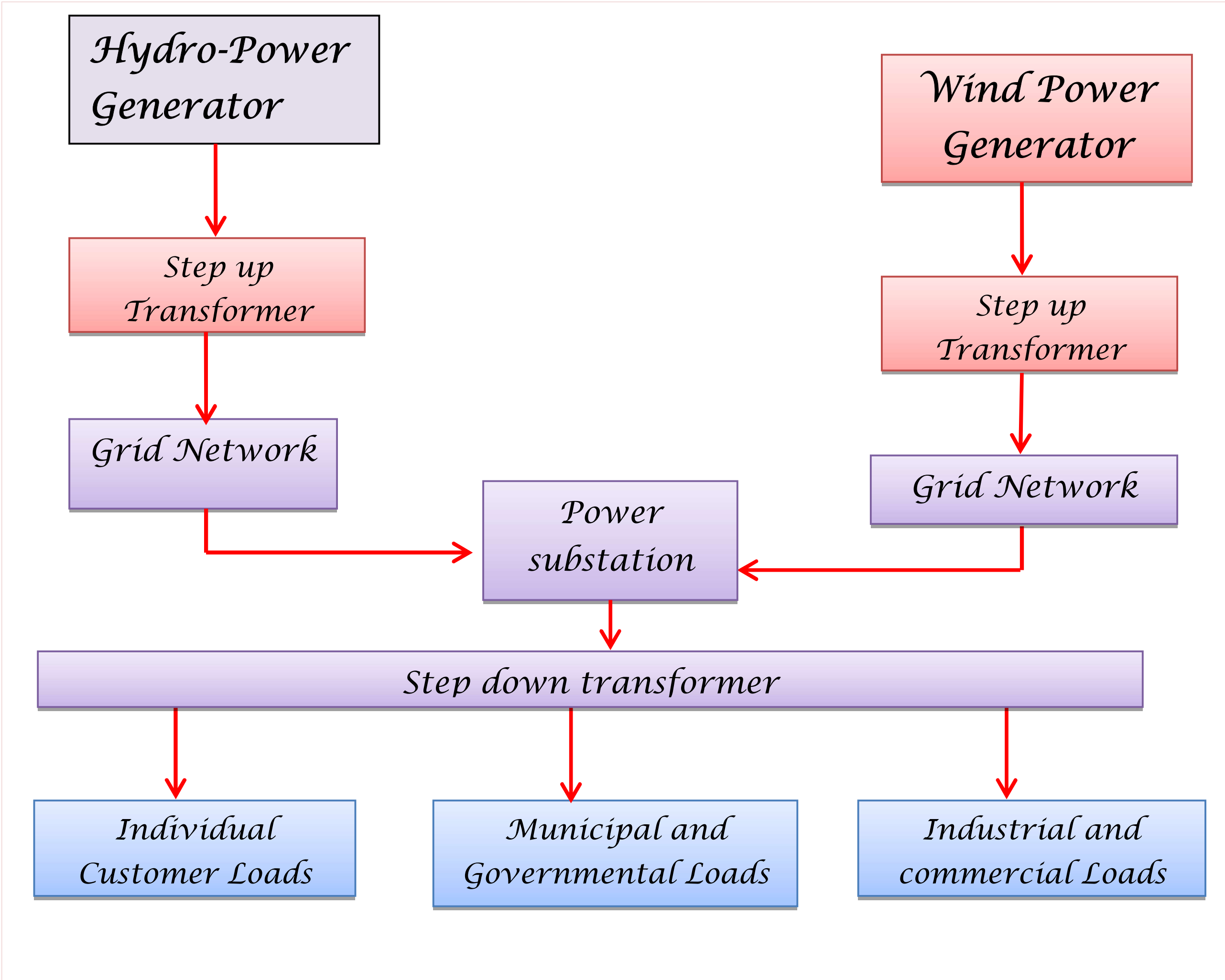


Figure. 1.1. Block representation, for Elements within a power network and the Connection between Source and end Consumers Including the Intermediate Interfaces.

As shown the figure 1.1 the hydro-power generation and Adama-II wind power generation had been studied with all interfacing elements of individual customer loads, municipal loads, Governmental loads; industrial loads and commercial loads have been explained in block diagram elements. And, finally generated power is serving end users through all distribution power elements. However, sources (150MW) are served with feeder from a national grid for auxiliary purpose or in order to run plant elements and enable plant function properly, as shown in fig. 1.2.

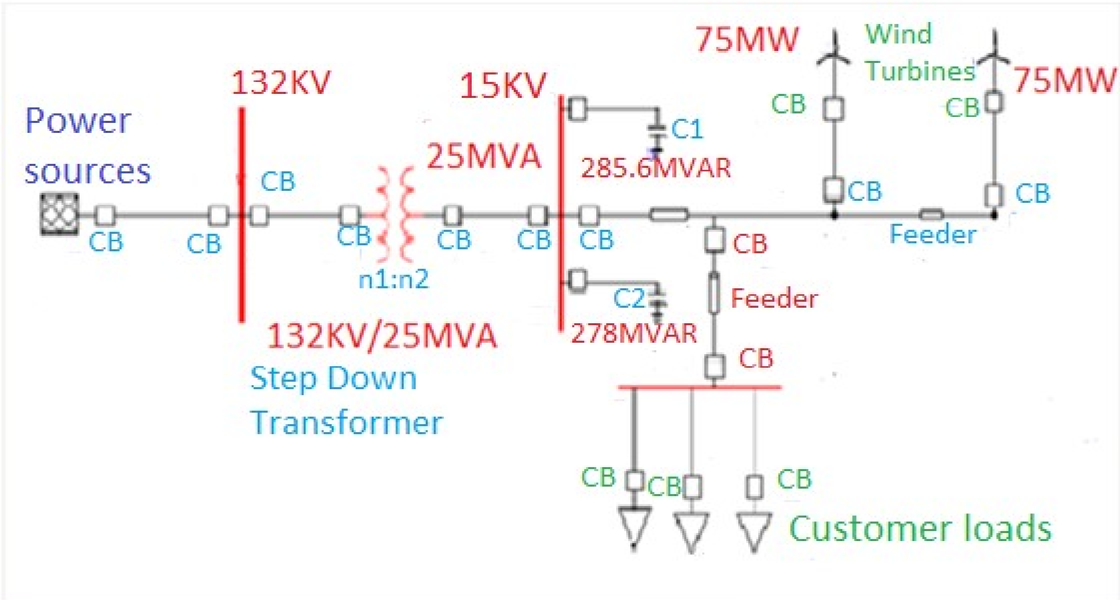


Figure.1.2. One-line diagram showing wind power system

Adama substation and Adama-II wind power generation of the single line diagram is connected in radial system and the power flow would be 33KV/25MVA step down transformer and 150MW wind power output. The transformer station has seven 15kV and four 33kVfeeders supplying Mojo, Sendafa, and Adama town domestic commercial and different industrial loads. The harmonic modeling of load is sensitive to load size and composition. It is difficult to establish a model based on theoretical analysis. The necessity of practical measurements on distribution points together with detailed information of the network is vital for the derivation of a realistic model. Although attempts to derive a model from measurements have been made, practical experience is still insufficient to guarantee the best representation. Therefore, harmonic studies often have to proceed with whatever information is available. The associated injection of harmonic currents into the distribution system may cause malfunction of harmonic-sensitive equipment if the injection of harmonic currents is allowed to reach excessive levels. The discrepancy, therefore, requires some form of power conditioning or conversion, normally implemented by power electronic circuitry that distorts the voltage and current waveforms. The behavior of circuits undergoing frequent topological changes that distort the waveforms cannot be described by the traditional single-frequency theory. In these cases, the steady state results from a periodic succession of transient states that require dynamic simulation. However, on the assumption of reasonable periods of steady-state behavior, the voltage and current waveforms comply with the requirements permitting Fourier analysis, and can, therefore, be expressed in terms of harmonic components. A harmonic is defined as the content of the function whose frequency is an integer multiple of the system fundamental frequency.

1.2. STATEMENT OF THE PROBLEM

Among all major problems related to a utility serving electricity to the public, accordingly (houses, industrial business....), is the quality of electric end users are forced to withdraw from the national grid network. Electricity quality can be explained in different forms relating to different parameters.

But, operational dynamicity of various elements operated inside a power plants generates harmonics or timely or in terms of its running phase uncontrolled amplitude fluctuation of sinusoidal electricity at a certain point along it path from source to end users.

Mentioning a typical existing experience regarding electric power quality problems, the public is facing, particularly of harmonics related challenges. As of the Engineering investigation determines, later after all the incidents, extended unresolved electricity power quality problem are identified as the one and only which takes all the accusation for the several damages encounters from the source up to the consumer ends in Adama town which causes interruption of water supply to the public, failure of equipment's which had been in service within hospitals and industries.

An electric technology had continued, presenting sophisticated and compact electrical modules for service as an integral component of a power network (from source up to consumer end). However, experiencing all the benefits, understanding every functional behaviors and technological poses associated with these incorporations, needs to be identified and defined as well, in order to pave a mechanism in compensation to all short comings. Commercial wind turbine technologies had been introduced in to service, as an alternate power source, since late 19's. And various technological improving had been made towards eliminating all the challenges it had brought with it, since.

Inverter interfaces wind turbine power sources with the rest of power system elements encompassing the utility or the national grid. And, in compliance to the service an inverter is designed for, an inverter seldom builds with the use of power electronic elements which exhibits a non-linear switching characteristic, whom and final introduces a harmonic voltage distortion. Harmonic distortions from wind power sources are utility nominal voltage disruption either by an increase, decrease or total failure of the nominal voltage since the detection of the inverter. Hence, undesired effects of wind farm electricity source could be sudden increase, decrease or total un-manageable distortion or voltage failure to the distribution network.

It is certain that the development of renewable energy source has a positive effect on the environment, even though these technologies had brought challenges, together. Regardless of its intended purpose, wind power turbine technology had a problem with its controllability, since its performances entirely dependent on the density of wind speed, it is exposed to. To avoid these dependencies and obtain optimum performance efficiency, numerous power electronic devices had been integrated, through the development of wind power extraction technologies. And, in their very nature power electronic devices introduces a voltage distortion with their switching mechanism, operation. Similarly, harmonic distortion from wind turbines is explained like that of power electronic device electricity converters, uncontrolled increase or decrease of nominal voltage level or total distribution voltage failure following introduction of wind electricity supply to the utility grid.

And, in the way this specific target electricity (150MW wind power generation) source were identified having all the above characteristics and which all these in return would result:

1. Excessive heating:

   Generation of unwanted heat within the network is one among those occurrences from system harmonic distortion. As devices serving on the power network or connected equipment's had their own respective design rating in which they can withstand utmost. And, exceeding these could damage or destroy expensive elements within the utility, while exposed.

   These damages will take different faces:

   - unnecessary, excessive expenditure, for replacing failed components

- ❖ Service reliability issue

2. Frequent failure of protection devices:

Protection devices are vital for power utility network to operate, properly. Power system element damages are not only from harmonics, always, but from various origins as well. And, protection devices had a significant role up on fusing them self's and avoid destruction of expensive power system devices and customer connected equipment's. While these protection devices exposed to sudden fluctuation, beyond halting service, leaks could result damage to consecutive expensive equipment's.

Major reasons which are identified as a cause for poor power quality network can be:

- ❖ The increasing incorporation and utilization of non-linear devices within the power network as the integral component.
- ❖ Inefficient plant operation due to harmonics in return plays a significant role in poor quality electricity.
- ❖ Assimilated or Pseudo real power injected from harmonics generated due to integration of such devices which identified as causes for harmonics.
- ❖ Micro grids like a geothermal power, Static capacitor, wind, diesel power generators and their major components supply harmonics to the utility networks.

Therefore, all the above narration describes how it is important to develop or design a mechanism to control or possibly, completely filter voltage harmonics from these two particular electricity sources, under consideration. And, it is already been studied in depth a mechanism by which harmonics from these sources is navigated on to the network and creates all the problems. Furthermore, above learning and developing a mathematical model for the pattern, an efficient filter is designed and simulated for its successful mitigation.

1.3. OBJECTIVE

1.3.1. GENERAL OBJECTIVE

The main objective of this study aimed at is to design and prove an Engineering mechanism to determine and mitigate harmonics from 150 MW wind power generator in to the distribution network through analysis and modeling tools currents in use of MATLAB software.

1.3.2. SPECIFIC OBJECTIVES

- To show the wave form of the voltage and current distortion with and without the addition of designed harmonic filters.
- To simulate the distribution network and evaluate the total harmonic distortion.
- To develop a model of the network impedance versus harmonics plots without capacitor and base operating case with 800KVAR.
- To investigate the harmonic distortion either using measurement or computer simulation.

1.4. RESEARCH SCOPE AND LIMITATION

As already been underlined through the previous sections, as the study targets alleviating the problems identified up to the most possible level, and in doing this the study paper determines a certain bounded reach's encompassed under the particular case study, the scope, and within this scope, too, among all the existing harmonics within the system a specific portion of these harmonics level are covered, which is the limitation. And these are listed as follow:

1.4.1. SCOPES

This thesis is focused on analyzing the content of harmonic impact of 150MWwind power generation on utility network and real power injection on cloudy and sunny day, wind power generation about 3m/s to 15m/s day and night time. The result is used to propose the fundamental harmonic injection from the solar farms and wind power generation to reduce the content of harmonics in the system and satisfy the IEEE-519 standard limit.

1.4.2. LIMITATIONS

As this research is very essential it needs huge effort in collecting the real and exact data of demand of power. Also requires long period of time for designing and making cost-benefit analysis. As far distance of the wind power generation, it is difficult to continuously update data assessment. The duration I have to finish the research has no problem in comparison with this large and essential research completion.

The system with hardware implementing is difficult, because of the components are not available in laboratory and they are too expensive to buy it. In addition to this, the shortage of material like: computer, library books, internet accesses, financial problems, lack of sufficient data written documents, lack of willingness from respondents to give available material and relevant information.

CHAPTER TWO

2. LITERATURE REVIEW

Harmonic modeling and simulation has been a subject of many researches. A number of different models have been proposed to represent harmonic sources. The most common model for harmonic sources is in the form of harmonic current source, specified by its magnitude and phase. The data can be obtained from an idealized theoretical model or from actual measurements. In many cases, the measured waveforms provide a more realistic representation of the harmonic sources to be modeled. The harmonic simulation can be in frequency-domain, time-domain, or both.

Johan Lundquist [8] presented a thesis dealing with the sources of distortion (loads) and the interaction between those and the propagation of the distortion in the power system. Effects on the power system were also studied, e.g. additional losses, harmonic resonance and related financial costs to this.

AngulaNashandiand Gary Atkinson-Hope [9] presented the harmonic contribution from CFL (Compact Fluorescent Lamp) in a network that supplies mostly residential customers and some commercial customers. The CFLs were represented as harmonic current sources for harmonic simulations. The analysis used Super Harm software to predict the distortion level on a distribution system. Results obtained were compared to the IEEE-519 limits.

Sharmistha Bhattacharyya, Johanna Myrzik, SjefCobben and Jasper van Casteren [10] made a research to investigate the cumulative harmonic current characteristics of a large number of single-phase electronic loads. A complete analytical model for the most common load types is derived. This model is then used to investigate the impact of interaction due to shared source impedance, variation in power level, and variations in circuit parameters, on individual and cumulative current harmonics. They showed that there is significant attenuation of current harmonics above the 3^{rd} multiple when a number of identical loads, such as televisions and desktop computers, share common source impedance. The THD of current in this case is approximately one-half of that obtained using superposition of individual load currents. However, the 3^{rd} harmonic, which is responsible for most harmonic-related neutral conductor overloading problems, experiences only slight attenuation (i.e., 0.8 - 0.9). Since the 3rd and 5th harmonics show little phase cancellation, the THD of the summed current is only slightly less than that obtained by using superposition. The key findings of this paper are that: (1) Diversity and attenuation are very important factors in predicting the behavior of distributed single-phase power electronic loads, especially for the higher-order harmonics, and that (2) Due to these two factors, the commonly-used fixed current injection method, using arithmetic sums of harmonic current magnitudes, can significantly overestimate the cumulative harmonic currents produced by these loads. The attenuation and diversity factors calculated in this paper give an indication of how much the commonly-used fixed current injection method, using arithmetic sums of harmonic current magnitudes, can overestimate the cumulative harmonic currents produced by distributed single-phase power electronic loads. For this reason, they recommended that the values obtained in their research to be applied to the arithmetic sums.

J.H.C. Pretorius, [11] presented the effect and interaction of mixed MV and LV linear and non-linear loads on the level of harmonic distortion. The paper used software called DIGSILENT Power Factory to simulate the MV and LV customer installation. Various household devices were measured and the harmonic spectrums of the connected devices obtained from measurement were fed into the software to perform harmonic simulations. Furthermore, a case study was carried out to evaluate the total current harmonic distortion level at a customer's installation when the grid voltage is polluted with a specific order of harmonics. The analysis of this paper shows that the use of non-linear loads in the household activities has significant influence on the network's harmonic current pollution level. The combined effects of various non-linear MV and LV devices (home appliances, etc) attenuate the total harmonic current distortion in the network mainly because of phase cancellation and diversity effects. In this study, it was found that the total current harmonic distortion level at the customer's installation is around 12% when the customer has mixed loads.

CHAPTER THREE

3. POWER QUALITY DESCRIPTION

With the intent to accommodate or assure electricity generation in accordance with demand, ranging from low to high power consumers, and reaching communities at a distant location from the source, up grading, capabilities of supplying utility from electricity its much originated feature were a must. Following all these pushes, immediate solutions brought challenges together, and beyond service reliability, good quality of circulating electricity became a great concern even during early periods, particularly of harmonics.

In order to develop an optimum solution for such identified problems several research findings had been applied and those were able to introduce a certain mechanism to improve power distribution quality. Whereas, Harmonics also had broader range of spectrum in its occurrence and effect, a general or one solution for a problem named harmonics were a quite difficult, yet. And in finding a solution to a problem identified in reviewed as well as incorporated concepts useful in their terms while referring numerous previous related works.

3.1. HARMONIC DEFINITION AND REPRESENTATION

Harmonics is a more important issue for the industry, commercial and home consumer now than it was a few decades ago. Modern consumers and commercial equipment's are not designed to cope with the increasing levels of power distortion or pollution. The discussion of the harmonics will start with the definition of harmonics, the discussion of theory of harmonics, representation, causes and other power quality disturbances. Harmonics are a sinusoidal component of periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency, fundamental frequency of 50Hz in Ethiopia or 60Hz in USA.

The equation representing harmonic frequency is given by:

$$f_h = 50Hz * h \tag{3.1}$$

Where h is harmonic order. In the power system, these harmonics interact with fundamental frequency wave and each other to produce a distorted waveform as shown in figure 3.1.

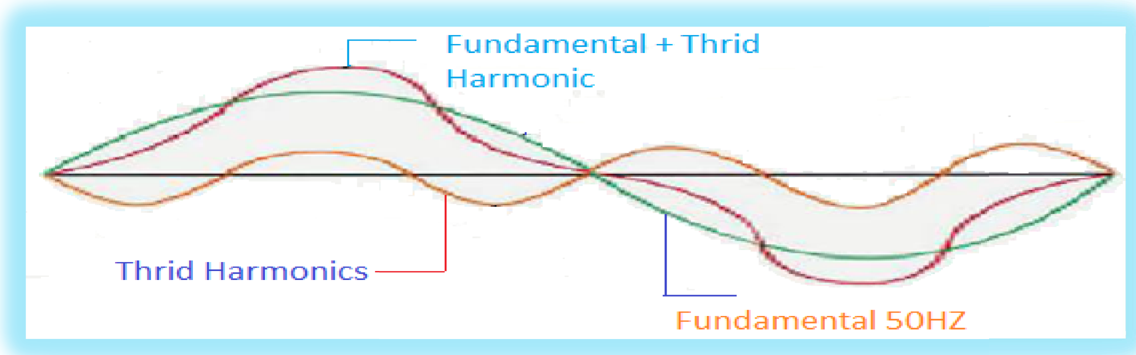


Figure 3.1: Distorted waveform composed of fundamental and 3rd harmonic.

In order to determine the relative distortion due to harmonics on a power system, the term Total Harmonic Distortion (THD) is used. It is a measure of the amount of distortion harmonics cause on the system voltage, expressed as a percentage of the fundamental. Both voltage and current waveform distortion may be represented by THD, with Total Harmonic Voltage Distortion (THVD) and Total Harmonic Current Distortion (THCD) used at times to distinguish between the two. According to IEEE Standard 519-1992 THD is defined for voltage and current signals, respectively, as follows:

$$THD_V = \frac{\sqrt{\sum_{h=2}^{\infty} V_h^2}}{V1} \text{ x } 100\% \tag{3.2}$$

$$THD_I = \frac{\sqrt{\sum_{h=2}^{\infty} I_h^2}}{I1} \text{x}100\% \tag{3.3}$$

Where, V1 and I1 are the RMS value of the fundamental, and V_h and I_h is the RMS value of the h-order harmonic component.

Total Demand Distortion (T_{DD}): Current distortion levels can be measured using the THD, but in the case of light loading, current THD will show at a high level due to the small current in the THD denominator. This measurement is misleading, because the high THD in the case of light loading is of no significant concern to the system. For example, many adjustable-speed drives will exhibit high THD values for the input current while operating at very light loads. This shouldn't be a concern, because the magnitude of harmonic current would be low in this instance, even though its relative current distortion is quite high. However, T_{DD} uses the maximum current load in order to calculate the current distortion level; it is similar to calculating the THD, but the maximum current load is used rather than the fundamental current in the T_{DD} denominator.

$$T_{DD} = \frac{\sqrt{\sum_{h=2}^{\infty} I^2}}{I_l} \tag{3.4}$$

where, I_L is the RMS value of maximum load demand

Harmonic Phase Sequences: For a balanced three-phase network with three-phase non-linear loads, harmonic current or voltage has phase sequences. Equations (3.5) until (3.7) describe the equation for each phase for the first three harmonics.

$$i_a(t) = I_1 sin(\omega t + \theta_1) + I_2 sin(2\omega t + \theta_2) + I_3 sin(3\omega t + \theta_3) \tag{3.5}$$

$$i_b(t) = I_1 sin\left(\omega t + \theta_1 - \frac{2\pi}{3}\right) + I_2 sin\left(2\omega t + \theta_2 - \frac{4\pi}{3}\right) + I_3 sin\left(3\omega t + \theta_3 - \frac{6\pi}{3}\right) \tag{3.6}$$

$$i_c(t) = I_1 sin\left(\omega t + \theta_1 + \frac{2\pi}{3}\right) + I_2 sin\left(2\omega t + \theta_2 + \frac{4\pi}{3}\right) + I_3 sin\left(3\omega t + \theta_3 + \frac{6\pi}{3}\right) \tag{3.7}$$

Where: I_h is the h^{th} current harmonic magnitude, ω is the fundamental frequency, θ_h is the h^{th} harmonic phase angle, and h = 1, 2, 3….N.

Current magnitude of all phases for all harmonic frequencies is equal for a balanced system. Looking at equations (3.5), (3.6) and (3.7), the first harmonic or the fundamental is positive sequence since $i_b(t)$ lags $i_a(t)$ by 120^0 and ic(t) leads ia(t) by 120^0.The second harmonic is negative sequence since and $i_b(t)$ leads $i_a(t)$ by 120^0 and ic(t) lags ia(t) by 120^0 . The third harmonics is zero sequence since $i_b(t)$ and $i_c(t)$ are in phase with ia(t). The sequence pattern for each harmonic order is shown in above equation. Harmonics such as the 7th, which "rotate" with the same sequence as the fundamental, are called *positive sequence*. Harmonics such as the 5th, which "rotate" in the opposite sequence as the fundamental, are called negative sequence.

3.2. INTRODUCTION OF HARMONIC ANALYSIS

The voltage and current waveforms at points of connection of nonlinear devices can either be obtained from appropriate transducers or calculated for a given operating condition, from knowledge of the devices' nonlinear characteristics. In 1822 J.B.J. Fourier postulated that any continuous function repetitive in an interval T can be represented by the summation of a d.c. component, a fundamental sinusoidal component and a series of higher-order sinusoidal components (called *harmonics*) at frequencies which are integer multiples of the fundamental frequency. Harmonic analysis is then the process of calculating the magnitudes and phases of the fundamental and higher-order harmonics of the periodic waveform. The resulting series, known as the Fourier series, establishes a relationship between a time-domain function and that function in the frequency domain. The Fourier series of a general periodic waveform is derived in the first part of this chapter and its characteristics discussed with reference to simple waveforms. More generally, the Fourier transform and its inverse are used to map any function in the interval from $-\infty$ to ∞, in either the time or frequency domain. The Fourier series therefore represents the special case of the Fourier transform applied to a periodic signal. In practice, data is often available in the form of a sampled time function, represented by a time series of amplitudes, separated by fixed time intervals of limited duration.

When dealing with such data, a modification of the Fourier transform, the discrete Fourier transform (DFT), is used. The implementation of the DFT by means of the so-called Fast Fourier transform (FFT) forms the basis of most modern spectral and harmonic analysis systems. The voltage and current waveforms captured from the power system, however, may contain transient or time-varying components. Even stationary signals when viewed from limited data (due to finite sampling) will introduce errors in the frequency spectrum of the signal. A variety of techniques have been developed to derive the frequency spectrum under those conditions. The chapter ends with a brief review of these alternative techniques.

3.3. FOURIER SERIES AND COEFFICIENTS

The Fourier series of a periodic function $\mathbf{x}(\mathbf{t})$has the expression of: -

$$x(t) = a_o + \sum_{n=1}^{\infty} an \cos\left(\frac{2\pi nt}{T}\right) + bn \sin\left(\frac{2\pi nt}{T}\right) \qquad (3.8)$$

This constitutes a frequency-domain representation of the periodic function. In this expression a_0 is the average value of the function *x(t)*, while *an* and *bn*, the coefficients of the series, are the rectangular components of the n^{th} harmonics. The corresponding n^{th} harmonic vector is with magnitude.

$$A_n < \emptyset_n = an + jbn \tag{3.9}$$

$$An = \sqrt{a_n^2 + b_n^2} \tag{3.10}$$

and phase angle

$$\Phi_n = \tan^{-1}\left(\frac{bn}{an}\right) \tag{3.11}$$

For a given function *x(t)*, the constant coefficient, a_o, can be derived by integrating both sides of equation (3.8) from $\frac{-T}{2}$ to $\frac{T}{2}$(over a period T):

$$\int_{\frac{-T}{2}}^{\frac{T}{2}} X(t)dt = \int_{\frac{-T}{2}}^{\frac{T}{2}} aodt + \sum_{n=1}^{\infty}\left[an \int_{\frac{-T}{2}}^{\frac{T}{2}} \cos\left(\frac{2\pi nt}{T}\right) dt + bn \int_{\frac{-T}{2}}^{\frac{T}{2}} \sin\left(\frac{2\pi nt}{T}\right) dt\right] \tag{3.12}$$

The first term on the right-hand side equals Ta_0, while the other integrals are zero.

hence, the constant coefficient of the Fourier series is given by

$$ao = \frac{1}{T}\int_{\frac{-T}{2}}^{\frac{T}{2}} x(t)\, dt \tag{3.13}$$

$$\int_{\frac{-T}{2}}^{\frac{T}{2}} x(t)\left(\frac{2\pi nt}{T}\right) dt = \int_{\frac{-T}{2}}^{\frac{T}{2}}\left[ao + \sum_{n=1}^{\infty} an \cos\left(\frac{2\pi nt}{T}\right) + bn \sin\left(\frac{2\pi nt}{T}\right)\right] * \cos\left(\frac{2\pi nt}{T}\right) dt$$

$$= ao \int_{\frac{-T}{2}}^{\frac{T}{2}} \cos\left(\frac{2\pi nt}{T}\right) dt + \sum_{n=1}^{\infty}\left[an \int_{\frac{-T}{2}}^{\frac{T}{2}} \cos\left(\frac{2\pi nt}{T}\right) * \cos\left(\frac{2\pi nt}{T}\right) dt + bn \int_{\frac{-T}{2}}^{\frac{T}{2}} \sin\left(\frac{2\pi nt}{T}\right) * \right.$$

$$\cos 2\pi ntTdt \tag{3.14}$$

The first term on the right-hand side is zero, as all are the terms in *bn* since in ($2\pi nt/T$) and cos($2\pi mt/T$) are orthogonal functions for all n and m. Similarly, the terms in *an is* zero, being orthogonal, unless $m = n$. In this case, equation (3.11) becomes:

$$\int_{\frac{-T}{2}}^{\frac{T}{2}} x(t)\cos\left(\frac{2\pi nt}{T}\right) dt = an \int_{\frac{-T}{2}}^{\frac{T}{2}} \cos\left(\frac{2\pi n}{T}\right) dt = \frac{an}{2}\int_{\frac{-T}{2}}^{\frac{T}{2}} \cos\left(\frac{4\pi nt}{T}\right) dt + \frac{an}{2}\int_{\frac{-T}{2}}^{\frac{T}{2}} dt \tag{3.15}$$

$$an = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)cos\left(\frac{2\pi nt}{T}\right)dt \;\; for\, n-1 \rightarrow \infty \quad (3.16)$$

$$bn = \frac{2}{T}\int_{-\frac{T}{2}}^{\frac{T}{2}} x(t)sin\left(\frac{2\pi nt}{T}\right)dt \;\; for\, n-1 \rightarrow \infty \quad (3.17)$$

$$ao = \frac{1}{\pi}\int_{-\pi}^{\pi} x(\omega t)d(\omega t) \quad (3.18)$$

$$an = \frac{21}{\pi}\int_{-\pi}^{\pi} x(\omega t)cos(n\omega t)dt \quad (3.19)$$

$$bn = \frac{21}{\pi}\int_{\pi}^{\pi} x(t)sin(n\omega t)dt \quad (3.20)$$

$$x(t) = ao + \sum_{n=1}^{\infty}[ancos(nwt) + bnsin(nwt)] \quad (3.21)$$

3.4. FACTORS INFLUENCING THE DEVELOPMENT OF STANDARDS

The development of harmonic standards is centered on the following issues:

- Description and characterization of the phenomenon;
- Major sources of harmonic problems;
- Impact on other equipment and on the power system;
- Mathematical description of the phenomenon using indices or statistical analysis to provide a quantitative assessment of its significance;
- Measurement techniques and guidelines;
- Emission limits for different types and classes of equipment;
- Immunity or tolerance level of different types of equipment;
- Testing methods and procedures for compliance with the limits;
- Mitigation guidelines;

The standards themselves may be either system standards, connection standards or, more usually, some combination of the two. In a system standard the emphasis is on the levels of harmonics that can be tolerated in the system, with little or no reference within the body of the standard to the source of harmonics. Details of the harmonic sources, and their likely influence on system harmonic content, are usually given as associated material in appendices. The limits may be expressed as absolute levels of current or voltage, which may not be exceeded, or as incremental limits allowing small changes to the harmonic source with limited consideration of system effects. The former approach usually permits the connection of certain types and ratings of distorting loads (e.g. converters) to the system without reference to existing harmonic levels. With higher converter ratings the existing harmonic content needs to be established prior to connection, and the proposed additional harmonic source considered in relation to these levels, in order to determine if the limits are likely to be exceeded. The application of absolute harmonic current limits for individual consumers would seem to provide equal rights for all consumers, large or small. However, this may be considered unfair distribution by a large consumer connected to a PCC together with a number of small consumers, as it takes no account of their share of the total load. If, instead, the limit is expressed in a way which takes account of the consumer's share of the total load, then this may well be seen as overly restrictive, particularly if a large consumer has little or no disturbing load. If the limits are expressed in terms of the levels of harmonic voltage at the PCC, then consumers connected to a strong PCC may well benefit relative to a consumer connected to a weak PCC. The adoption of harmonic voltage limits may also mean that, where existing levels are high, new consumers may be forced to install expensive additional circuitry before, connection is permitted. This latter situation constitutes the 'first come, first served' approach. In considering the type and nature of the limits to be adopted, the different problems presented by the various types of load must be taken into account; the two extremes are groups of small distributed disturbing loads and large industrial loads. An industrial consumer may also have a number of individual components of plant, each capable of generating significant harmonic content. Such a consumer is faced with the double problem of ensuring that no harmonic-induced effects occur within its own system, and maintaining the levels at the PCC within the prescribed limits. Experience shows that in many instances where high harmonic levels exist at points within the consumer's own net-work; these levels do not necessarily penetrate to the external system. The way in which harmonic from a number of sources interact on the power system is governed by the random nature of such sources and the variation of their distribution throughout the system, both physically with time. The random nature of the sources can be accounted for by introducing a diversity factor. This changes the actual ratings of the disturbing loads into an effective rating, which is assessing its relationship with the standard.

3.5. EXISTING HARMONIC STANDARDS

The organization widely recognized as the curator of electric power quality standards is the IEC (International Electro technical Commission or Commission Electro technique International), based in Geneva. The IEC has defined a series of standards, called Electromagnetic Compatibility (EMC) Standards, to deal with power quality issues. The IEC 61000 series includes harmonics and inter-harmonics as one of the conducted low-frequency electromagnetic phenomena. A widespread alternative to the IEC series is the IEEE 519–1992 document, which provides guidelines on harmonics. There are also standards dealing with specific equipment under the influence of harmonic distortion, such as those of references. While the international standards are used as a basis for global co-ordination, individual countries make their own adjustments to accommodate various national priorities. These are normally motivated by the special characteristics of their power system configuration and load management (e.g. the use of ripple control in some countries). Consider as an illustration the power systems of the UK and New Zealand. In the UK a highly interconnected power system with distributed generation serves a large number of load centers, always relatively close to the points of generation. This contrasts with the New Zealand situation, where remote generation centers provide supply to a few, widely separated, major load centers and a large number of scattered small loads. The resulting long transmission lines and comparatively low fault levels increase the vulnerability of the system to harmonic penetration. These factors, taken together with the extensive use made of ripple control, present very different problems than those encountered in the UK to their respective standards committees. The European Union, through the Electromagnetic Compatibility directive, has sought to ensure the removal of technical barriers to trade by requiring equipment to operate satisfactorily in its specified electromagnetic environment, and by protecting the public electricity distribution from disturbances emitted by equipment through limiting these emissions. Engineering recommendation ER came into force in the UK in March 2001 to ensure that the objectives of the directive are met for harmonic disturbances. In the revised recommendation planning levels for individual harmonics and for total harmonic distortion (THD) are given for all system voltages from 400V to 400 kV. It must also be recognized that no standard relating to system harmonic content can be regarded as permanent, but rather as the current interpretation of system requirements, taking into account the state of monitoring and modeling techniques. As understanding improves through the application of improved measurements and analytical techniques, so must be the standards change.

3.6. GENERAL HARMONIC INDICES

The most common harmonic index, which relates to the voltage waveform, is the THD, which is defined as the root mean square (r.m.s.) of the harmonics expressed as a percentage of the fundamental component, i.e

$$\mathrm{THD} = \frac{\sqrt{\sum_{\mathrm{n}=2}^{\mathrm{N}} V_n^2}}{\mathrm{V}_1} \tag{3.22}$$

Where Vn is the single frequency r.m.s. voltage at harmonic *n*, *N* is the maximum harmonic order to be considered and *V*1 is the fundamental line to neutral r.m.s. voltage. For most applications, it is sufficient to consider the harmonic range from the 2^{nd} to the 25^{th}, but most standards specify up to the 25^{th}. Current distortion levels can also be characterized by a THD value but it can be misleading when the fundamental load current is low. A high THD value for input current may not be of significant concern if the load is light, since the magnitude of the harmonic current is low, even though its relative distortion to the fundamental frequency is high. To avoid such ambiguity a total demand distortion (T_{DD}) factor is used instead, defined as:

$$\mathrm{T_{DD}} = \frac{\sqrt{\sum_{n=2}^{N} I_n^2}}{\mathrm{I_l}} \tag{3.23}$$

This factor is similar to THD except that the distortion is expressed as a percentage of some rated or maximum load current magnitude, rather than as a percentage of the fundamental current. Since electrical power supply systems are designed to withstand the rated or maximum load current, the impact of current distortion on the system will be more realistic if the assessment is based on the designed values, rather than on a reference that fluctuates with the load levels.

Perhaps the most noticeable consequence of power system harmonics is the degradation of telephone communications caused by induced harmonic noise. There are, however, more disastrous effects, such as the mal operation of important control and protection equipment and the overloading of power plant. Very often the presence of harmonics is only detected following an expensive casualty (like the destruction of power factor correction capacitors). Normally these components have to be replaced, and the equipment protected by filters, at the customer's expense. In recent times there have been considerable developments in industrial processes that rely on controlled rectification for their operation, and therefore generate harmonic currents. The design of such equipment often assumes the existence of a symmetrical voltage source free of harmonic distortion, a situation that only occurs in the absence of other harmonic sources or when the supply system is very strong (i.e. of negligible impedance). Consequently, the smaller industrial users of electricity are being subjected to increasing operating difficulties as a result of the harmonic interaction of their own control equipment with the power supply.

With open electricity markets, the number of players will increase considerably. The competitive electricity trade should not degrade the level of security, for which the requirements of clients are likely to be more stringent. A general power quality or real power injection standard, although difficult to define, must be guaranteed by the system operator. However, power quality can raise complicated problems that require detailed information and technical skills to find adequate solutions. Although interruptions and voltage dips can, be a certain extent is mastered by the system operator, harmonic voltage fluctuations cannot, since they are generally customers' emissions. It is not clear, then, who should take the risk of ensuring specified levels of harmonic distortion. The obvious thing to do is to put standards on emission limits, but the question is to decide who will control the users' voltage disturbance emissions and who will charge them for this. An innovative approach is for the distribution companies to be responsible for supplying electricity to any user with defined disturbances levels, with a system of penalization or compensation if these levels are exceeded. Utilities are likely to accept different levels of compromise between security and cost, and the consequence of this difference is that the party with stricter standards might be left to solve its neighbors' 'problems'. In practice, the party with relaxed standards will rely on others for the provision of support services. If it is not possible to harmonies' the power quality standards between the interconnected utilities, proper commercial arrangements will be needed to reflect the consequences of these differences. While it may seem obvious that hardware and software systems should be installed to monitor performance and delivery of agreed service provision, in reality these are not always available Power quality awareness in general, and waveform distortion in particular, is likely to increase with deregulation as the competitive environment will try to drive to the limit the use of existing facilities and networks with as little expenditure as possible. The risk of harmonic resonances and their effect on shunt capacitor destruction is well documented. However, some of the negative consequences of this approach may not be immediately obvious, particularly the effect of harmonics on equipment overloading. For instance, the life of a transformer will be considerably reduced by the extra current loading imposed by harmonics. Thus there is a need to adapt existing recommendations, put in place appropriate commercial arrangements and, most of all, and monitor their implementation more in pre-deregulation days, the allocation of responsibilities to maintain adequate standards, largely determined by the supply companies, given the inadequate simulation and monitoring tools available, could not be technically challenged effectively. Deregulation will encourage the use of advanced simulation and assessment tools for the customer to make informed decisions when dealing with the power supply companies. The competitive electricity market has made utilities more conscious of the need to satisfy their customers' needs and not simply to supply them with electricity. For instance, Electricity France conducts surveys to analysis customers' expectations. The new environment provides a considerable challenge that will force the utilities to ensure that individual customer's needs are met. This implies developing complementary services taking into account the customer's specific requirements. The lack of enforceable harmonic standards in the past did not encourage the use of expensive monitoring, testing and software tools. The development of such tools has accelerated with the acceptance of more stringent standards. Deregulation is leading to more transparent considerations of injection of real power (power quality) issues and to a more contestable environment, where the independent parties can be adequately represented. In this environment, information about harmonics itself has become a valuable commodity, giving rise to profitable consulting services. This presents an important problem for the system operators that of maintaining injection of real power or power quality when the parties are reluctant to provide all the necessary information. In the competitive environment, waveform distortion can be jeopardized by excessive confidentiality. To allow the interconnected network to maintain adequate harmonic levels at low cost, this must be given priority over confidentiality. To ensure this policy, it is essential that the system operator obtains information and makes it generally available to all market participants. Determining limits on harmonic levels is a difficult exercise. Current knowledge is still insufficient to ascertain the extent to which any given power system can sustain a particular level of harmonics and remain viable in terms of the functions that the system has to perform. Two major impediments to such understanding are the ability to make accurate measurements and the state of computer simulation discussed. It is relatively easy, though expensive, to keep the harmonic contribution of large nonlinear plant components such as HVd.c. converters under control, normally by the connection of passive filters. The situation is less straightforward in power distribution systems, where the exact location and/or operating characteristics of the dispersed loads are not well defined. Moreover, the harmonic distortion levels of distribution systems appear to be increasing at a consistent rate. A report on extensive field tests carried out in several New England Power Service Co-distribution feeders indicated an increase in THD of the order of 0.1% per year, with the fifth harmonic causing the greatest concern. There is a need for more global planning for the limitation of harmonic distortion in distribution systems. Concern for waveform distortion must be shared by all the parties involved in order to establish the right balance between exercising control by distortion and keeping distortion under control. Early co-ordination between the interested parties is essential to achieve acceptable economic solutions rigorously than in the past.

Figure 3.1(a) Power flow at the fundamental frequency; (b) harmonic power flow Prior to the appearance of power semiconductors, the main sources of waveform distortion were electric arc furnaces, the accumulated effect of fluorescent lamps, and to a lesser extent electrical machines and transformers. The increasing use of power electronic devices for the control of power apparatus and systems has been the reason for the greater concern about waveform distortion in recent times. A power electronic converter can be viewed as a matrix of static switches that provides a flexible interconnection between input and output nodes of an electrical power system. Through these switches power can be transferred between input and output systems operating at the same or different frequencies (one or both of which can be d.c.). The most common power electronic aid is the single-phase rectifier, used to power most modern office and domestic appliances. Although the individual ratings are always small, their combined effect can be an important source of waveform distortion. Because of their considerable power ratings, three-phase static power converters are the main contributors to the harmonic problem. The terms *rectification* and *inversion* are used for power transfers from a.c. to d.c. or d.c. to a.c., respectively and the term *conversion* is used when the power electronic device has bi-directional power transfer capability. According to the relative position of the firing instant of the switches from one cycle to the next on the steady state, four basically different power electronic control principles are in common use:

1. Constant phase-angle control produces consecutive valve firings equally spaced with reference to their respective commutating voltages.
2. Equidistant firing control produces consecutive firings at equal intervals of the supply frequency.
3. Modulated phase-angle control produces time-varying phase-modulated firings.
4. Integral cycle control selects an integer number of complete cycles or half cycles of the supply frequency.

The Fourier analysis as described in this Chapter is directly applicable to the controlled and equidistant-firing controlled waveforms, whereas modulated firing and integral cycle controls require special analysis. Inverter feed a.c. drives are normally supplied from the a.c. power system through a line-commutated three-phase rectifier and thus their harmonic contribution to the power network is covered under the various static converter categories. However, the inverter side of the drive uses either pulse width modulation (PWM) and/or multi-level configurations to reduce the harmonic content and, thus requires special consideration.

CHAPTER FOUR

4. MATERIAL AND METHODOLOGY

4.1. INTRODUCTION

In this research, the methodology used is to conduct a case study and carry out simple representative model for an existing distribution network and harmonic impact of medium scale Adama-II (150MW) wind power generation. By using this data, the harmonic supply load modals responses which are used to study the impact of harmonics on the Utility network, problem of power quality, active power injection and power system stability. Case study research excels at bringing and understanding of a complex issue or objects and can extend experience or increase capacity, verification and explanation to what is already known through previous research.

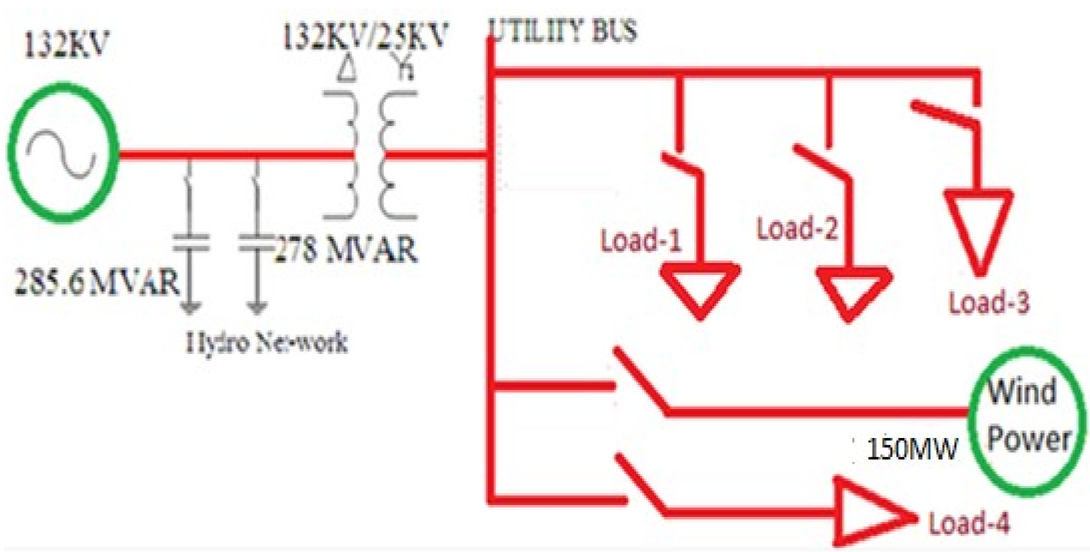


Figure.4.1 Simple model representation of wind power and utility net work

4.2. DESCRIPTION OF THE STUDY AREA

Adama-II wind power project is located about 95 km from Addis Ababa and 7 km from Adama town, at elevations of 1741~2173 m. The central geographical position of the wind power project is 39° 12' 10" E, 8° 34' 18" N. At the ground surface of the wind

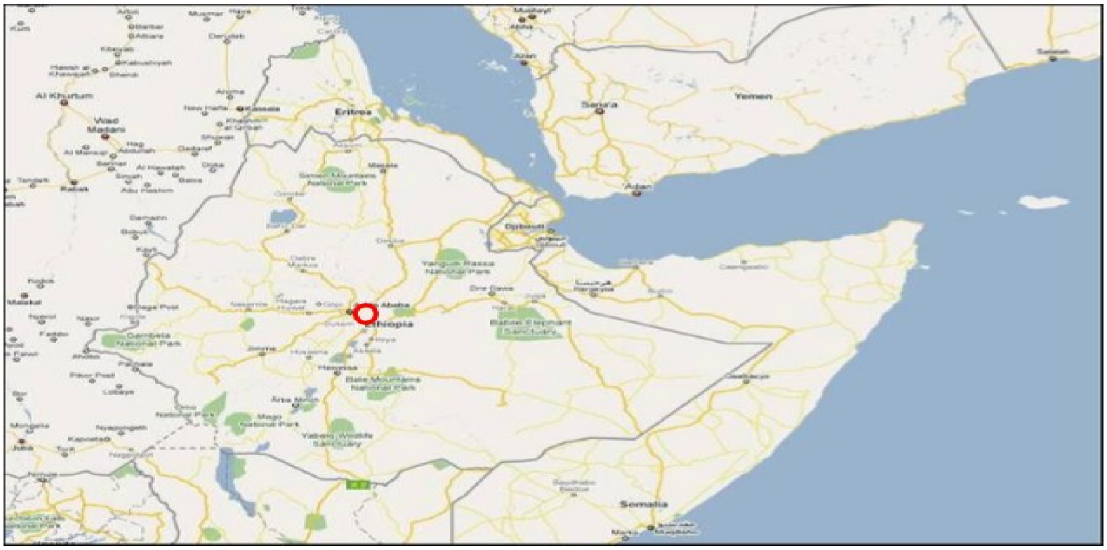


Figure. 4.2. Location of Adama-II Wind Power Project

The proposed site is located near the Great Rift Valley and the northwest dipping fault crushed zone, the micro topography is slightly undulating hilly ground, and the top of hill is relatively flat. The ground surface is mainly formed with gravels and broken stones. A number of outcrops, rocks, thin overburdens and thick vegetation. There are sparse residents in the wind power project site, medium and strong earthquake activities in this area are relatively frequent.

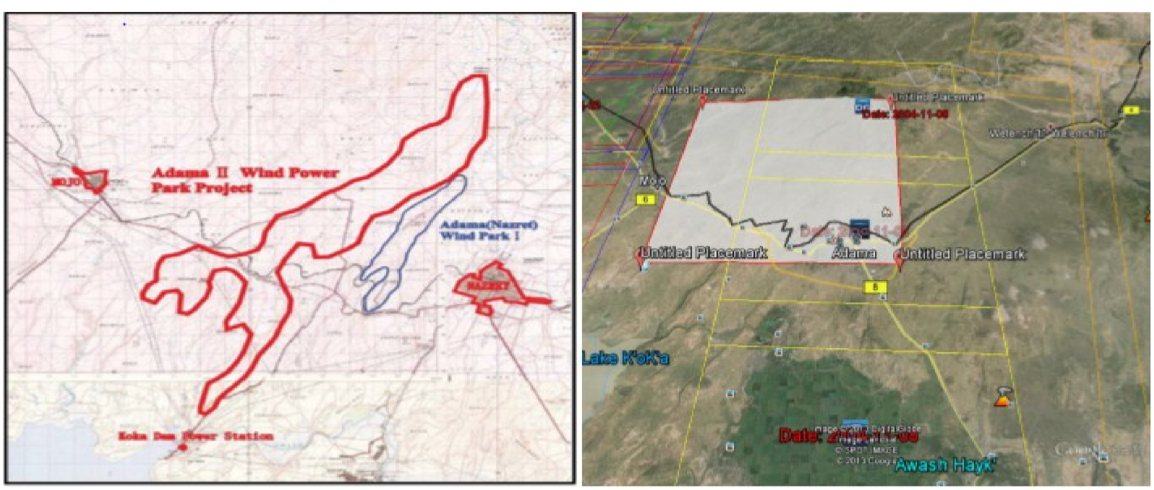
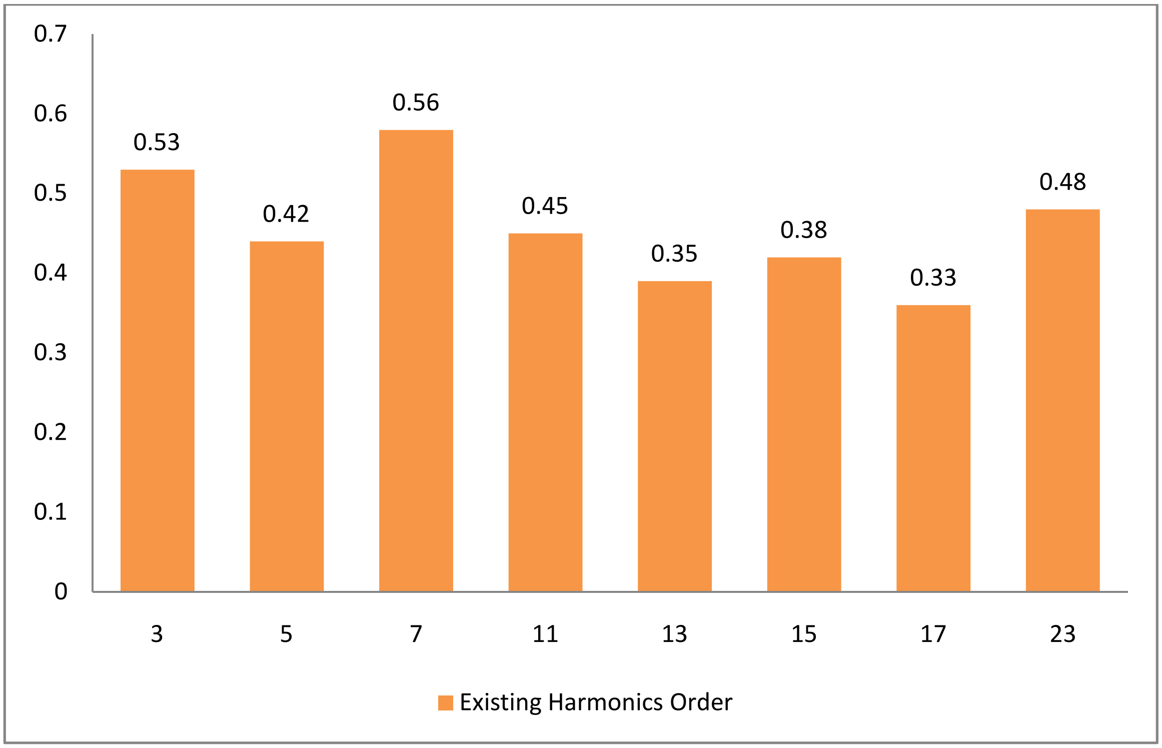


Figure. 4.3.Adama-II Wind Park areas plant



Figuer .4.4.Adama-II wind power generation existing Harmonics [Jiangsu Sieyuan Hertz and Adsma-II wind power operation manual]

The knowledge of power system harmonics is important to determine and avoid a dangerous resonance condition in the network, when harmonic currents propagate along the networks increase losses and power quality detororation. But this study focuses on the existing Harmonic spectrum identified at the engineering connection and interaction between medium scale wind farm source, and the receiving Adama Substation. Particularly, Adama-II wind power farm serving Adama substation and synchronizing networks.

4.3. ORGANIZING DATA

Because all the characteristics parameter describing the stated problems are measurable as well as previous record and running time data are available, quantitative data is obtained and analyzed. Data is collected from different operation condition; from different wind speed data ranging between 4m/s- 15m/s had been obtained to analyze the harmonic impact.

4.4. METHODOLOGY FOR COMPUTING HARMONIC DISTORTIONS

Step 1**:** Compute the individual current harmonic distortion at each dedicated bus or tables that provide the current distortion of nonlinear loads by measurements.

Step 2**:** Compute the voltage and current harmonic content at the Point of Common Coupling, (PCC) which is located at the input of the industrial and individual of all customer power system. Each individual harmonic current at the PCC is the sum of harmonic current contribution from each dedicated bus. The load current at PCC is the sum of the load current contribution from each dedicated bus.

Step 3**:** Choose a base MVA and base KV for the system by using the following equations in order to compute individual and total current harmonic distortions at PCC and any other point within the power system.

$$I_b = \text{Base current in Amps} = \frac{MVA_b}{\sqrt{3}KV_b P_f} \text{ Amps} \tag{4.1}$$

The percentage impedance of the transformer is calculated as:

$$\%Z = \frac{Impedancevoltage}{Ratedvoltage} * 100 = \frac{ZI}{V} * 100, \text{ similarly:}$$

$$\text{Percentage reactance, } \%X = \frac{IX}{V} * 100 \tag{4.2}$$

where,

I= full load current

V= phase voltage

X = reactance in ohms per phase

Short circuit current for three-phase circuit can be expressed as,

$$I_{SC} = \frac{I_b}{\%X} * 100 \tag{4.3}$$

Isc = Short Circuit current at the point under consideration

The three-phase or total short circuit kVA= $\frac{3VI_{SC}}{1000} = \frac{3VI}{1000} * \frac{100}{\%X}$ or

Short circuit KVA= Base KVA * $\frac{100}{\%X}$ or

$$= \sqrt{3}\, KV_{LL} I_{SC} \tag{4.4}$$

where, I_{SC} is in KVA

Where, Base KVA is KVA rating of a single transformer.

Percentage reactance can be expressed in terms of KVA and KV as,

$$\%X = \frac{X.KVA}{KV^2} * 100 \tag{4.5}$$

In short circuit analysis since the reactance X is generally greater than three times the resistance, resistances are neglected. But, in case percentage resistance and therefore, percentage impedance values are required then, in a similar manner we can define.

$$\%R = \frac{I.R}{V} *100 \tag{4.6}$$

$$\%Z = \frac{I.Z}{V} *100 \tag{4.7}$$

The percentage values of R and Z do not change with the side of the transformer or either side of the transformer they remain constant. The ohm values of R, X, and Z change from one side to be the other side of the transformer.

$$\mathbf{Zs} = \text{System impedance} = \frac{\boldsymbol{MVA_b}}{\boldsymbol{MVA_{sc}}} \text{p.u} \tag{4.8}$$

where,

MVA_b= Base MVA,

MVA_{sc}= short circuit MVA at the point of interest

V_H = Percent individual harmonic voltage distortion

$$V_H = \frac{I_h}{I_b} (h) (Z_s) *100 \text{ volt} \tag{4.9}$$

where h = harmonic order

$$I_H = \text{Percent individual harmonic distortion} = \frac{I_h}{I_L} *100 \tag{4.10}$$

I_L = Estimated maximum demand load current

$$\text{S.C. Ratio} = \text{Short circuit Ratio} = \frac{I_{SC}}{I_L} \tag{4.11}$$

In a power system or even in a single power station different equipment may have different ratings. Calculations are required to be performed where different components or units are rated differently. The percentage values specified on the nameplates will be with respect to their nameplate ratings. Hence, it is necessary to select a common base KVA and base KV.

The following are some of the guidelines for selection of base values.

- ❖ Rating of the largest plant or unit for base MVA or KVA.
- ❖ The total capacity of a plant or system for base MVA or KVA.
- ❖ Any arbitrary value.

Once the short circuit ratio is known which will be calculated for the utility network power system in the IEEE current harmonic limits of the IEEE 519-1992 power quality standards.

Step 4: Determine preliminary filter design.

Step 5: Compute THDv and THDi magnitudes with filters added to the system, one at a time SIMULINK software programs can be used to see variations with filters added to the modeled power system.

Step 6: Analyze results and specify final filter design.

4.5. HARMONIC ANALYSIS FOR DISTRIBUTION NETWORK OF THE POWER SYSTEM

Harmonic analysis is performed to determine harmonic filtering requirements within the facility. The nonlinear loads inter connected with wind farm and simulations are performed to determine the filter specifications and effectiveness. The application of harmonic filters will significantly change the response of the system. An evaluation of the harmonic voltage and current limits (e.g. IEEE 519) is completed to determine the effectiveness of the proposed filter installation.

The potential for harmonic distortion problems is dependent on two important factors:

1. The level of harmonic generation that can be associated with loads in the distribution network. Loads that have nonlinear voltage-current characteristics generate harmonic currents. The number and sizes of these devices at a given bus determines the level of harmonic current generation.

2. The frequency response at a given bus is dominated by the application of capacitors at that bus. Problems occur when the system response exhibits a parallel resonance near one of the harmonic components generated by the loads on the system (usually the 3^{rd}, 5^{th}, 7^{th}, 11^{th}, 23^{th} harmonics). The combination of these two factors determines whether or not a harmonic problem will exist at a particular bus.

4.6. DEVELOPING SYSTEM MODELS

The first step in the power quality study is to develop a system model to be used for the analysis of harmonic distortion level at various load sites. The model is developed from the one-line diagrams, the electrical equipment data (transformers, cables, inverters, buses, capacitors, reactors, impedance's, and filters etc.), the utility system characteristics, and the loading information.

The result is a sample data base that should include the following elements:

1. Representation of the utility system supplying the facility.
2. Step down transformers (ratings and nameplate impedances).

3. Important low voltage circuits.
4. Load data for each bus (KW, KVAR, and KVA).
5. Capacitor data (level of compensation, (KVAR).

The electrical data base developed at this stage is used for the development of the harmonic analysis model of the system.

A list of non-linear loads is compiled and a representation of these loads as harmonic generating devices is developed.

Loads at the individual buses are categorized as follows:

1. AC Motor Loads
2. Resistive Loads
3. House hold customer loads
4. Bridge Rectifiers
6. Other Loads (municipal loads, Agricultural loads, service center loads, governmental loads)

Power quality related problems or real power injection is like failure of inverters/rectifiers, failure of capacitor banks, absences of filters, complex interconnect networks etc have been experienced at the distribution networks as an interview with substation engineers.

The main cause of harmonic distortion was expected to be the non-linear. The notable harmonics measured at this substation and PCC are the 3^{rd}, 5^{th}, 7^{th}, 11^{th} and 13^{th}. Some of the power quality problems being experienced at the distribution networks were bulky interconnected problems, capacitor-switching problems etc.

4.7. CONSTRUCTING THE MODELS

This section will describe the calculations carried out and methods used to build the models to simulate harmonic distortion.

- **Transformer, Capacitor and Load Calculations**

Transformers are specified by their output voltage, KVA rating, percent impedance (%Z), and X/R ratio. The X/R ratio is the ratio of reactance to resistance. This information, with the exception of X/R, is usually on the transformer nameplate. If X/R is not specified on the nameplate and cannot be obtained, a value of 4.9 is typical and can be used in calculations. Impedance (Z) is calculated from V, KVA, and %Z.

$$Z = \frac{\%Z*V^2}{KVA*100{,}000} \quad \text{or} \quad Z = \frac{\%Z}{100} * \frac{V^2}{VA} \tag{4.12}$$

Resistance and reactance are then calculated from Z and X/R. Again, they are used for short circuit current calculation at the secondary of the transformer.

Calculations will now be given describing the process by which the transformers, loads and capacitor banks have been modeled. The values required by this model for many transformers in the networks are consistent with the simple series inductance, series resistance. Resistances of transformer (Rtr), inductances of transformer (Ltr) are the variables to be determined. Series R and L values must be taken to the secondary side of the transformer. Calculations for transformers will be used as listed bellows, those transformers are 315 kVA, 50kV / 400V, Z=2.5%, primary current, Iprim=30.73A, secondary current, Isec=1154.7A, 0.8 p.f, from the nameplate of the transformer. Since, X/R is not obtained from the nameplate data of the power transformer, a typical value of 4.9 is taken for calculations. All R and L values will be referred to the secondary side of the transformer. The secondary side voltage is 400V, therefore, on 315kVA base:

$$\text{Zbase} = \frac{V^2}{S} \tag{4.13}$$

$$= \frac{400^2}{315000} = 0.5\Omega \tag{4.14}$$

$$\text{2.5 percent of } 0.3\Omega \text{ is } 0.013\Omega \tag{4.15}$$

This represents the magnitude of Z, or $|R + jX| = 0.013\Omega$

A common X/R ratio for transformers is 4.9. Using this value, we find a simultaneous equation:

$$R_{tr}=0.001\Omega,\ X_{tr}= j0.0049\Omega \tag{4.16}$$

using a power system frequency of 50Hz, we have:

$$L_{tr}= \frac{Xtr}{2\pi f} = \frac{0.0049}{2*3.14*50} = 16\mu H \tag{4.17}$$

Since the other transformer is one and the same, its value remains similar with the calculated one as listed in Table 4.1. below.

- For the second transformers we can calculate in the same method: -

The MVA base =20MVA, then Z base = $\frac{V^2}{S} = \frac{230*230}{20000} = 2.645\Omega$, now 2.5 percent of 26.45Ω is <u>0.066Ω</u>, this represents the magnitude of Z or

$$|R+jXtr| = 0.066\ \Omega \tag{4.18}$$

$$Rtr = 0.001\Omega \tag{4.19}$$

Xt= j0.0049Ω using a power system frequency of 50Hz, the inductance of the transformer is:

$$L_{tr} = \frac{Xtr}{2\pi f} = \frac{0.0049\Omega}{2*3.14*50} = 16\mu\text{H} \tag{4.20}$$

- For the third transformers we can calculate in the same method: -

The MVA base = 10MVA, then the Z base

$$= \frac{V^2}{S} = \frac{400*400}{10000} = 16\Omega \tag{4.21}$$

For 2.5 percentage impedance, the magnitude of Z is $|R+jXtr| = 0.4\Omega$

$$Rtr = 0.001\Omega \tag{4.22}$$

Xtr=j0.0049Ω using a power system frequency of 50Hz, the inductance of the transformer is

$$L_{tr} = \frac{Xtr}{2\pi f} = \frac{0.0049\Omega}{2*3.14*50} = 16\mu\text{H, for all transformers} \tag{4.23}$$

Table.4.1. Transformers data

Transformer	Values
T_1	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH
T_2	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH
T3	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH
T3	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH
T4	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH
T5	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH
T6	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH
T7	R_{tr}=0.001Ω, X_{tr}= 0.0049Ω, $L_{tr\,=16}$μH

The next calculation to examine is for the MVAR capacitor banks for automatic compensation in the substation of the study area.

At substation, there is a 1.2KVAR, 20KVAR, 10KVAR and 0.5KVAR capacitor bank, working on a per phase basis, there is 31.7KVAR/3= 10.57 KVAR per phase. The three-phase value of voltage at the primary of feeder from all transformers are 400KVwith a line to neutral rms voltage of $\frac{400}{\sqrt{3}}$ = 230.92V rms. Now,

$$X_{c1} = \frac{V^2}{Q} \quad (4.24)$$

$$= \frac{230.92^2}{10.57} * 1000 \quad (4.25)$$

$$= 5.044848\Omega = 5\Omega \quad (4.26)$$

therefore, for a power system frequency of 50Hz,

$$C_1 = \frac{1}{2*\pi*f*Xc} = \frac{1}{2*3.14*50*5} \quad (4.27)$$

$$= 636.94\mu F \text{ per phase} \quad (4.28)$$

For example, some local industries may represent loads of 85.7kW (28.57KW per phase), at a power factor of 0.90 measured. The average line to neutral voltage measured is 215V (rms). Resistance and inductance values per phase are required. The load is connected in wye and delta configuration, and assuming a balanced load, we have, S = 28.57KW/0.9 =31.74KVA per phase, now Q_C can be calculated as follows:

$$Q_c = \sqrt{S^2 + P^2} \quad (4.29)$$

$$= 13.83 \text{ KVAR} \quad (4.30)$$

Now, the resistor and inductor each have a voltage of 215V across them as connected in parallel. By using Ohms law:

$$X_L = \frac{V^2}{Q} = \frac{215^2}{13830} = 3.34\Omega \quad (4.31)$$

$$L = \frac{X_L}{2*\pi*f} = 10.64\text{mH} \quad (4.32)$$

$$R = V^2/P = \frac{215^2}{28570} = 1.62\Omega \quad (4.33)$$

All other loads in the town were developed into linear loads in a similar manner and their calculated values are displayed in below.

Table.4.2. Loads in terms of R and L components

Load Component	R(Ω), X_L, L, Per phase
Flour mail	R=21.62Ω, X_L= 33.34Ω, L=50.64mH
Welding machine	R=5.81Ω, X_L= 17.67Ω, L=56.3mH
Municipal	R=2.09Ω, X_L= 3.37Ω, L=10.74mH
Health center load	R=17.93Ω, X_L= 37.01Ω, L=117.87mH
Governmental	R=4.27Ω, X_L= 8.82Ω, L=28.08mH
Service center	R=3.71Ω, X_L= 4.95Ω, L=15.75mH
Industry	R=5.81Ω, X_L= 11.99Ω, L=38.19mH
Agricultural	R=6.75Ω, X_L= 10.55Ω, L=44.95mH
Individual customer	R=1.92Ω, X_L= 2.33Ω, L=10.17mH
Incubation industry	R=1.48Ω, X_L= 2.39Ω, L=7.61mH
Commercial center	R=2.85Ω, X_L= 0Ω, L=10mH
Welding machine	R=36.3Ω, X_L= 0Ω, L=20mH
Micro and macro enterprise	R=5.19Ω, X_L= 8.37Ω, L=26.65mH

The Institute of Electrical and Electronics Engineers (IEEE) has set recommended limits on both current and voltage distortion in IEEE 519-1992 as shown in the appendix**.**

ISC is short-circuiting current at the PCC. I_L is the fundamental component of the maximum demand load current at the PCC. It can be calculated as the average of the maximum monthly demand currents for the previous 2 years. All power generation equipment is limited to these values of current distortion, regardless of actual I_{SC}/I_L.T_{DD} is total demand distortion (uses maximum load current as the base, rather than the Fundamental current), which is identical with THD.

$$T_{DD} = \frac{\sqrt{\sum_2^{\infty} I_h^2}}{I_L} * 100 \tag{4.34}$$

$$I_L = \frac{KW}{\sqrt{3}KV*P_f} \quad (4.35)$$

$$\text{Short-circuit ratio} = \frac{I_{Sc}}{I_L} \quad (4.36)$$

The billing information indicates the portion of billing information of customer of power system over 2 months. For the calculation of maximum demand load current (I_L) at the PCC, the above 2 months sample bills are taken randomly from the total customer bill information. The maximum consumption of 531,000KWH from 60 days is considered to determine the maximum demand. That is, KWH = 531000 at power factor = 0.8.

$P_D = \frac{KWH}{H}$ Where, P_D is Power demand, but the number of days corresponding to this value is 7 and 12 hours per day (19 hour per days).

$$P_D = \frac{531000}{24*2} = 106,895.8KW \quad (4.37)$$

from equation 4.35,

$$I_L = \frac{1}{\sqrt{3}} * \frac{PD}{KV*Pf} \quad (4.38)$$

$$= \frac{1}{\sqrt{3}} * \frac{106,895.8KW}{0.4*0.8} = 334,049.8A \quad (4.39)$$

$$\%X = \frac{X_{tr}*S_{base}}{KV^2} * 100 = \frac{0.0049*315}{0.4^2KV} * 100 = 9.65 \quad (4.40)$$

$$\%R = \frac{I_{sec*}R_{tr}}{V} * 100 = \frac{115.7*0.001}{400} * 100 = 0.29 \quad (4.41)$$

$$I_L = \frac{KWD}{KV*\mathcal{P}_f*\sqrt{3}} \quad (4.42)$$

There are 759 Transformers in the town with the following equal ratings: 10* 315kVA, 20*50KVA, 25*100KVA, 2*200KVA and2*25KVA of 50Hz, Z=2.5 and 0.8 pf.KWD=10*315*0.8=2,520kW, where KWD is active power demand.

Now,

$$I_{L315} = \frac{KW_D}{KV*pf*\sqrt{3}} = \frac{2,520}{0.4*0.8*\sqrt{3}} = 4,546.28A \quad (4.43)$$

$$I_{L50} = \frac{KW_D}{KV*pf*\sqrt{3}} = \frac{1000}{0.4*0.8*\sqrt{3}} = 1802.19A \quad (4.44)$$

$$I_{L100} = \frac{KW_D}{KV*pf*\sqrt{3}} = \frac{2,500}{0.4*0.8*\sqrt{3}} = 4,473.07A \quad (4.45)$$

$$I_{L200} = \frac{KW_D}{KV*pf*\sqrt{3}} = \frac{400}{0.4*0.8*\sqrt{3}} = 715.69A \quad (4.46)$$

$$I_{L25} = \frac{KW_D}{KV*pf*\sqrt{3}} = \frac{50}{0.4*0.8*\sqrt{3}} = 90.108A, \text{ at } 100\% \text{ load} \quad (4.47)$$

$$I_{LTotal} = I_{L315}+I_{L50}+ I_{L100}+ I_{L200}+ I_{L25} \quad (4.48)$$

$$= (4,546.3+1802.2+4,473.1+715.7+90.11) \text{ A} \quad (4.49)$$

$$=11,627.34A \quad (4.50)$$

Actually, this value is indicated on the nameplate of transformer as secondary current=11,627A. By multiplying Isec with the number of transformers in the town i.e. then, gives the value 56,590.10A, which is equivalent to the calculated one.

$$I_{sc}= \frac{I_L*100}{\% X} \quad (4.51)$$

$$= \frac{334,049.8*100}{2.45} = 13,634,685.71A \quad (4.52)$$

Now, short-circuit ratio can be calculated as:

$$S.C. = Isc/I_L=13,634,685.714 /334,049.80 = 40.82 \quad (4.53)$$

Assuming the two Switching station in the distribution network where measurements taken have equal consumption,

$$S.C = \frac{I_{sc}}{I_L} = 40.82 \quad (4.54)$$

This is between 20 –50, to be compared with IEEE-519 power quality standard which is used to determine the limits on harmonic currents.

In such a case a full load current calculated in the above case i.e. I_L=2,309.4A is used.

$$I_{sc}= \frac{I_L*100}{\% X} \quad (4.55)$$

$$= \frac{56,590.10*100}{2.45} = 2,309.8KA \quad (4.56)$$

the three-phase or total short circuit

$$KVA = \frac{3*V*I_{sc}}{1000} \quad (4.57)$$

$$= \frac{3*400*2,309.8*1000}{\sqrt{3}*1000} = 1,590.10MVA \quad (4.58)$$

short circuit KVA= Base KVA * $\frac{100}{\%X}$

$$= (2*200+100*20+50*25+315*10+25*2)*\frac{100}{2.45} \quad (4.59)$$

$$= 2,897.56MVA \quad (4.60)$$

therefore,

short circuit KVA= 2,897.56MVA (4.61)

and

$$S.C = \frac{I_{sc}}{I_L} = \frac{2309.8*1000}{11{,}627.34*1000} * 100 \quad (4.62)$$

$$= 19.899548, \text{ dividing again in to two} \quad (4.63)$$

$$S.C = \frac{I_{sc}}{I_L} = 19.899548 = 20.00, \text{ which is again between } 20 - 50 \quad (4.64)$$

The maximum allowable voltage and current distortion is specified by IEEE standard 519-1992. For most customer loads of power systems, the maximum acceptable voltage THD level is 3.47%, with the maximum percentage of 1.5% for individual harmonic components. IEEE standard 519 imposes limits on the harmonics that a customer may contribute to a network, and the harmonics that a utility may produce, measured at the point of coupling to a customer. This ensures that individual customers do not overly distort the electricity supply for other customers. The electricity utility has also an obligation to supply clean power to all its customers.

4.8. SOLUTIONS TO POWER HARMONIC PROBLEMS

Two approaches are available for mitigating the effects of harmonics and hence power quality problems, and a combination of the two approaches is often implemented. One strategy is to reduce the magnitude of the harmonic waveforms by harmonic Filters. The other method is to use system components that can handle the harmonics more effectively like un-interruptible power suppliers. Harmonic Filters are preferred since they provide reactive compensation as well.. As it can be seen from the power distribution system above the power-factor-correction capacitor bank, which is connected on the 400 Volts bus, can create a parallel resonance between the capacitors and the system source inductance. The single-phase equivalent circuit of the distribution system is shown below.

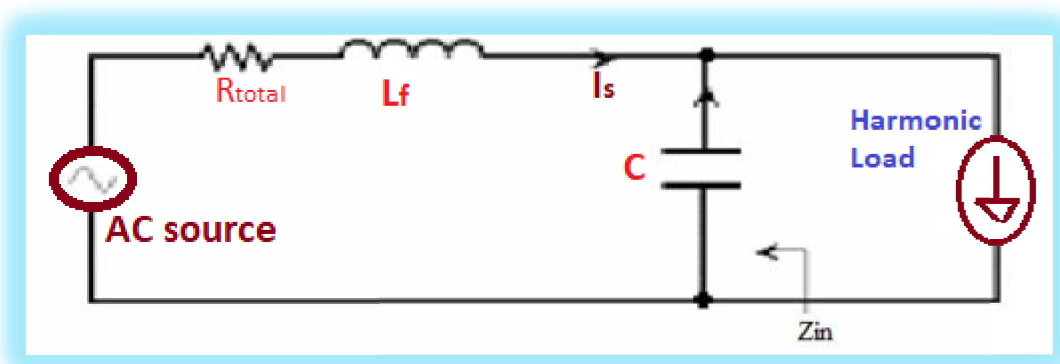


Figure.4.5. the single-phase equivalent circuit of the distribution system

Using the above circuit, the following equations hold:

$$R_{sys} = \frac{KV_{LL}^2}{MVA_{sc}} * \cos\left[\tan^{-1}\left(\frac{X}{R}\right)\right], \quad R'_{sys} = \frac{R_{sys}}{\alpha^2} \tag{4.65}$$

$$X_{sys} = \frac{KV_{LL}^2}{MVA_{sc}} * \sin\left[\tan^{-1}\left(\frac{X}{R}\right)\right] \tag{4.66}$$

$$X'_{sys} = \frac{X_{sys}}{\alpha^2} \tag{4.67}$$

Where, α = the turn's ratio of the transformer at PCC

$$R_{total} = R'_{sys} + R_{tr} \tag{4.68}$$

$$X_{total} = X'_{sys} + X_{tr} \tag{4.69}$$

$$X_c = \frac{KV_{cap}^2}{KVAR_{cap}} \tag{4.70}$$

$$C = \frac{1}{\omega\, X_c} \tag{4.71}$$

$$X_c = \frac{1}{\omega C} \tag{4.72}$$

$$L_{total} = \frac{X_{total}}{\omega} = \frac{X_{total}}{2\pi f} \tag{4.73}$$

$$Z_{in} = \frac{(R_{tot} + j\omega L_{tot}) * (-j/\omega C)}{R_{tot} + j\omega L_{tot} - j\frac{1}{\omega C}} \tag{4.74}$$

The impedance Z_{in} looking into the system from the load, consists of the parallel combination of source impedance $R_{tot} + jX_{tot}$ and the capacitor impedance.

$$\omega_0 L_{total} = \frac{1}{\omega_0 C}, \quad f_0 = \frac{1}{2\pi\omega_0} \tag{4.75}$$

The equation for Z_{in} can be used to determine the equivalent system impedance for different frequencies. The harmonic producing loads can resonate (parallel resonance) the above equivalent circuit. Designating the parallel resonant frequency by ωo (rad/sec) or fo (Hz) and equating the inductive and capacitive reactance**.** Harmonic current components that are close to the parallel resonant frequency are amplified. Higher order harmonic currents at the PCC are reduced because the capacitors are low impedance at these frequencies. The figure below shows, the effect of adding capacitors on the 400 Volts bus for power factor correction.

- The sampling Transformer rate:

10*315 kVA, 20*100KVA, 25*100KVA, 2*200KVA and 2*25KVA is 15kV/ 0.4 kV, 50Hz, Z=2.5%, Iprim=30.73A, Isec=1154.7A, 0.8 p.f and ratio Zs is 2.4 of each transformers.

The capacitor banks are installed in the power substation for voltage regulation under study:

378.8kVAR a group of 18 on the substation feeder and

285.6kVAR a group of 10 on the substation feeder

The parallel resonant frequency for every case of voltage regulation and power factor correction is calculated as follows:

$$R_{sys}= \frac{KV_{LL}^2}{MVA_{sc}} * \cos [\tan^{-1} (\frac{X}{R})] \quad (4.76)$$

$$= \frac{15^2}{200} * \cos [\tan^{-1} (2.4)] = 0.433\Omega \quad (4.77)$$

$$X_{sys} = \frac{KV_{LL}^2}{MVA_{sc}} * \sin [\tan^{-1} (\frac{X}{R})] \quad (4.78)$$

$$= \frac{15^2}{200} * \sin [\tan^{-1} (2.4)] = 1.038\Omega \quad (4.79)$$

$$\alpha = \frac{15}{0.4} = 38 \quad (4.80)$$

$$R_{sys} = \frac{R_{sys}}{\alpha^2} = \frac{0.433}{38^2} = 0.0003\Omega \quad (4.81)$$

$$X_{sys} = \frac{X_{sys}}{\alpha^2} = \frac{1.038}{38^2} = 0.0007\Omega \quad (4.82)$$

$$R_{tr} = 0.001\Omega, X_{tr}= 0.0049\Omega \text{ (calculated before)} \quad (4.83)$$

$$R_{tot} = R_{sys} + R_{tr}= 0.0003+ 0.001 = 0.0013\Omega \quad (4.84)$$

$$X_{tot} = X_{sys} + X_{tr}= 0.0007 +0.0049 = 0.0056\Omega \quad (4.85)$$

$$L_{tot} = \frac{X_{tot}}{2\pi f} = \frac{0.0056}{2*3.14*50} = 18Mh \quad (4.86)$$

Case 1**:** When 378.8kVAR capacitor bank at outgoing feeder of the substation, per phase analysis:

$$\frac{378.8}{3} = 126.27KVAR \quad (4.87)$$

$$X_c = \frac{V^2}{Q_c} = \frac{230.92^2}{126200} = 0.422\Omega \quad (4.88)$$

$$C = \frac{1}{2\pi} = \frac{1}{2*3.14*50*0.422} = 132.51\mu F \quad (4.89)$$

$$f_0 = \frac{1}{2\pi\sqrt{C*L_{tot}}} = \frac{1}{2*3.14\sqrt{0.0055386*0.000018}} = 504.345HZ \quad (4.90)$$

For 378.8 KVAR, the harmonic order at which parallel resonance occurs is:

$$h = \frac{f_0}{f} = \frac{504.34}{50} = 10.08 \quad (4.91)$$

It is clear from the above system that in the 378.8KVAR case at outgoing feeder of the substation; there exists a parallel resonant frequency f_o close to the 11^{th} harmonic.

Case 2: when 285.6KVAr capacitor bank at outgoing feeder of the substation is considered, per phase analysis:

$$\frac{285.6}{3} = 95.2\text{KVAR} \tag{4.92}$$

$$X_c = \frac{V^2}{Q_c} = \frac{230.92^2}{95200} = 0.560\Omega \tag{4.93}$$

$$C = \frac{1}{2\pi f Xc} = \frac{1}{2*3.14*50*0.560} = 3695\mu F \tag{4.94}$$

$$f_0 = \frac{1}{2\pi\sqrt{C.L_{tot}}} = \frac{1}{2*3.14\sqrt{0.003695*0.000018}} = 617.44HZ \tag{4.95}$$

For 378.8 KVAR, the harmonic order at which parallel resonance occurs is:

$$h = \frac{f_o}{f} = \frac{617.44}{50} = 12.35 \tag{4.96}$$

It is clear from the above system that in the 285.6KVAR case at outgoing feeder of the substation is; there exists a parallel resonant frequency f_o close to the 3^{rd}, 11^{th},17^{th} ,5^{th} ,7^{th} ,21^{th} ,19^{th} and 13^{th} harmonic.

Power Factor Correction and Harmonic Treatment Using Tuned Filters

Basic configuration of a tuned 3-ϕ capacitor bank for power factor correction and harmonic treatment is shown in figure below.

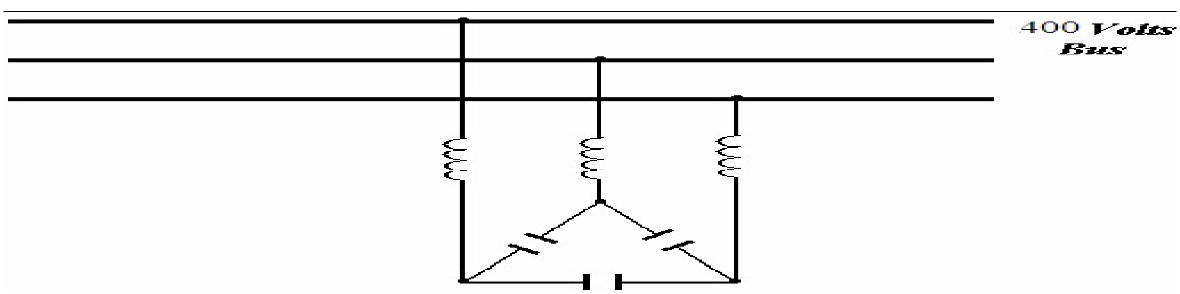


Figure 4.6. Configurations of a tuned 3-ϕ capacitor bank and harmonic treatment

The single-phase equivalent circuit of the power distribution system with the tuned filter is shown below.

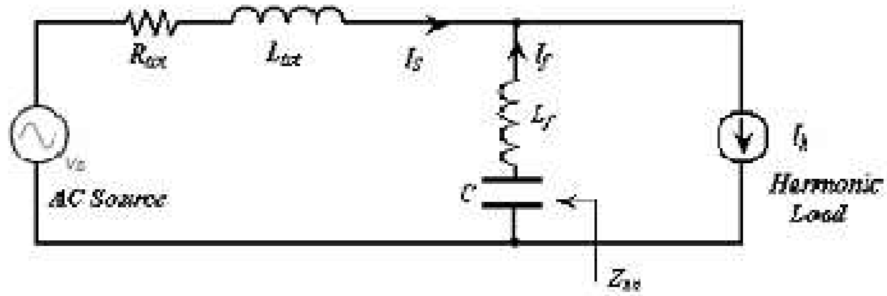


Figure .4.7. Single-phase equivalent circuits with the tuned filter

Using the above circuit, the following equations hold:

$$f_{os} = \frac{1}{2\pi\sqrt{C.L_f}} \tag{4.97}$$

f_{os}= Resonant frequency of the series filter

$$L_f = \frac{1}{C.(2\pi f)_{os}^2} = \frac{2\pi f.X_C}{(2\pi f_{os}^2)} = \frac{f(Kv_{cap}^2)}{2\pi f_{os}^2.KVAR_{CAP}} \tag{4.98}$$

The new parallel combination is having resonant frequency when

$$\omega_0 L_{tot} + \omega_0 L_f - \frac{1}{\omega_0 C} = 0 \text{ (parallel Resonance)}$$

$$f_0 = \frac{1}{2\pi\sqrt{((L_{tot}+L_f).C)}} \tag{4.99}$$

= Resonance frequency of the equivalent distribution circuit.

$$I_f = I_h * \frac{R_{tot} + j\omega L_{tot}}{R_{tot} + j(\omega L_{tot} + \omega L_f - 1/\omega C)} \tag{4.100}$$

$$V_h = I_s * (R_{tot} + j\omega L_{tot}) \tag{4.101}$$

$$Z_{in} = \frac{(R_{tot} + j\omega L_{tot}) * (j\omega L_f - j\frac{1}{\omega C})}{R_{tot} + j\omega L_{tot} + j\omega L_f - j\frac{1}{\omega C}} \tag{4.102}$$

Selecting fo = 235Hz order harmonic, With KVcap= 0.4,

Case 1: KVA Rcap = 378.8KVAR, per phase = 126200VAR

$$L_f = \frac{f(Kv_{cap}^2)}{2\pi f_{os}^2.KVAR_{CAP}} \tag{4.103}$$

$$L_f = \frac{50*400^2}{2*3.14*235^2*126200} = 182.78\mu H \tag{4.104}$$

The new parallel combination is having resonant frequency:

$$f_0 = \frac{1}{2\pi\sqrt{((L_{tot}+L_f)C)}} \tag{4.105}$$

$$f_0 = \frac{1}{2*3.14\sqrt{((18\mu+248\mu)*5638.6\mu)}} = 132\text{Hz} \quad (4.106)$$

$$h = \frac{132}{50} = 2.6 \text{ (without Lfw as)} \quad (4.107)$$

Case 2: KVA Rcap= 285.6KVAR, per phase =95,200VAR

$$L_f = \frac{f(Kv_{cap}^2)}{2\pi f_{0S}^2 . KVAR_{CAP}} \quad (4.108)$$

$$L_f = \frac{50*400^2}{2*3.14*235^2*95200} = 182.78\mu\text{H} \quad (4.109)$$

The new parallel combination is having resonant frequency**:**

$$f_0 = \frac{1}{2\pi\sqrt{(L_{tot}+L_{f}).C)}} \quad (4.110)$$

$$f_0 = \frac{1}{2*3.14\sqrt{((18\mu+372.9\mu)*3695\mu)}} = 132\text{Hz} \quad (4.111)$$

$$h = \frac{132}{50} = 2.6 \text{(without Lf was 12.35)} \quad (4.112)$$

Table .4.3. The variation of Parallel resonant frequency with and without resonant inductor

Capacitor bank (KVAR)	C (μF)	L_f added (μH)	Parallel resonant, f_0(Hz)		Harmonic order, (h)	
			Without Lf	With Lf	Without Lf	With Lf
378.8	5613.6	524.4	505.62	132	10.08	2.64
285.6	7695.0	341.5	769.25	132	12.35	2.64

CHAPTER FIVE

5. SYSTEM DESIGN AND ANALYSIS

5.1. ANALYSIS OF HARMONIC POLLUTION

This section analyzes the possible resonance phenomenon in electrical networks where a large number of DP (distributive power) inverters are concentrated. This equivalent capacitance can vary over a wide range from around 0.6 to 6 F. The typical values for the inverter input capacitance change also over a wide range as discussed in the above. Commercial inverters in the 1–3 kW power range typical use values of 0.5 to 10 F for the output capacitance. The resonance phenomenon for these networks with large numbers of DP (distributive power) inverters connected on the low-voltage network can be divided into the following.

5.2. PARALLEL RESONANCE

The parallel network capacitance C_p (inverter, household, and cable) and the supply inductance (transformer leakage and cable), resulting from distortion currents generated internally, i.e., within the point of common coupling (PCC). In this case, the inverter can be assumed to be the generating harmonic source I_h. In this case, the impedance at the resonance is high, resulting in higher voltage distortion at the PCC, or where the inverter and the household load are connected.

5.3. SERIES RESONANCE

The network capacitance C_s, and the supply reactance L_s, result from externally generated or injected distortion. In this case, the background supply voltage distortion is the generating mechanism. Here, the impedance at the resonance is low, resulting in higher current distortion through the load and inverter capacitor. This effect will be enhanced if the inverter output impedance is low at the different background harmonics. In practice, these two phenomena are linked in one circuit and both the increased voltage and the current distortions are practically measured. The series and parallel resonance can simply be calculated at the frequency, using the following simple equation:

$$f_r = \frac{1}{2\pi\sqrt{LC}} \tag{5.1}$$

One of the harmonics present in the network background distortion (series resonance mechanism) corresponds with the series resonance frequency, very high-resonance currents will flow in the network, damped only by the associated network resistance. The load is parallel to the network resistance for a parallel resonance and can be ignored since it is much higher than the network resistance. Assuming that there are about 800 to 1300 households on one phase of a single 400-V cable feed, the natural resonance frequency can be as low as the third, fifth, seventh, eleventh, thirteenth, nineteenth, and twenty-three harmonic (50 Hz).

5.3.1. WIND POWER SYSTEM POWER CALCULATIONS

The following are the definitions of various variables used in this model for wind energy calculations: Piecewise electrical power is given by;

$$P_e = \begin{cases} 0, U < U_c \text{ or } > U_F \\ a + b * U^k, \ U_c \le U \le U_R \\ p_e, U_R \le U_f \end{cases} \tag{5.2}$$

Where P_e, R is the turbine rated electrical power and U is the wind speed ,Uc, 'U_R and Up are the turbine cut-in speed, rated speed and the turbine cut-out speed respectively, K is the shape parameter of Wei bull distribution given by;

$$K = \left(\frac{\sigma}{\mu}\right)^{-1.086}, \text{ For } 1 \le K \le 10 \tag{5.3}$$

Where U is the average speed found by;

$$U = \frac{1}{n}\sum_{i=1}^{n} Ui \tag{5.4}$$

For a sample of size n and σ is the standard deviation found by taking the square root of the variance(σ^2);

$\sigma^2 = \frac{1}{n-1}\sum_{i=1}^{n} (U1 - U)^2$, a and b are constants, given by;

$$a = \frac{P_{e,R}}{(U_c)^K - (U_f)^K} \tag{5.5}$$

$$b = \frac{P_{e,R}}{(U_R)^K - (U_c)^K} \tag{5.6}$$

so that, to find the average power output from the wind turbines we can use

$$P_{e,R} = \left[\frac{e^{\left[\frac{-U_c}{C}\right]^K} - e^{\left[\frac{-U_R}{C}\right]^K}}{\left(\frac{U_R}{C}\right)^K - \left(\frac{U_c}{C}\right)^K} - e^{\left(\frac{-U_F}{C}\right)^K}\right] \quad (5.7)$$

where, c is the Wei bull scale parameter given by;

$$C = 1.12 * U \text{ for } 1.5 \leq K \leq 3.0 \text{ or;}$$

$$C = \frac{U}{r\left(1+\frac{1}{K}\right)} \quad (5.8)$$

In which (is the gamma function already imbedded in Microsoft Excel). To find the total energy generated by the wind turbines we use; Energy = Power * number of seconds in a year

5.4. ECONOMIC ANALYSIS

The LCOE is the total cost of installing and operating a project expressed in dollars per kilowatt-hour of electricity generated by the system over its life time. The calculated LCOE is then compared with current grid tariff. If the LCOE is greater than the prevailing grid tariff, then the system might not be economically feasible, it might be better to buy the electricity from the grid. The main objective is to decrease the LCOE by varying the capacity as well as the number of turbines numbers.

$$LCOE = \frac{LCOE_{RES} * D_{RES} * GridTariff * D_{grid}}{D} \quad (5.9)$$

Where $D_{RES}$is the demand met by the hybrid system,D_{grid} is the deficit supplied by the grid, Grid Tariff is the current grid tariff rate, D is the energy demand of the location and $LCOE_{RES}$ is given by (5.11) below;

$$LCOE = C_i + \frac{\sum_{t=1}^{n} \frac{Mt}{(i+r)^t}}{\sum_{t=1}^{n} \frac{E_{gen,t}}{(i+r)^t}} (USD/KWH) \quad (5.10)$$

Where C_i is the initial cost of investment, M_t is the annual fixed Operation and Maintenance cost, F_t is the annual fuel cost, $E_{gen,t}$ is the annual energy generation, r is the annual discount rate and n is the life time of the system in years. The initial cost includes the cost of equipment, cost of land, transport cost, labor cost and the cost of connecting the system to the grid.

5.4.1. ADAMA AIR DENSITY

The formula of air density is shown by:

$$\rho = \frac{1.276}{1+0.00366*t}\left(\frac{p-0.378*e}{1000}\right) \quad (5.11)$$

P is the atmospheric pressure, t is the average temperature, and e is the pressure of water vapor. According to the data collected from Adama station, we can calculate the long term average temperature is 21.2C^O, and the atmospheric pressure is 853.3hpa, the pressure of water vapor 14.25pa. The air density of Adama station is 1.004kg/m^3.and based on this, the extrapolated air density of wind mast is 0.976kg/$m^3$and the air density of the turbines hub height in Adama-II Wind Park ranges from 0.959-0.973kg/m^3.

5.4.2. THE SITUATION OF SITE ANEMOMETER MAST

Adama wind park area has four anemometer masts; basic data of four masts are shown in table blows.

Table.5.1. basic data of anemometer masts in Adama-II Wind Park

No	Northing	Easting	Height of the tower(m)	Elevation(m)	Wind speed observation height (m)	Wind direction observation height(m)
1	094390	0523917	10	1877	10	10
2	0944090	0524917	40	1869	10/40	10
3	0945054	0525580	40	1879	40	None
4	0946839	0526192	10	1934	10	10

5.4.3. CALCULATION OF WIND ENERGY OF DIFFERENT HEIGHT

After the long-term revision, according to wind shear coefficient we calculate the average wind speed and the power density of the representative year at different height.

Table.5.2. the representative of wind average speed power density at 65m height

Item	10m	40m	50m	65m	70m
Average wind speed(m/s)	6.74	8.74	9.11	9.56	9.69
Average wind power density(w/m^2)	216.5	499.6	565.6	654.5	682.0

Table 5.3. Each month's average wind speed power density at 65m height

Average wind speed at power density of months January through June							
Time (Months)	Jan.	Feb.	Mar.	Apr.	May	June	Average
Wind speed (m/s)	11.25	12.03	10.61	8.58	7.89	8.44	8.44
Power density(w/m^2)	960.8	1118.20	1009.0	519.20	398.60	374.60	624.69
Average wind speed at power density of months July through December							
Time (Months)	July	August	Seb.	Oct.	Novem.	Dec.	Average
Wind speed (m/s)	8.71	8.65	5.72	8.51	12.08	12.41	9.35
Power density(w/m^2)	391.0	409.1	133.8	472.9	1019.7	1172.9	439.95

5.4.4. BLADES

The Gold wind 1.5 MW wind turbine rotor is equipped with 3 reinforced fiber glass blades that are produced by qualified international blade manufacturers. The high aerodynamic efficiency of the rotor is based on the efficient design of the airfoils used in each blade. Different blade lengths are used depending on the wind class of the site that the turbine will be placed. This optimizes energy output and loads. The following table shows the respective blades used for each Gold wind1.5 MW turbine model and the resulting swept area.

5.4.5. ADAMA WIND FARM AREA LOCATION

Adama is located 97km south-east of Addis Ababa the municipal city of Ethiopia. This site is located at (083241N and 0391348E) and the land province, Ethiopia. Adama has a maximum altitude of 1869m, and there is a water body near to the site. The wind speeds and solar irradiance data were obtained at typical meteorological year (TMY) data from Meteonorm7 software and were analyzed using Microsoft Excel. The average monthly wind speeds and solar irradiance data for Adama location can be seen that the average solar insulation 204.48Wh/m which is suitable for wind power generation. The average wind speed is 12m/s of which both conditions predict an energy production. The hourly solar insulation was used for the determination of the energy generated by the wind speeds were calculated for a hub height of 70m.

5.4.6. INSPECTION ITEMS AND RESULTS

Inspection resistance measurement

Table.5.4. Winding resistance measurement

Measured winding	Measured values				Maximum Unbalanced rate	Unbalanced Specified Value (%)	
HV Winding	Tap Position	R_{AB}	R_{BC}	R_{CA}	0.33	≤ 4	
	1	13.06	13.04	13.07			
	2	12.69	12.66	12.70			
	3	12.33	12.31	12.34			
	4	11.97	11.94	11.98			
	5	11.61	11.59	11.62			
LV Winding	R_{ab}	R_{ac}		R_{bc}	R_{ao}	R_{bo}	Rco
	0.005392	0.005479		0.005387	0.002710	0.002703	0.002715

5.4.7. MEDIUM VOLTAGE DISTRIBUTION SYSTEMS

As shown in Figure.5.1, unlike the conventional MV filters, the distributed filters are installed in the 0.4KV voltage level of the secondary systems either directly connected to the low-voltage side of the transformer or installed at one of the customer houses. This system presents the initial feasibility studies on the distributed active filters idea to identify the main challenges for both its implementation and performance. Theories and measures are developed to support the proposed filter scheme design, configuration and placement. In addition, the overall harmonic mitigation effectiveness of the proposed distributed filters scheme is evaluated by using primary system simulations. Both of the actual and ideal feeders are studied with some supporting sensitivity analyses to achieve a better understanding of the overall performance of the filters in suppressing the distribution system harmonics.

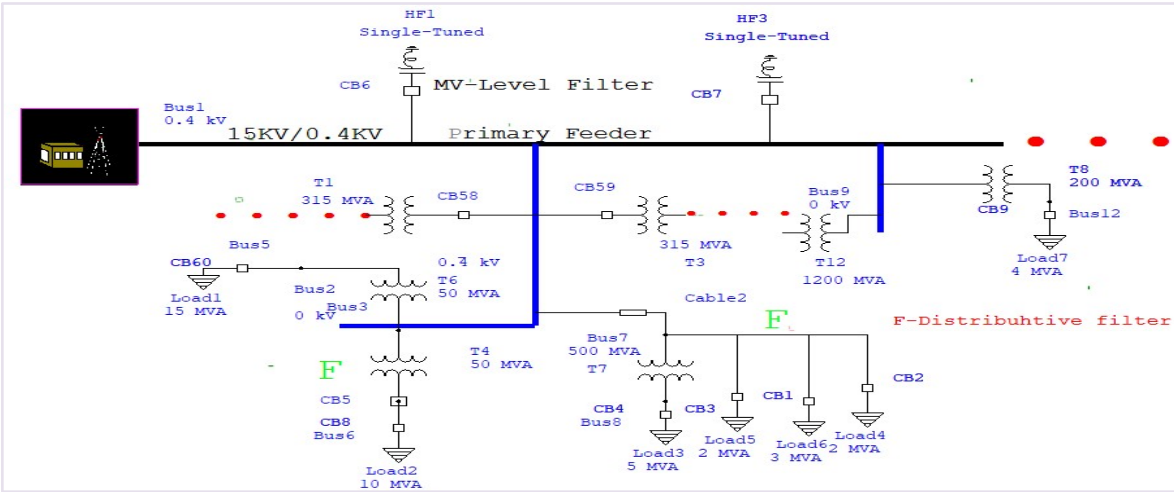


Figure .5.1.Residential distribution feeder illustrating different possible filter schemes

5.4.8. LOW VOLTAGE DISTRIBUTION SYSTEMS

Figure.5.2. shows a typical schematic of a low voltage distribution system supplying residential loads. The system is consisting of the primary and secondary feeders. The primary feeder transfers are the electrical power from substation to several service transformers. Each secondary system consists of a service transformer and the various houses supplied by it. As shown in the figure, the houses are connected to 0.4KV voltage level of the service transformers through the secondary conductors.

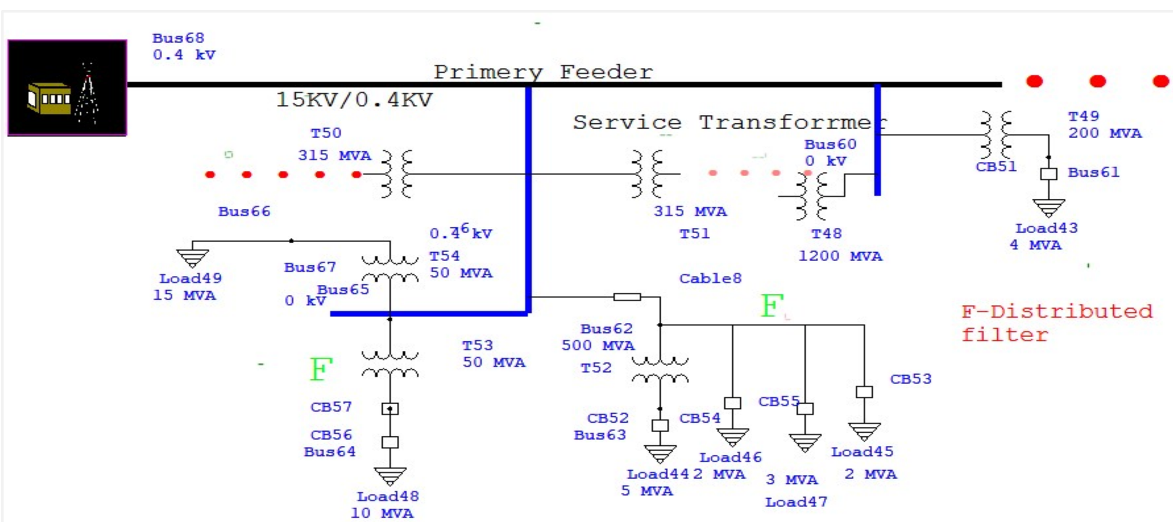


Figure.5.2. A typical schematic of a low voltage distribution system supplying residential loads

5.4.9. PASSIVE FILTER DEFINITIONS

A shunt filter is said to be tuned to the frequency that makes its inductive and capacitive reactance's equal. The quality of a filter (Q) determines the sharpness of tuning and in this respect; filters may be either of a high or a low Q type. The former is sharply tuned to one of the lower harmonic frequencies (e.g. the fifth) and a typical value is between 30 and 60. The low Q filter, typically in the region of 0.5–5, has low impedance over a wide range of frequency. When used to eliminate the higher-order harmonics (e.g. 17^{th} up wards) it is also referred to as a high-pass filter. Typical examples of high and low Q filter circuits and their impedance variation with frequency are illustrated in Figures 5.3 and 5.4. In the case of a tuned filter Q is defined as the ratio of the inductance (or the capacitance) to resistance at the resonant frequency, i.e.

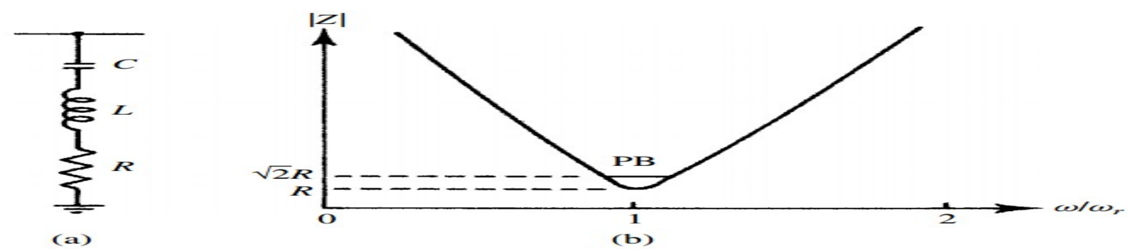


Figure.5.3.Single-tuned shunt filter circuit (b) Single-tuned shunt filter impedance versus frequency: [Ebooks club.Drg_ power system Harmonics]

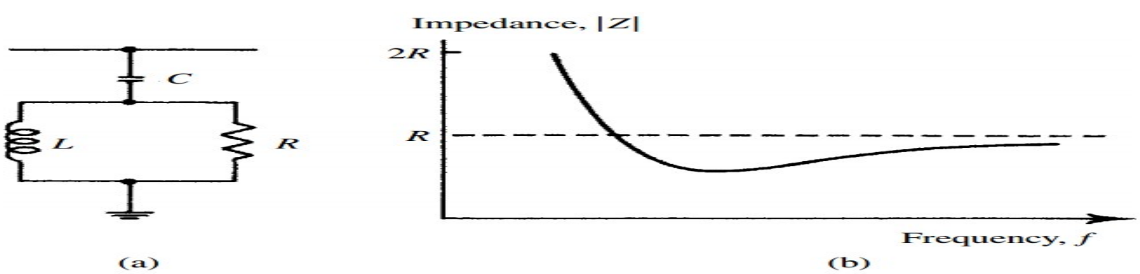


Figure.5.4. Second-order damped shunt filter; (b) second-order damped shunt filter impedance versus frequency: [Ebooks club.Drg_ power system Harmonics]

$$Q = \frac{X_0}{R} \quad (5.12)$$

As shown in Figure 5.4 the filter pass band (PB) is defined as being bounded by the frequencies at which the filter reactance equals its resistance, i.e. the impedance angle is 45°

and the impedance module $\sqrt{2R}$. The quality factor and pass band are related by the expression of the following equation.

$$Q = \frac{\omega_n}{PB} \tag{5.13}$$

Where ω_n is the tuned angular frequency in radians per second, the sharpness of tuning in high-pass damped filters is the reciprocal of that of tuned filters, i.e. Q = $\frac{X}{R}$ .The extent of filter detuning from the nominal tuned frequency is represented by a factor δ. This factor includes various effects: (i) variations in the fundamental (supply) frequency; (ii) variations in the filter capacitance and inductance caused by ageing and temperature; and (iii) initial off-tuning caused by manufacturing tolerances and finite size of tuning steps. The overall detuning, in per unit of the nominal tuned frequency, is

$$\delta = \frac{(\omega - \omega_n)}{\omega_n} \tag{5.14}$$

Moreover, a change of L or C of say 2% causes the same detuning as a change of system frequency of 1%. Therefore, δ is often expressed as

$$\delta = \frac{\Delta f}{f_n} + \frac{1}{2}\left(\frac{\Delta L}{L_n} + \frac{\Delta C}{C_n}\right) \tag{5.15}$$

5.5. FILTER DESIGN CRITERIA

5.5.1. CONVENTIONAL CRITERIA

The size of a filter is defined as the reactive power that the filter supplies at fundamental frequency. It is substantially equal to the fundamental reactive power supplied by the capacitors. The total size of all the branches of a filter is determined by the reactive power requirements of the harmonic source and by how much this requirement can be supplied by the a.c. A more practical approach is to try to reduce the problem to an acceptable level at the point of common coupling with other consumers, the problem being expressed in terms of harmonic current, harmonic voltage, or both. A criterion based on harmonic voltage is more convenient for filter design, because it is easier to guarantee staying within a reasonable voltage limit than to limit the current level as the a.c network impedance changes. The voltage THD index is more representative than the arithmetic sum, because it corresponds to the power of the harmonics and is therefore more closely related to the severity of the disturbance. The recommended criteria for HV converter filters are the maximum level of any single harmonic and the THD. In general, it will be sufficient to include all harmonics up to the 25^{th} order. The maximum values of individual harmonics generally occur for different conditions. It is therefore necessary.

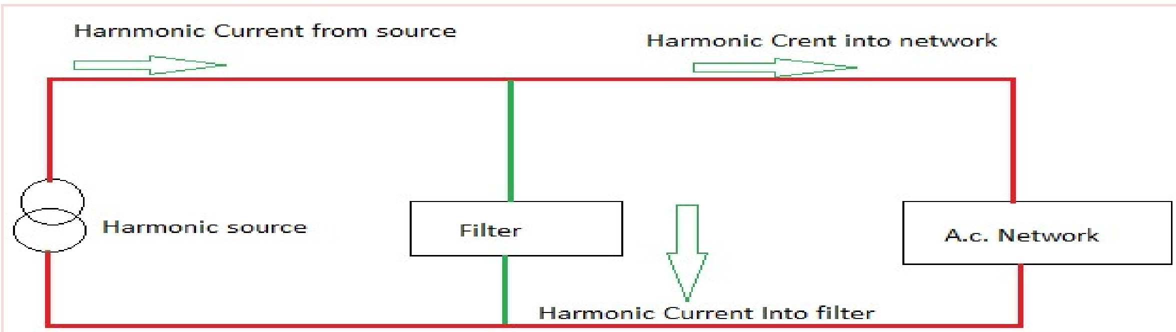


Figure .5.5. Circuit for computation of voltage harmonic distortion

To clarify whether the THD should use those values of individual harmonics which are simultaneously present, or the non-coincident maximum values of each harmonic, regarding telephone interference, although used in a number of projects, the IT index into a node of a meshed transmission system has little meaning. However, in cases when earth resistivity is high there is justification to limit the magnitudes of harmonic currents flowing in particular transmission lines which run close to telephone lines; this is normally achieved with the use of the 'equivalent disturbing current' concept to comply with the required harmonic limitations, the design of filters involves the following steps:

1. The harmonic current spectrum produced by the nonlinear load is injected into a circuit consisting of filters in parallel with the a.c. system and the harmonic voltages are calculated.
2. The results are used to determine the specific parameters, i.e. the THD, TIF and IT factors.
3. The stresses in the filter components, i.e. capacitors, inductors and resistors, are then calculated and with them their ratings and losses.

The obvious filter design is a single broad band-pass configuration capable of attenuating the whole spectrum of injected harmonics (e.g. from the fifth up in the case of a six-pulse converter). However, the capacitance required to meet such a target is too large, and it is usually more economical to attenuate the lower harmonics by means of single arm tuned, high pass, C-type and damped filters.

5.5.2. ADVANCED FILTER DESIGN CRITERIA

The conventional criteria described above provide adequate filter designs for most applications. However; the in cases where the nonlinear plant has a very large power rating, such as Hva.c. Converter, these criteria can lead to inadequate solutions and even harmonic instabilities. The reason is that the conventional approach ignores the interaction that exists between the nonlinear device and the rest of the power system. Such interaction affects the harmonic current injections as well as the overall system harmonic impedances (which should include the effective contribution of the nonlinear device), and thus requires an iterative solution, rather than the direct solution of the conventional approach.

5.5.3. TUNED FILTERS

A single tuned filter is a series *RLC* circuit a tuned to the frequency of one harmonic (generally a lower characteristic harmonic). Its impedances given by:

$$Z_1 = R + j(\omega L - \frac{1}{\omega C}) \tag{5.16}$$

Which at the resonant frequency (*fn*) reduces to *R*. There are two basic design parameters to be considered prior to the selection of *R*, *L* and *C*. These are the quality factor (*Q*), and the relative frequency deviation (δ), already defined. In order to express the filter impedance in terms of *Q* and δ, the following relationships apply:

$$\omega = \omega_n(\delta + 1) \tag{5.17}$$

$$\omega_n = \frac{1}{\sqrt{LC}} \tag{5.18}$$

the reactance of inductor or capacitor in ohms at the tuned frequency is:

$$X_0 = \omega_n L = \frac{1}{\omega_n C} = \sqrt{\frac{L}{C}} \tag{5.19}$$

$$Q = \frac{X_0}{R}, C = \frac{1}{\omega_n X_0} = \frac{1}{\omega_n RQ}, L = \frac{X_0}{\omega_0} = \frac{RQ}{\omega_n} \quad (5.20)$$

substituting equation above in to each other it yields: -

$$Z_f = R\left(1 + jQ\delta\left(\frac{2+\delta}{1+\delta}\right)\right) \quad (5.21)$$

or, considering that δ is relatively small as compared with unity,

$$Z_f = R(1 + j2\delta Q) = X_0(Q^{-1} + j2\delta) \quad (5.22)$$

$$||Z_f| = R(1 + 4\delta^2 Q^2)^{\frac{1}{2}} \quad (5.23)$$

generally, more convenient to deal with admittances rather than impedances in filter design, i.e. is shown as bellows.

$$Y_f = \frac{1}{R(1+j2\delta Q)} = G_f + jB_f \quad (5.24)$$

$$where,\ G_f = \frac{Q}{x_0(1+4\delta^2 Q^2)}, B_f = -\frac{2\delta Q^2}{X(1+4\delta^2 Q^2)} \quad (5.25)$$

the harmonic voltage at the filter bus bar is: -

$$V_n = \frac{I_n}{Y_{nf}+Y_{sn}} = \frac{I_n}{Y_n} \quad (5.26)$$

Therefore, to minimize the voltage distortion it is necessary to increase the overall admittance of the filter in parallel with the a.c. system. For a prediction of the largest Vn, the variables that are not accurately known have to be chosen pessimistically; these are the frequency deviation δ and the network admittance Ysn. Since the harmonic voltage increases with δ, the largest expected deviation δm must be used in the analysis. Again, the worst realistic system condition (the lowest admittance) must be represented. With certain limits the designer can decide on the values of Q and filter size (VA rating at the fundamental frequency).

$$|V_n| = I_n\left\{\left[G_{sn} + \frac{1}{R(1+4Q^2\delta^2)}\right]^2 + \left[B_{sn} - \frac{2Q\delta}{R(1+4Q^2\delta^2)}\right]^2\right\}^{\frac{-1}{2}} \quad (5.27)$$

The case of purely inductive a.c. network admittance, often used in filter design, is unduly pessimistic.

$$|V_n| = I_n\{(|Y_{sn}|\cos\phi_{sn} + G_f)^2 + (-Y_{sn}\sin\phi_{sn} + B_f)^2\}^{-1/2} \quad (5.28)$$

taking ϕ_{sn} positive and δ negative

if$|Y_{sn}|$ is left unrestricted, the admittance giving maximum $|V_n|$is

$$Y_{sn} = \frac{\cos\phi\sin(2Q\delta ta \quad sn-1)}{R(1+4Q^2\delta^2)} \quad (5.29)$$

$$|V_n| = I_n\omega_n L\left[\frac{1+4Q^2\delta^2}{Q(\sin\phi_{sn}+2Q\delta\cos\phi_{sn})}\right] \quad (5.30)$$

$$Q = \frac{1+\cos \quad sn}{2\delta\sin \quad sn} \quad (5.31)$$

$$|V_n| = I_{n\delta}\omega_n L\left[\frac{4}{(1+\cos\phi_{sn})}\right] = \frac{2I_nR}{\sin\phi_{sn}} \quad (5.32)$$

Nevertheless, it should be noted that filters are not usually designed to give minimum harmonic voltage under these conditions. Normally a higher Q is selected in order to reduce losses. A condition that also has to be considered in the design of filters, and which can restrict the operation of the converters, is an outage of one or more filter branches. The remaining filter branches may then be over-stressed as they have to take the total harmonic current generated by the converter.

Types of damped filters

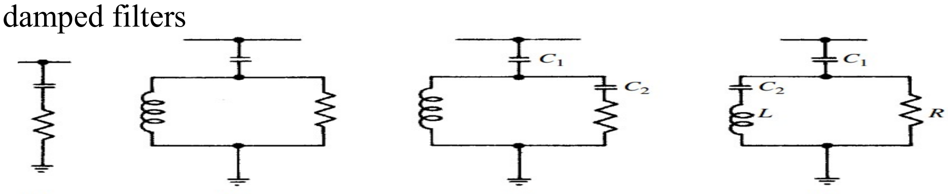


Figure .5.6. High-pass damped filters: (a) first order; (b) second order; (c) third order; (d) c-type order: **[Ebooks club.Drg_ power system Harmonics]**

The main disadvantage of damped filters is as follows

1. To achieve a similar level of filtering performance the damped filter needs to be designed for higher fundamental VA ratings, though in most cases a good performance can be met within the limits required for power factor correction.
2. The losses in the resistor and reactor are generally higher.

5.5.4. TYPE OF DAMPED FILTERS

Four types of damped filters are shown in Figure 5.6, first-order, second-order, third order and C-type.

1. The first-order filter is not normally used, as it requires a large capacitor and has excessive loss at the fundamental frequency.
2. The second-order type provides the best filtering performance, but has higher fundamental frequency losses as compared with the third-order filters.
3. The main advantage of the third-order type over the second-order type is a substantial loss reduction at the fundamental frequency, owing to the increased impedance at that frequency caused by the presence of the capacitor $C2$. Moreover, the rating of $C2$ is very small compared with $C1$.
4. The filtering performance of the C-type filter lies in between those of the second- and third-order types. Its main advantage is a considerable reduction in fundamental frequency loss, since $C2$ and L are series tuned at that frequency. However, this filter is more susceptible to fundamental frequency deviations and component value drifts.

5.5.5. DESIGN OF DAMPED FILTERS

When designing a damped filter, the Q is chosen to give the best characteristic over the required frequency band and there is no optimal Q as with tuned filters. The behavior of damped filters has been described by Ainsworth with the help of two parameters.

$$F_0 = \frac{1}{2\pi CR} \tag{5.33}$$

$$m = \frac{L}{R^2} \tag{5.34}$$

Typical values of m are between 0.5 and 2. For a given capacitance these parameters (and hence L and R) are decided to achieve an appropriately high admittance over the required frequency range. The conductance and suspectance terms of second-order damped filter admittance are

$$G_f = \frac{m^2x^2}{R[(1-mx^2)^2+m^2x^2]} \quad (5.35)$$

$$B_f = \frac{x}{R_1}\left[\frac{1-mx^2+m^2x^2}{(1-mx^2)^2+m^2x^2}\right] \quad (5.36)$$

Where, $x = \frac{f}{f_0}$ the minimum total admittance (i.e the filter Y_F plus the a.c systemY_{sn}) can be shown to be

$$Y = B_f\cos\Phi_m + G_f\sin\Phi_m \quad (5.37)$$

With both terms in equation (5.39) being positive and x being less than the value that gives

$$|cos\Phi_f| = \left|\frac{G_f}{B_f}\right| = |tan\Phi_m| \quad (5.38)$$

where,Vc, V_l and represent the, inductor and supply voltages, respectively the filter size is expressed as:

$$S = \frac{V_s^2}{X_c-X_L} \quad (5.39)$$

For greater values of x the minimum total admittance is that of the filter (i.e with$Y_{sn} = 0$).Figure 5.7 illustrates typical minimal admittances for a second-order damped filter in parallel with a lossless system (i.e. Φm= ±90◦*)*. For comparison the conductance component G_f *of* a third-order damped filter, for the case of equal capacitors. These figures show that the third-order filter peaks are much sharper than those of the second order.

5.5.6. CONVENTIONAL FILTER CONFIGURATIONS

5.5.7. SIX-PULSE DESIGN

Static converters of large ratings are normally designed for at least 12-pulse operation. In many schemes, however, to cope with maintenance and other partial temporary outages, six-pulse operation is permitted. Under such conditions they produce considerable 5^{th} and 7^{th}

harmonics as well as the characteristic 12-pulse-related orders. These are conventionally filtered by using a hybrid combination of tuned branches for the low orders.

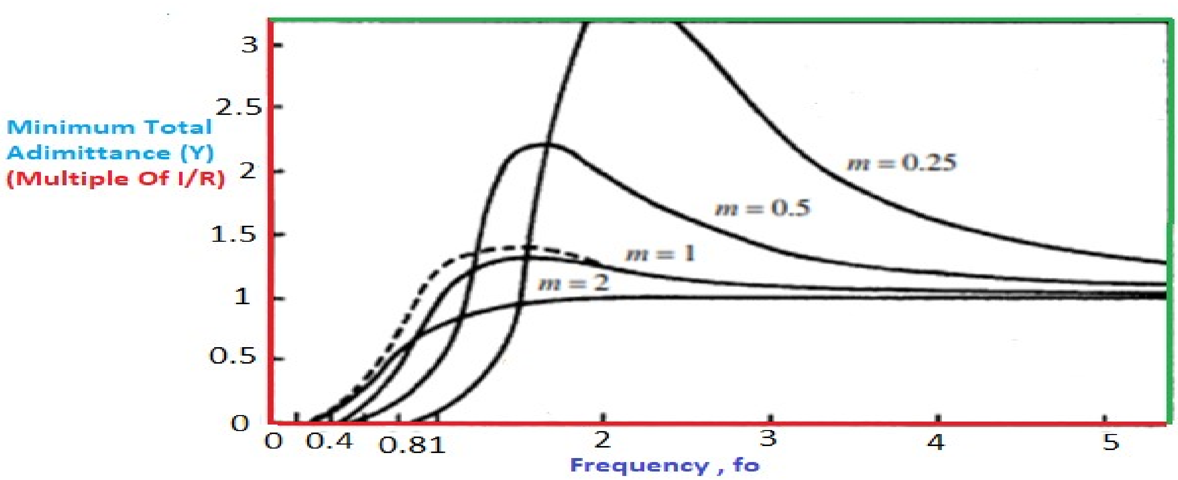


Figure 5.7. Admittance of second-order low-pass filter: [Ebooks club.Drg_ power system Harmonics]

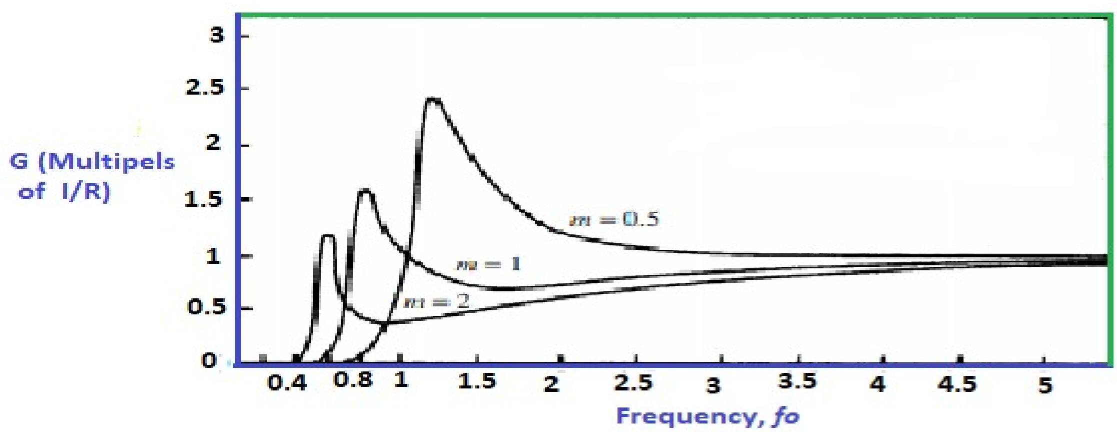


Figure 5.8. Conductance components for third-order low-pass filter orders, i.e. 5^{th}, 7^{th}, 11^{th} and 13^{th}, and a high-pass damped filter for the 17^{th} and higher orders: [Ebooks club.Drg_ power system Harmonics]

5.5.8. SINGLE –TUNED FILTERS

In a high Q is circuit it may be assumed that

$$V_c = V_l + V_s \tag{5.40}$$

Where, Xc and X_l are the fundamental frequency reactance's of the capacitor and inductor. But for a filter tuned to harmonic n,

$$X_0 = nX_l = \frac{X_c}{n} \tag{5.41}$$

$$X_L = \frac{X_c}{n^2} \text{ and } V_l = \frac{V_c}{n^2} \tag{5.42}$$

Therefore,

$$S = \frac{V_s^2}{\left[X_c\left(1-1\frac{1}{n^2}\right)\right]} = \left(\frac{V_s^2}{X_c}\right)\left[\frac{n^2}{(n^2-1)}\right] \text{MVAr} \tag{5.43}$$

also

$$V_c - V_l = V_c\left(1-\frac{1}{n^2}\right) = V_s \tag{5.44}$$

that is

$$V_c = \left[\frac{n^2}{(n^2-1)}\right] V_s \text{kv} \tag{5.45}$$

The loading for each filter component is determined for cost evaluation as follow as: fundamental loading:

$$\frac{V_c^2}{X_c} = \left(\frac{V_s^2}{x_c}\right) * \left[\frac{n^2}{n^2-1}\right]^2 = s\frac{n^2}{(n^2-1)} \tag{5.46}$$

harmonic loading:

$$I_n^2\left(\frac{X_c}{n}\right) = \left[\frac{I_n^2 * V_s^2}{s*n}\right] * \left[\frac{n^2}{n^2-1}\right] \text{MVAr} \tag{5.47}$$

the power loss:

$$\text{Kcl*(total loading)} = Kcl * \left[s + \left(\frac{I_n^2 * V_n^2}{(s*n)}\right)\right][n^2 - 1]\text{kW} \tag{5.48}$$

Where, Kcl is the loss factor of the capacitors (in$\frac{KW}{MVAr}$)

Inductor fundamental loading is defined as,

$$\frac{V_L^2}{X_L} = \left(\frac{V_c}{n^2}\right)^2 * \left(\frac{n^2}{X_c}\right) = \frac{V_c^2}{n^2 X_c} = \left(\frac{s}{n^2}\right) * \left[\frac{n^2}{n^2-1}\right] \text{MVAr} \quad (5.49)$$

Harmonic loading is the same as for the capacitor since the reactance are equal at harmonic frequency. For cost purposes, it is convenient to consider the losses in the total effective resistance R, where

$$R = \frac{X_0}{Q} = \frac{X_c}{nQ} \quad (5.50)$$

the fundamental current is

$$I_1 = \frac{S}{V_s} \text{kA}$$

and the total power loss

$$(I_1^2 + I_n^2)R = \left(\frac{S^2}{V_s^2}\right) * \frac{X_c}{nQ} + \frac{I_n^2 X_c}{nQ}$$

$$= \left[\frac{S^2}{nQ}\right] * \left(\frac{1}{S}\right) * \left[\frac{n^2}{(n^2-1)}\right] + \left[\frac{I_n^2 V_s^2}{nSQ}\right] * \left[\frac{n^2}{n^2-1}\right]$$

$$= \left[\frac{S}{nQ} + \frac{I_n^2 V_s^2}{snQ}\right] * \left[\frac{n^2}{n^2-1}\right] * 10^3 \text{kw} \quad (5.51)$$

for comparison purpose, the cost of energy losses is expressed in terms of equivalent capital cost by use of a present value factor:

$$P_v = \frac{[(1+i)^N - 1]}{[i((1+i)^N)]} \quad (5.52)$$

Where, the interest rate and N is the budgeted filter life. Thus, the present value cost of energy losses is:

$$P_v U_u F_u * 365 * 24 * (\text{total power losse})$$

$$= 8760 P_v U_u F_u * (\text{total Power loss}) \quad (5.53)$$

Where U_u is the cost of energy loss per kilowatt-hour and f_u is the filter utilization factor. The complete expression for the total cost is

$$\mathrm{TCOST} = \mathrm{U_T} + \left[\frac{\mathrm{n^2}}{(\mathrm{n^2}-1)}\right]\left\{\mathrm{U_c} + \left(\mathrm{S} + \frac{\mathrm{V_s^2 I_n^2}}{\mathrm{nS}}\right) + \mathrm{U_L}\left(\frac{\mathrm{S}}{\mathrm{n^2}} + \mathrm{V_s^2 I_n^2}\right) + 8760\mathrm{P_v U_u F_u}\left[\mathrm{Kcl}\left(\frac{\mathrm{S}}{\mathrm{nQ}} + \frac{\mathrm{V_s^2 I_n^2}}{\mathrm{nSQ}}\right)\right]\right\}$$

That is $\mathrm{TCOST} = U_T + As + \frac{B}{S}$ (5.54)

Where $\mathrm{U_T}$ is the total cost of the filter branch, Uc is the capacitor incremental cost MVAr, $\mathrm{U_L}$ is the inductor incremental cost per MVAr,

$$A = \left[\frac{n^2}{(n^2-1)}\right]\left[U_c + \frac{U_L}{n^2} + 8760 P_v U_u F_u\left(Kcl + \frac{10^3}{nQ}\right)\right] \quad (5.55)$$

and

$$\mathrm{B} = \left[\frac{\mathrm{n^2}}{(\mathrm{n^2}-1)}\right] * \left[\frac{\mathrm{V_s^2 I_n^2}}{\mathrm{n}}\right] * \left[\mathrm{U_c} + \mathrm{U_L} + 8760\mathrm{P_v U_u F_u}\left(\mathrm{Kcl} + \frac{10^3}{\mathrm{Q}}\right)\right] \quad (5.56)$$

$$\frac{\mathrm{d(TCOST)}}{\mathrm{dS}} = 0 \quad (5.57)$$

that is when

$$\mathrm{S_{MIN}} = \sqrt{\frac{\mathrm{B}}{\mathrm{A}}}\mathrm{MVAr} \quad (5.58)$$

5.5.8.1. BAND-PASS FILTER

The component loadings at fundamental and all harmonic frequencies may be determined as for the single-tuned filter, i.e.

$$\mathrm{S} = \left(\frac{\mathrm{V_s^2}}{\mathrm{X_c}}\right)\left[\frac{\mathrm{n_0^2}}{(\mathrm{n_0^2}-1)}\right]\mathrm{MVAr} \quad (5.59)$$

Where, n_o is the ratio of the tuned frequency to the supply frequency and capacitor rating of the fundamental loading is

$$\mathrm{S} = \left[\frac{\mathrm{n_0^2}}{(\mathrm{n_0^2}-1)}\right]\mathrm{MVAr} \quad (5.60)$$

the loading at harmonic n is

$$\mathrm{I_n^2}\left(\frac{\mathrm{X_c}}{\mathrm{n}}\right) \quad (5.61)$$

and using equation (5.47) this becomes

$$\frac{1}{S}\left(\frac{I_n^2}{n}\right)\frac{V_S^2 n_0^2}{(n_0^2-1)} \tag{5.62}$$

thus, the total harmonics loading is

$$\left[\frac{1}{S}\left(\frac{V_S^2 n_0^2}{(n_0^2-1)}\right)\right]\sum_{n=n_{min}}^{N}\left(\frac{I_n^2}{n}\right)\text{MVAr} \tag{5.63}$$

inductor rating

by using the Q value is 1.5 such that

$$R = 1.5X_0 = 1.5n_0X_L \tag{5.64}$$

thus, if the filter is tuned to a frequency close to the 17^th^harmonics

$$R \approx 25X_L \tag{5.65}$$

Since, $I_c = I_L + jI_R$it follows that, at fundamental frequency,

$$I_c = I_L \tag{5.66}$$

and the fundamental loading is

$$I_L^2X_L = \frac{I_c^2X_c}{n_0^2} = \left(\frac{S}{V_s}\right) * \left[\frac{V_S^2}{n_0^2}\right] * \left[\frac{n_0^2}{n_0^2-1}\right] = \left(\frac{S}{n_0^2}\right) * \left[\frac{n_0^2}{(n_0^2-1)}\right]\text{MVAr}$$

at harmonic n,

$$(I_L)_n = \frac{I_nR}{(R+jX_L)} = \frac{I_nQ}{\left[Q+\left(\frac{jn}{n_0}\right)\right]} \tag{5.67}$$

and

$$|(I_L)_n| = \frac{I_nQ}{\left[Q^2+\left(\frac{n}{n_0}\right)^2\right]^{1/2}} \tag{5.68}$$

the inductive reactance at harmonic n is

$$(X_L)_n = X_0\left(\frac{n}{n_0}\right) = \left(\frac{n}{n_0}\right) * \left(\frac{X_0}{n_0}\right)$$

$$= \left(\frac{n}{n_0^2}\right) * \left(\frac{V^2}{S}\right) * \left[\frac{n_0^2}{n_0^2-1}\right] \quad (5.69)$$

thus, the loading at harmonic n is

$$(I_L)_n^2(X_L)_n = \frac{1}{S}Q^2V_0^2\left[\frac{n_0^2}{(n_0^2-1)}\right] * \left[\frac{nI_n^2}{(Q^2n_0^2+n^2)}\right]\text{MVAr} \quad (5.70)$$

and the total harmonic loading is

$$= \frac{1}{S}Q^2V_0^2\left[\frac{n_0^2}{(n_0^2-1)}\right]\sum_{n=n_{min}}^{n_{min}}\left[\frac{nI_n^2}{Q^2n_0^2+n^2}\right]\text{MVAr} \quad (5.71)$$

Where, power losses of the capacitor are:

(1) The power loss in the capacitor is $Kcl * (total\ rating\ in\ kilowatts)$

(2) The inductor series resistance at fundamental frequency is

$$R_L = \frac{X_0}{Q_0} = \left(\frac{n_0}{Q_l}\right)X_L \quad (5.72)$$

Where, QL is the quality factor of the inductor, and the corresponding power loss is

$$I_L^2R_L = \left(\frac{n_0}{Q_L}\right)\text{MVAr loading}$$

$$= \left[\frac{S}{(n_0Q_L)}\right] * \left[\frac{n_0^2}{(n_0^2-1)}\right]\text{MW} \quad (5.73)$$

Similarly, the harmonic power loss is

$$\sum(I_L)_n^2\,(R_L)_n = \frac{1}{S}\left(\frac{Q^2V_S^2n_0}{Q_L}\right) * \left[\frac{n_0^2}{n_0^2-1}\right]\text{MW} \quad (5.74)$$

(3) The power loss in the shunt resistor R may also be expressed as a fraction of the inductor of the fundamental frequency,

$$R = QX_0 = QX_L, |I_R| = \frac{|X_L|}{R} = \frac{I_LX_L}{R} = \frac{I_L}{Qn_0} \quad (5.75)$$

and the power loss is

$$\mathrm{I_R^2R} = \left(\frac{1}{\mathrm{Qn_0}}\right) * \mathrm{I_L^2} * \mathrm{X_L}$$

$$= \left(\frac{1}{Qn_0}\right)(MVAr\ loding)$$

$$= \left[\frac{S}{Qn_0^3}\right] * \left[\frac{n_0^2}{n_0^2-1}\right] * 10^3\mathrm{kw} \qquad (5.76)$$

5.5.8.2. THE DC SIDE FILTERS

at harmonic n,

$$|(I_R)_n| = |(I_L)_n|\left(\frac{X_L}{R}\right) \qquad (5.77)$$

and the power loss is

$$\sum(I_R)_n^2\,(R)_n = \frac{1}{S}\left(\frac{QV_S^2}{n_0}\right)\left[\frac{n_0^2}{(n_0^2-1)}\right]\sum_{n=n_{min}}^{n_{max}}\left[\frac{n^2 I_n^2}{Q^2n_0^2+n^2}\right] * 10^3\mathrm{kw} \qquad (5.78)$$

Total cost

Applying the present –value factor to energy cost and collecting terms in S and I/S as for the single tuned filter, it can be shown that once again the total cost is given by:

$$TCOST = U_T + As + \frac{B}{S} \qquad (5.79)$$

Where,

$$A = \left[U_c + \frac{U_L}{n_0^2} + 8760P_uU_uF_u\left(Kcl + \frac{10^3}{Q_Ln_0} + \frac{10^3}{Qn_0}\right)\right]\left(\frac{n_0^2}{n_0^2-1}\right) \qquad (5.80)$$

and

$$B = \left[\frac{n_0^2}{n_0^2-1}\right]V_S^2\sum_{n=n_{min}}^{n_{max}} I_n^2\left[\frac{U_c}{n} + \frac{Q^2U_Ln}{Q^2n_0^2+n} + 8760P_vU_uF_u\left(\frac{Kcl}{n} + \frac{Q^2n_0*10^3}{Q_L(Q^2n_0^2+n^2)}\right)\right] \qquad (5.81)$$

Where, TCOST cost is a minimum when,

$$S = S_{MIN} = \sqrt{\frac{B}{A}}\text{MVAr} \quad (5.82)$$

5.6. ECONOMIC ANALYSIS

Economic analysis by considering the harmonic filter device cost, frequently electrical device filters and power loss due to the current injection and heat dissipation in the system. This section analyzes and compares the overall costs of the filter schemes and the losses of power due to harmonic impacts of Adama-II wind power generation. For estimating the cost of MV (medium voltage) and LV (low voltage) network filters is used. Since the data belongs to the year of 2011, an annual inflation rate of 2.5% is also considered to obtain up-to-date cost estimation. The overall cost of designed MV filter packages and low voltage network is estimated as presented in blows. The power losses from each parameters or devices are as follows

$$P_R = \sum_{h=1}^{h_{max}} I_h^2 R_h + cost\ of\ equipment$$

where, $P_{LL} \rightarrow P_R + P_{EC} + P_{ST}$

$$P_{CE} \rightarrow P_{Ec} - \sum_{h=1}^{h_{max}} I_h^2 \mathrm{V}_\mathrm{h}^2\,, V_H = \frac{V_h}{V_1} I_H = \frac{V_H}{\sqrt{3} * R_1} = \frac{Percent of harmonic voltage}{\sqrt{3} * Resistance\ of\ R}$$

$$power\ loss = \sum I_h^2 V_h^2 = 0.0346^2 * 0.00865^2$$

$$= 0.11972 * 18hr * 365yr + cost\ of\ equipment$$

$$= 786.55Whryr + \$309{,}287.36$$

$$= 786.55MWhryr + \$309{,}287.36$$

When adding the harmonic filters to the system, voltage harmonic distortion become 0.030%and the magnitude of power losses before adding the filters and after adding the filters is calculated as bellows.

Power losses after the filters added $P_l = \sum I_h^2 V_h^2 = 0.0046^2 * 0.00115^2$

$$P_l = 2.79841 * 10^{-1}\ W * 18hr * 365yr$$

$$P_l = 3.971 * 10^{-2} Whrdayyr$$

$$P_l = 0.03971 MWhryr$$

The injection of power in the system due to impact of harmonics is 786.55MW/yr real power would be injected annually. By comparing power injection with using and without using the harmonic filters is 0.03791MW/yr and 786.55MW/yr energy would have been saved. Based on the southern region EEEPCo bill of quantity payment the loss of energy should be covert to money. The EEEPCo bill of quantity payment system or flat rate system is 1KWhr for 1.0522birr paid. By considering this information, when the total loss of power is multiplied with the factors would be as bellows table 5.5

Table. 5.5. EEPCo Bill tariff analysis for 2011 through 2014

Demand Category	Monthly demand in KWh	Existing tariff	December 2011	December 2012	December 2013	December 2014
1	1-50	0.2730	0.2730	0.2730	0.2730	0.2730
2	51-100	0.3564	0.4591	0.5617	0.6644	0.7670
3	101-200	0.4993	0.7807	1.0622	1.3436	1.6250
4	201-300	0.5500	0.9125	1.2750	1.6575	2.0000
5	301-400	0.5666	0.9750	1.3833	1.7917	2.2000
6	401-500	0.5880	1.0423	1.4965	51.9508	2.4050
7	Above 500KWh	0.6943	1.1410	1.5870	2.0343	2.810

$$P_l = (786.55 - 0.03791)MW/yr$$

$$P_l = 786.51MW/yr$$

therefore, using the above value of the total payment for energy loss is

$$Bill\ of\ quantity = \frac{786.51MW * 1.0ETB}{1KWhr * \frac{28ETB}{Dollar}} = \frac{786.51 * 1.00 * 1000}{28} = \$28,089.64$$

Table. 5.6. The cost of harmonic filters, frequently equipment damages and energy losses

No	Probability of Frequently Equipment Failures Unit Price and harmonic filters	
	Equipment	Unit Price
1	Switch gears	$10,240/yr
2	IGBT	$355.2/yr
3	Transformer	$24,000/yr
4	Harmonic tuned filers	$90,859.80
5	Television	$26,785/yr
6	Computer	$28,557.15/yr

7	Fridge	$17,707.15/yr
8	Ac machine	$100,000/yr
9	Dc Machine	$100,000/yr
10	Home appliances	$1,642.86/yr
11	Cost of energy loss from all branches	$10,265.21/yr
	Total cost	$410,265.21/yr

Table. 5.7. The cost comparing of single tuned harmonic filters, frequently equipment damages and energy losses

No	Cost of single tuned harmonic filters	Cost of energy loss and equipment damage	
		Per week	Per Year
1	$90,895.8($5^{th}$-$13^{th}$)	$58,721/Week	$411,051.72/yr
2	$154,522.86($5^{th}$-$n^{th}$)	$25,721/Week	$411051.72/yr

From the above conclusion the cost of energy loss and the cost frequently damage equipment yearly is $411,051.72 and the cost of filter devices are $90,859.80.Finally, by using a proper filter design would be saved $320,191.92 annually.

5.7. WIND TURBINE SYSTEM MODELING AND DESIGN METHODOLOGY

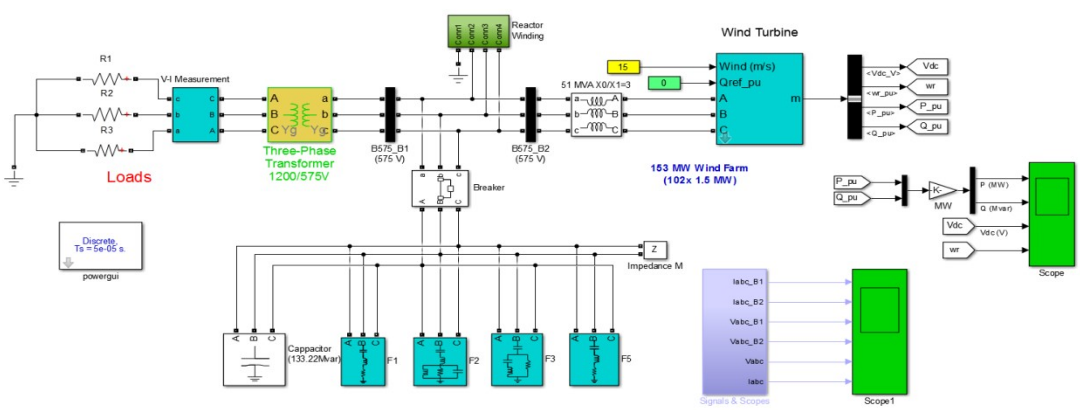


Figure.5.9. Simple model representation of wind turbine system approach

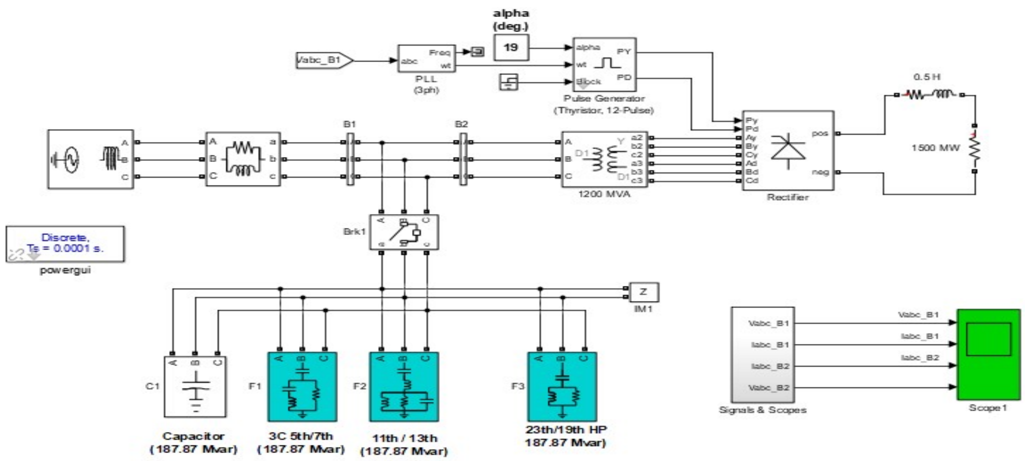


Figure. 5.10. Harmonic system design without wind turbine

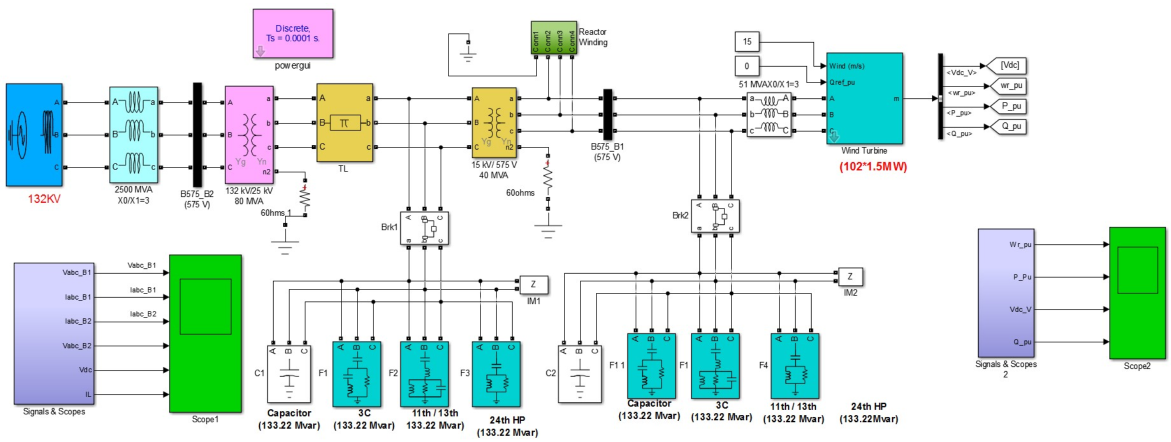


Figure. 5.11. Harmonic system design by using two filter station networks

5.8. WINDITURBINE MODELING AND HYDRO INTERCONNECTED DESIGN METHODOLOGY

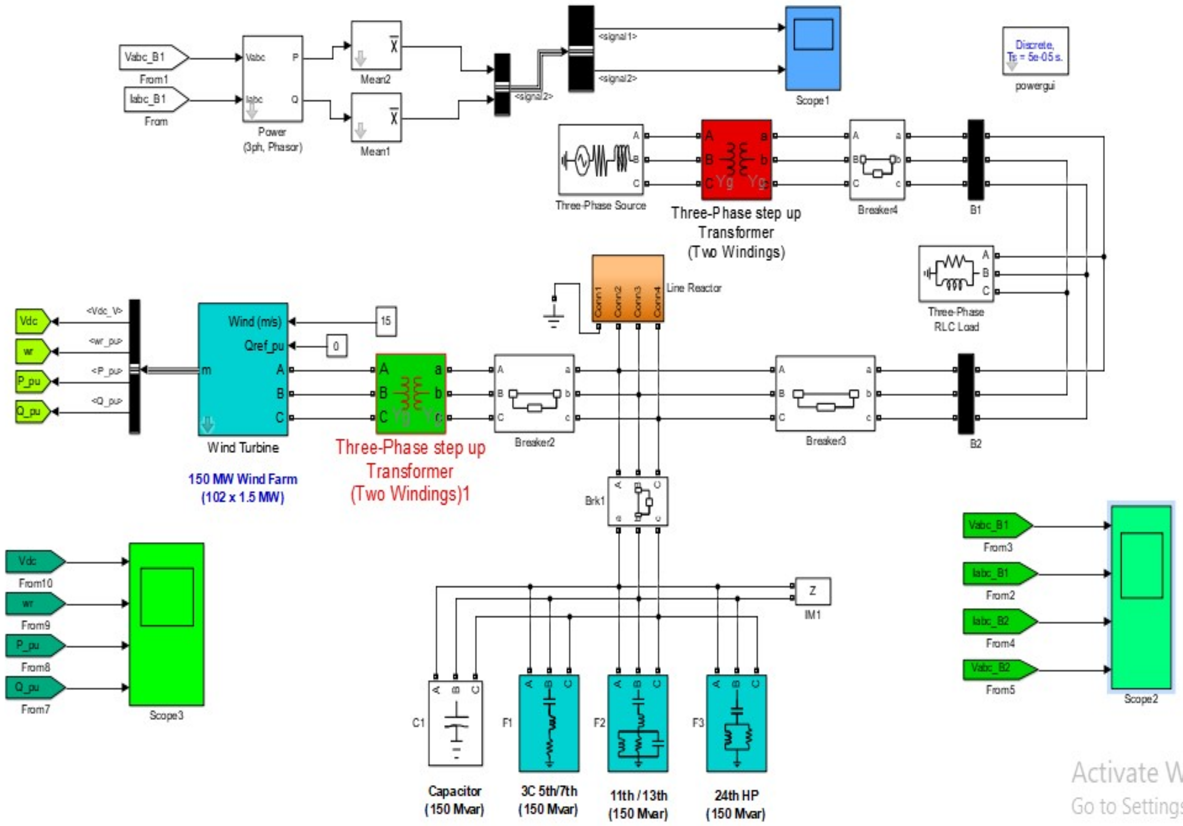


Figure. 5.12. System modeling design by combining the distribution network and wind turbine power generation

5.9. Review of wind turbine converters methods

Wind power is at the moment in a globally expansive phase with different kinds of technical solutions and suppliers. In most solutions power electronics is incorporated to smaller or larger extent. Most wind power plants currently operate with a horizontal axis turbine, however vertical axes turbines is an interesting generator. The power voltage output from the generator is rectified by an inverter connected to a DC-grid which is then connected via another inverter to a three phase grid. The reason to why an internal DC-grid is utilized is mainly to decouple the rotational speed of the wind power units from the grid frequency; the DC grid also acts as both filter and buffer.

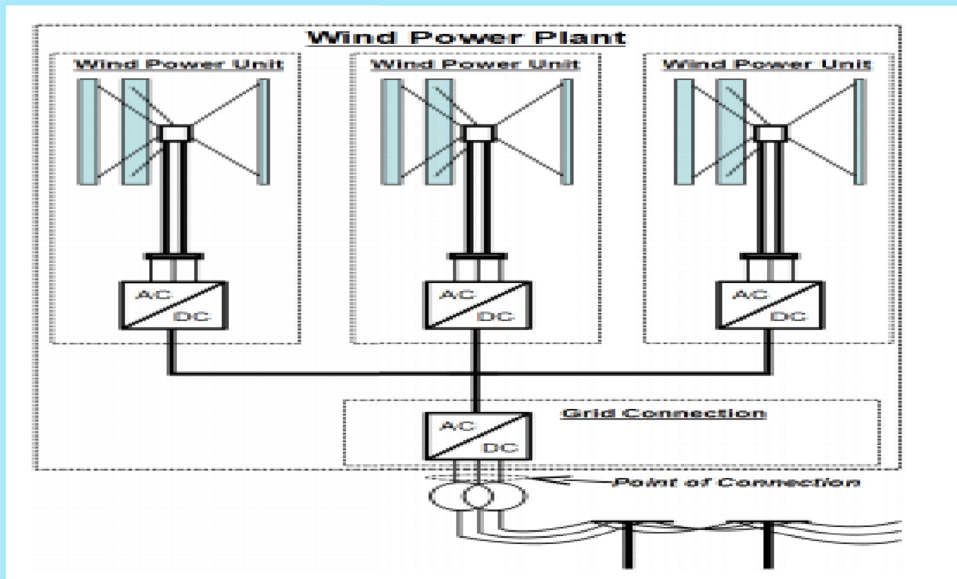
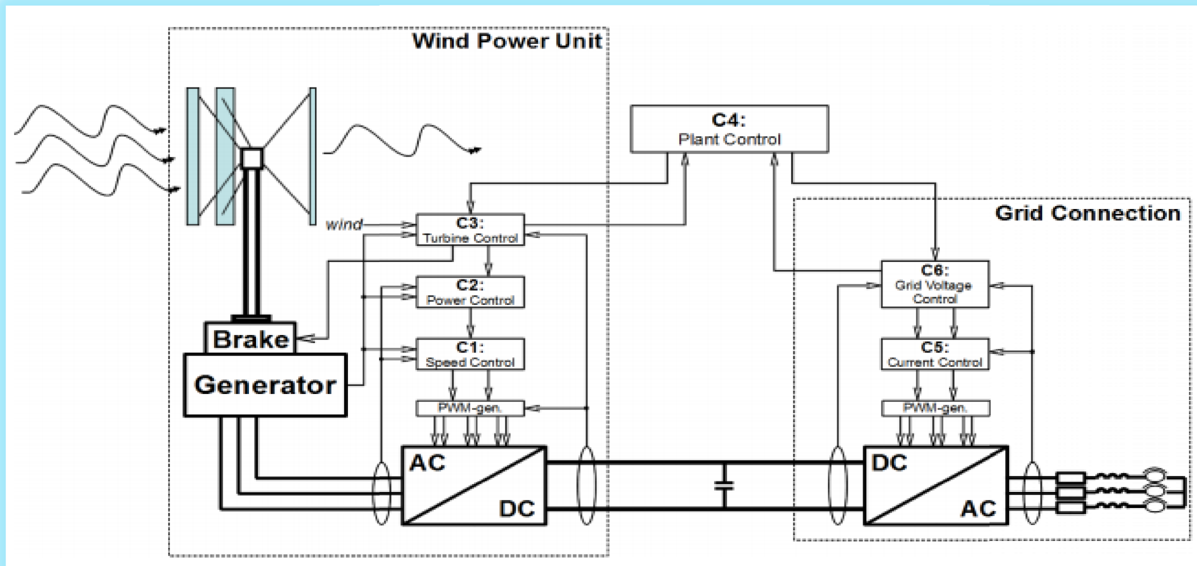


Figure .5.13. Wind turbine model external structure

Wind turbine power generations depend on the interactions between the wind and the rotor. The power extracted from the wind by the rotor can be described as the kinetic energy of the wind times an efficiency coefficient. The efficiency coefficient is varying with the pitch angle of the blades and tip speed ratio. The tip speed ratio is the wind speed relative the speed of the tip of the turbine's blades.

5.10. Modeling Wind turbine design methods

The system to be modeled consists, as depicted of a wind turbine connected through a break to the area swept by a vertical wind power turbine is simply expressed as the rotor diameter times the rotor length. The efficiency coefficient, Cp, can be calculated according to the mechanical torque Tω can be obtained by dividing the power absorbed, P, with the rotational speed of the turbine, ωT . A component modeling the effect of tower shadow was also implemented according to the tower shadowing effect occurs when a rotor blade passes behind the tower, this since it is then shadowed from the wind by the tower. This was modeled by subtracting a torque component each time a rotor blade passes behind the tower.



Tω = P ωT

Figure.15.14. Wind turbine model

5.11. Wing turbine inverter design of DC/AC (290V /15KV) feeder out going at the terminals

The dynamic behavior of wind turbine generators (WTGs) is quite different to that of synchronous generators. It is to be expected, therefore, that the dynamic performance of power systems may change as traditional generation is displaced by ever increasing numbers of WTGs. Numerous studies have investigated this issue, and have drawn various conclusions. This current report does not address the system-wide implications of large-scale wind generation. Rather, it focuses on the dynamic modeling of WTGs. In particular, the modeling of WTGs is considered, as they are currently the dominant technology for new wind farm developments. Such WTGs are also known as doubly fed induction generators (DFIGs) or doubly fed asynchronous generators. The electrical characteristics of WTGs are governed by interactions between the wound-rotor induction machine and the back-to-back inverter. The inverter excites the rotor of the induction machine with a variable AC source. This provides control of the rotor flux frequency, enabling the rotor shaft frequency to optimally track. This work is designed to assist the IGBT module selection process as well as offer guidance through the inverter/motor drive design and evaluation process. To build a successful inverter or drive requires an understanding of not only the power switches, but that of the load, line, associated transients, switching frequencies and power loss budget.

With these as the cornerstones or top level concerns, there is a clear need to understand the parasitic interactions of the IGBT module with the bus and the load and the actual losses beyond the theoretical calculations. This is a practical guide that will go through device selection, measurement techniques and related design issues.

5.12. Design Considerations for Using IGBT Modules in wind turbine Inverters and Drives

The inductor is internal and the user cannot bypass it at the output terminals. With this in play the 5 or 10us short circuit rating in the IGBT is not required. There is no way the end user can cause peak currents beyond what the filter inductors will allow by manipulating the outputs. The impedance of the inductor is chosen such that it is quite low at the fundamental output frequency, usually less than 1% PU and high enough to offer fairly low ripple current at the switching frequency at some given minimum load. For motor drives, the output of the half bridge conversion stage is often directly available to the end user. It is then possible to have the end user short one of the half bridge stages to some other terminal. Perhaps the earthing terminal, another phase terminal, a DC link terminal or any of the control terminals. In these circumstances, the drive must fail safely. This often requires the short circuit current to be sensed and acted upon thereby shutting down the appropriate power switches. The sensing event takes time. The output current needs to be sensed, the motion control engine needs to respond to the over current threshold, the gate drive needs to shut down the IGBT. If the turn off delay of a large IGBT is perhaps 1500ns at max temperature, with a propagation delay through the galvanic ally isolated gate drive circuit of 500ns worst case, with a worst case motion control engine interrupt of 2000ns and a current transducer settling time of 1us, the IGBT in the circuit must then be able to withstand a short circuit for at least 5us before shutdown can ensue. In larger drives, the short circuit interrupt event can take up to 7us or so by conventional design and motion control methodologies. In these cases, devices with a 10us short circuit withstands rating are required. There is an alternative to this for smaller machines and applications. The inverters in these machines are often built into the end bell housing of the machine and wired directly to the stator. In this configuration it is not physically possible to have the end user short an output to anything without massive disassembly effort. In these circumstances, the short circuit withstand requirement is not required.

5.13. DC/AC Power Inverter

A DC/AC power inverter is a circuit which modifies an input varying or non-varying direct current (DC) to an alternating current (AC) of a specified voltage and frequency, and a regulated DC voltage. In the case of this thesis, the input DC voltage source will be a mechanical rotation of wind turbine would convert by DC generator of wind turbine, which is synchronized to the hydro substation. As such, the DC voltage will likely be inconsistent, and considerations will need to be made in order to produce the desired output. This desired AC output is a 120Vrms, 60Hz pure sine wave. The desired DC output at the terminals is 690V regulated.

DC to AC power inverters, which aim to efficiently transform a DC powersource to a high v oltage AC source, similar to power that would be available at an electrical wall outlet.Inverte rs are used for many applications, as in situations where low voltage DC sources such as batt eries,
solar panels or fuel cells must be converted so that devices can run off of AC power. One exa mple ofsuch a situation would be converting electrical power from a car battery to run a lapto p, TV or cellphone.The method in which the low voltage DC power is inverted, is completed in two steps. The firstbeing the conversion of the low voltage DC power to a high voltage D C source,and the second stepbeing the conversion of the high DC source to an AC waveform using pulse width modulation. Anothermethod to complete the desired outcome would be to first convert the low voltage DC power to AC, andthen use a transformer to boost the voltage to 120 volts. This project focused on the first methoddescribed and specifically the transfor mation of a high voltage DC source into an AC output.Of the different DCAC inverters on th e market today there are essentially two different forms of Acoutput generated: modified sine wave, and pure sine wave. A modified sine wave can be seen as moreof a square wave than a sine wave; it passes the high DC voltage for specified amounts of time so that theaveragepo wer and rms voltage are the same as if it were a sine wave. Hese types of inverters are much cheaperthan pure sine wave inverters and therefore are attractive alternatives.Pure sine wave inverters, on the other hand, produce a sine wave output identical to the powercoming out of an electrical outlet. These devices are able to run more sensitive devices that a modifiedsine wave may cause damage to such as: laser printers, laptop computers, power tools, digital cloc ks andmedical equipment. This form of AC power also reduces audible noise in devices such

as fluorescentlights and runs inductive loads, like motors, faster and quieter due to the low h armonic distortion.

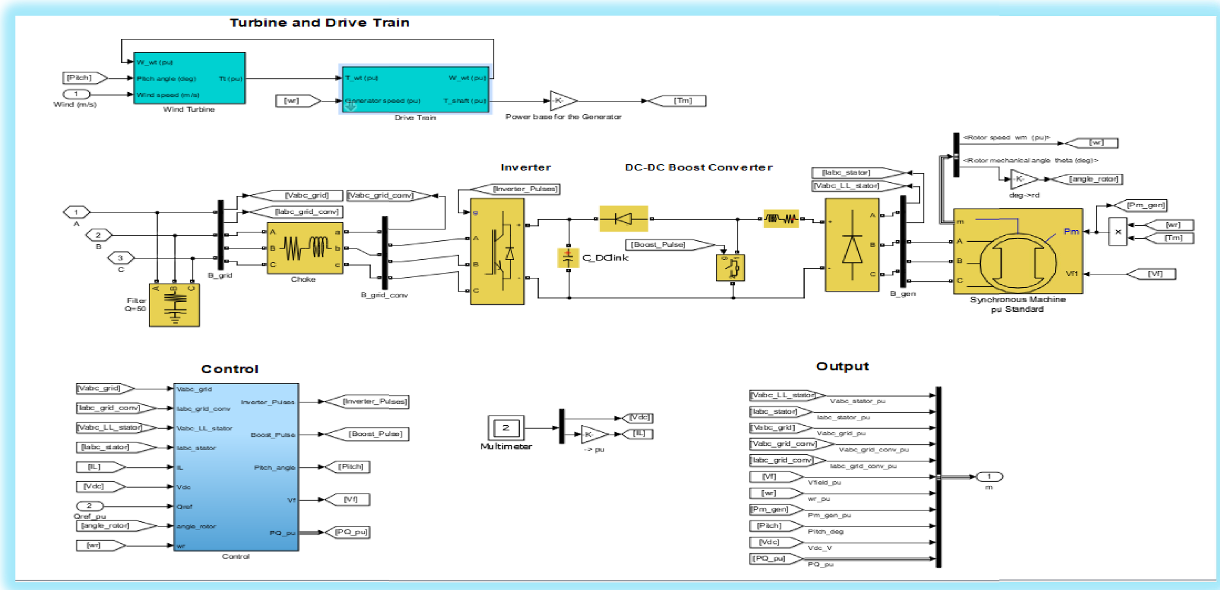


Figure.5.13. The internal wind turbine inverter design strictures in sub consistency

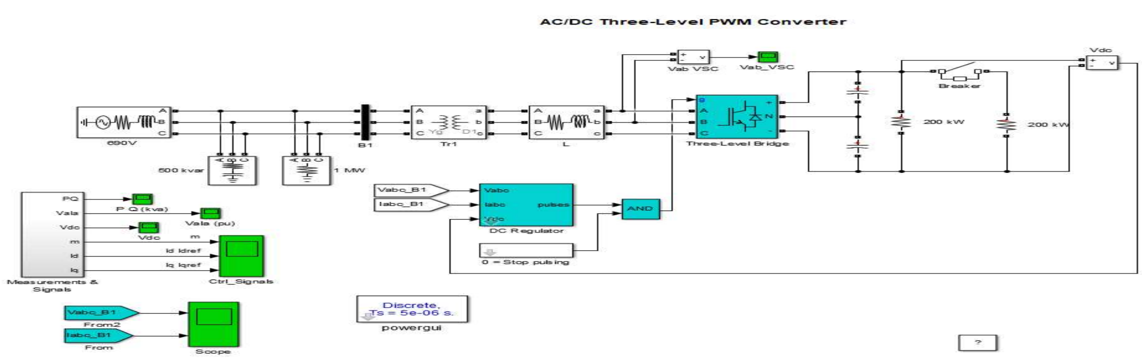


Figure .5.15. Wind turbine generator ac/Dc converter design model

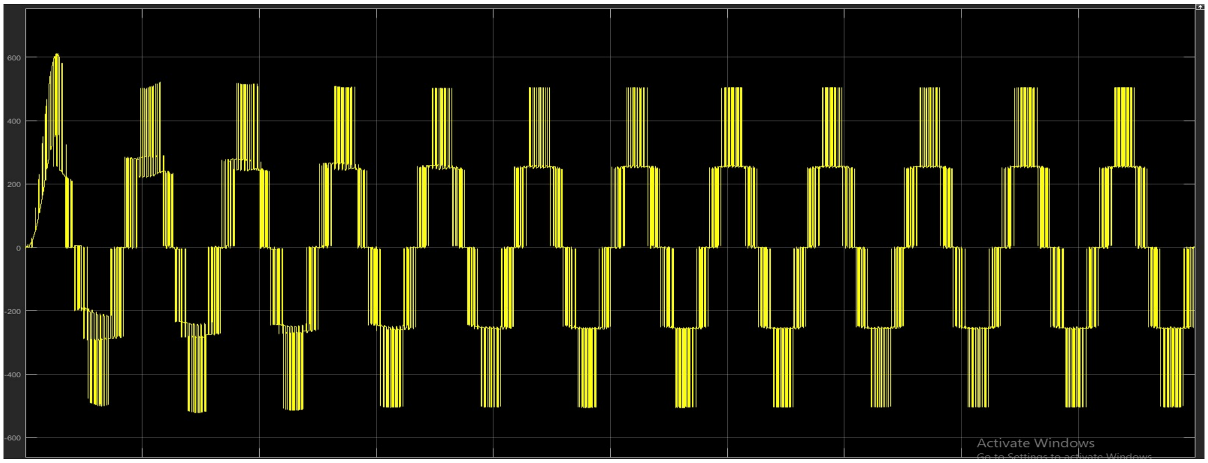


Figure .5.16. Dc voltage pulse width modulation out put

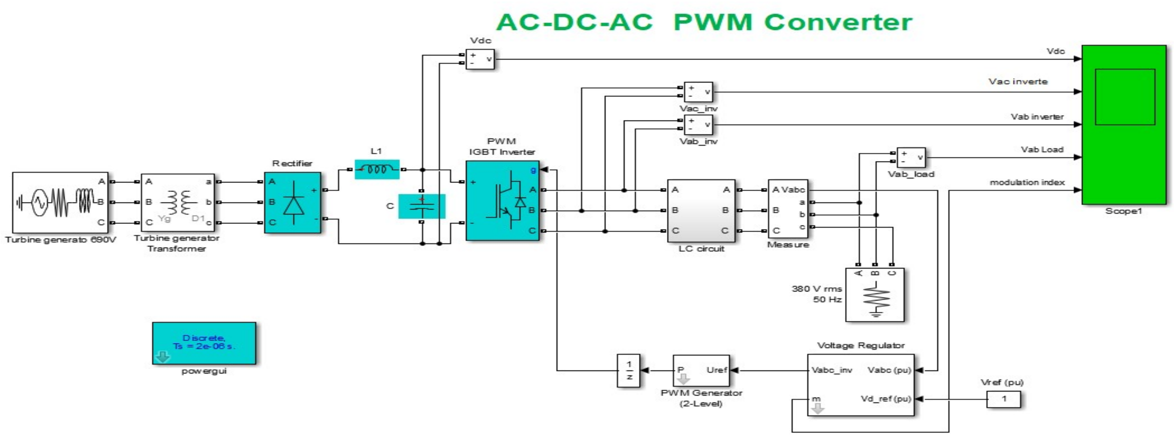


Figure .5.17. AC/Dc/AC wind turbine converter design model

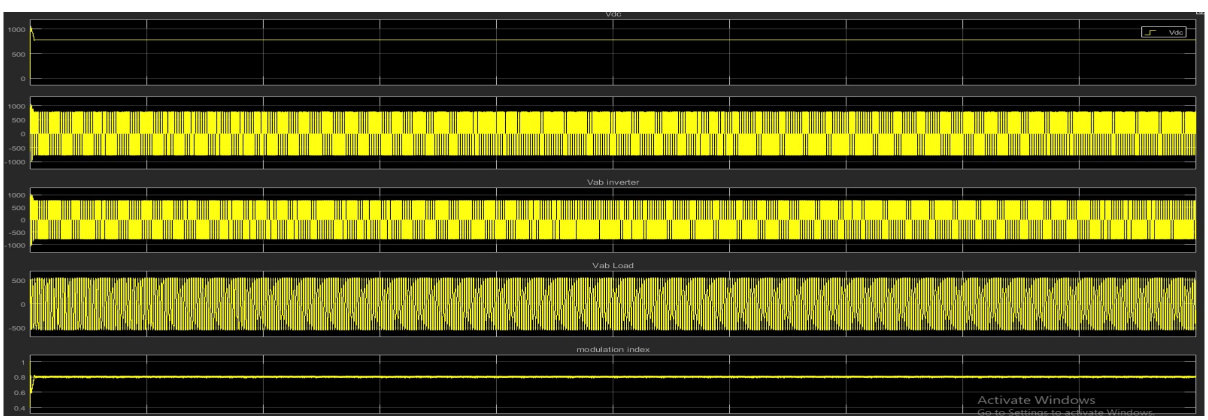


Figure .5.18. Vdc, Vab inverter,Vbc inverter and Vab load output

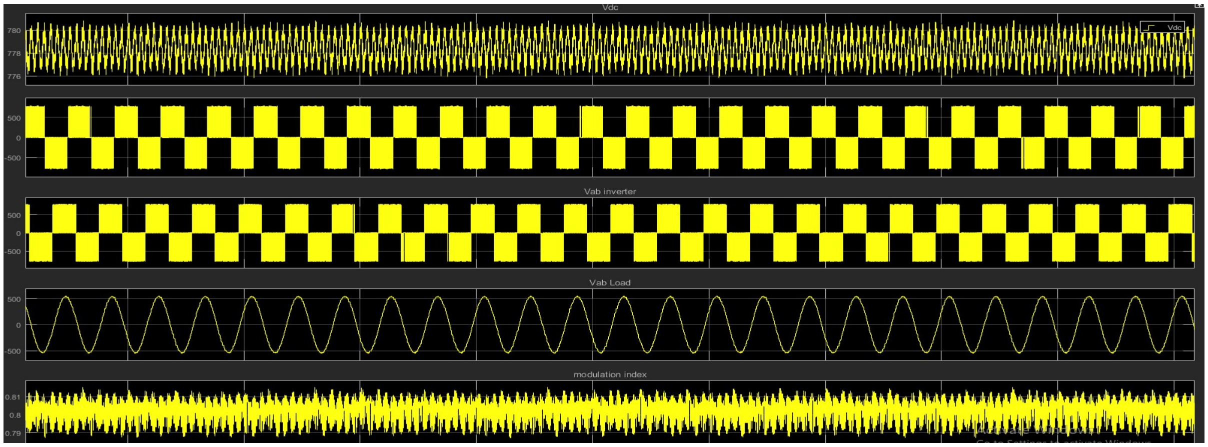


Figure .5.19. Vdc, Vab inverter,Vbc inverter and Vab load modified output

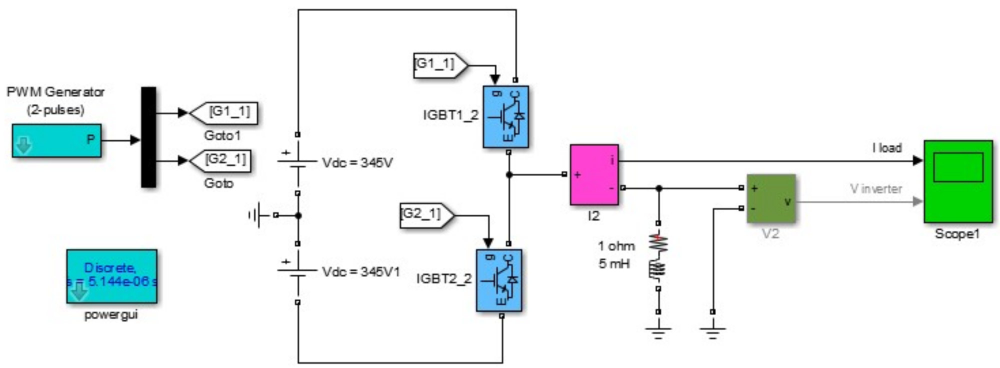


Figure .5.20. Half Bridge single phase inverters wind turbine

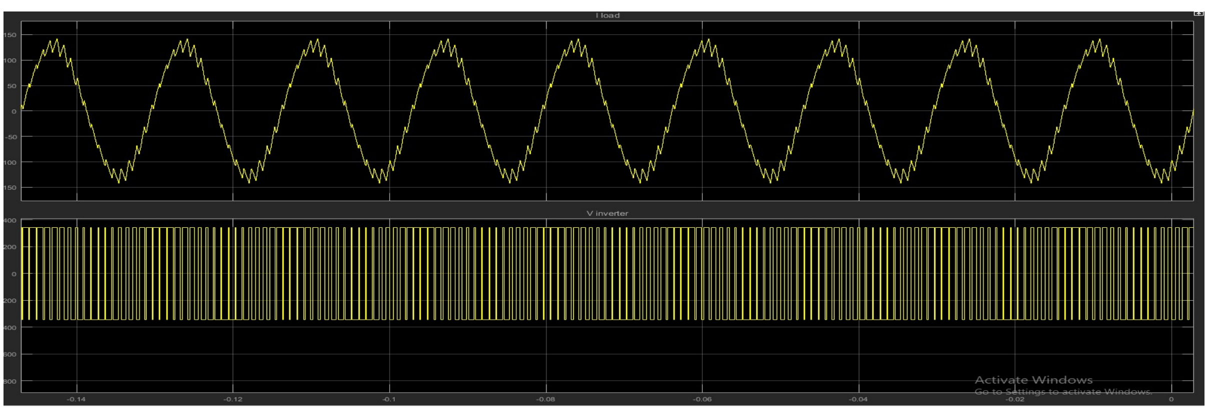


Figure.5.21. Voltage and current half bridge inverter output patterns

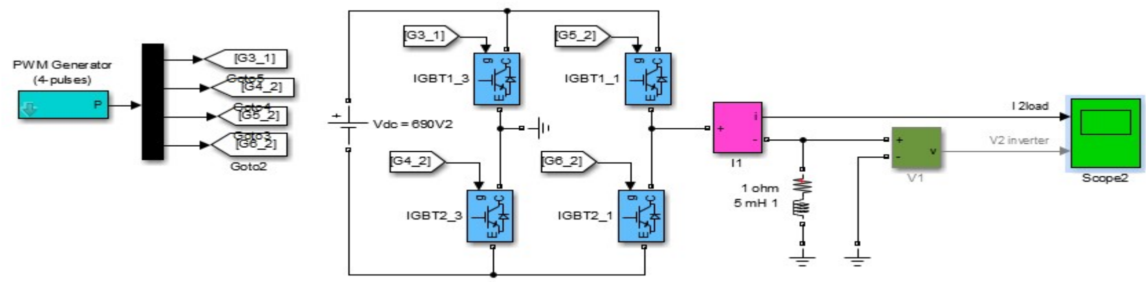


Figure.5.22. Full begrudge single phase inviter wind turbine

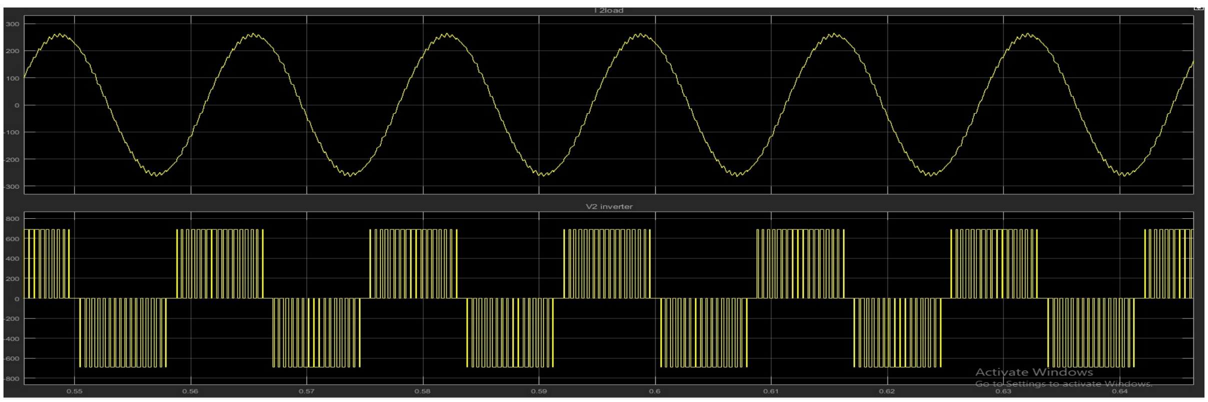


Figure.5.23. Voltage and current single phase full bridge inverter output patterns

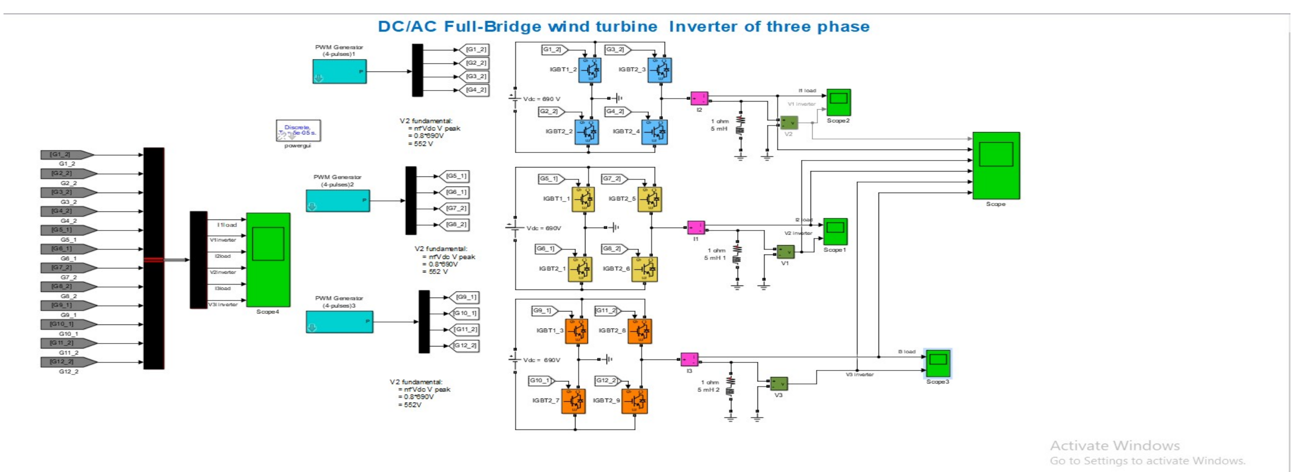


Figure.5.24. Voltage and current single phase full bridge inverter output patterns

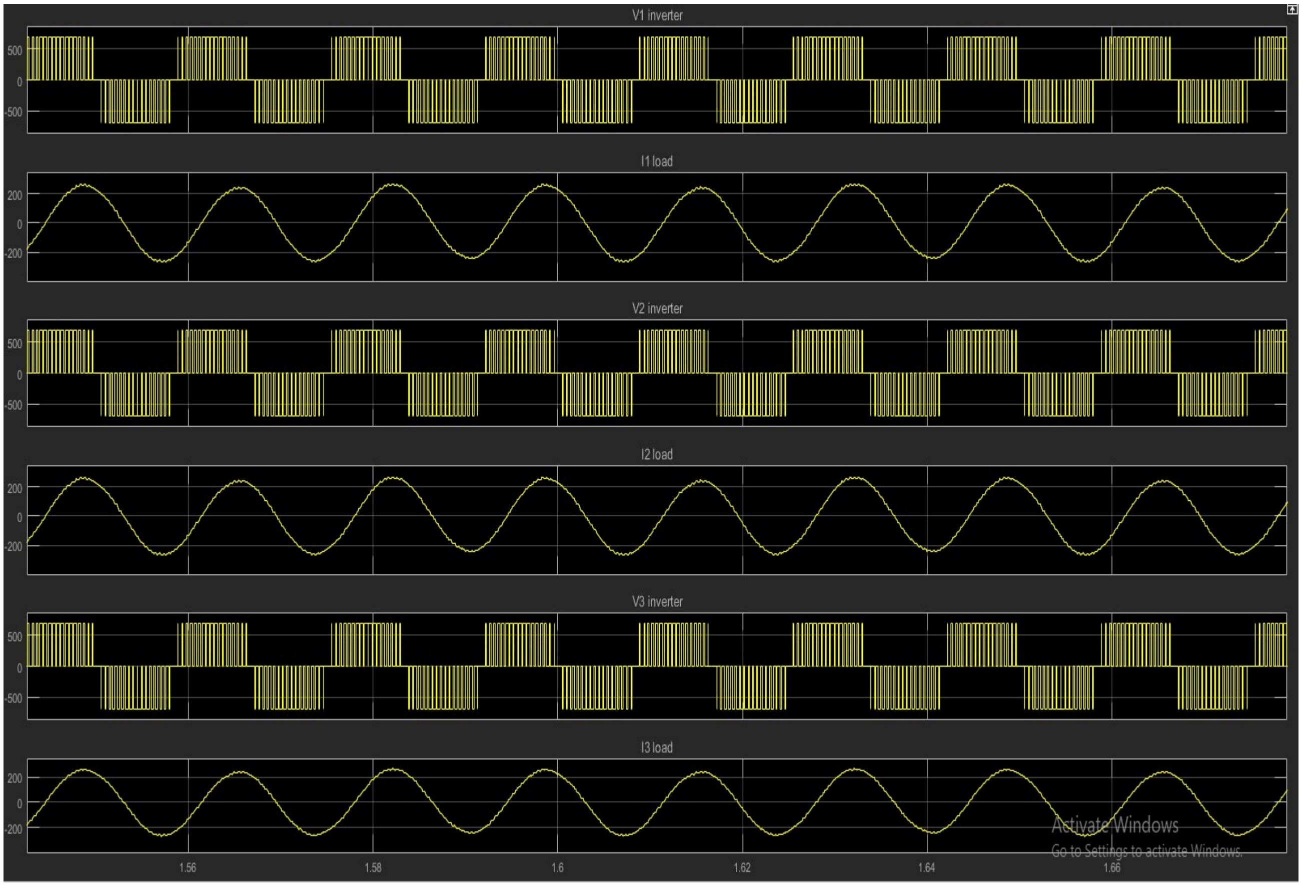


Figure.5.25. Voltage and current single phase full bridge inverter output patterns

Figure .15.19. Indicate voltage inviter (V1inverter) wave form magnitude in range of (-50, 50) pulse width (PWM), the patterns of (-20, 20) wave forms indicated that the load (I1) current output sinusoidal wave form, the voltage wave patterns (V_2inverter) magnitude of (-50, 50), the wave patterns of load current (I2) would be shown in the rage of (-20, 20) in the same method the wave patterns of V3inveter and I3 would be in the range of (-50,50) and (-20,20) respectively.

5.14. Modeling and designing of 1.5MW inverter

5.14.1. Modeling of the Inverter

The main circuit is the part where the DC electric power is converted to AC. This is virtually implemented with the one that is shown at the figure bellows, in this circuit we use a 2 leg inverter for single phase conversion which is composed of 4 IGBTs and the control unit. The last generates control pulses to drive the IGBTs. The pulse generator gives a digital signal to the IGBTs. When the signal from the pulse generator is not zero then it reacts as a switch and opens. This would be consists the basic operation in order to convert the DC to AC, with the technique of the Pulse Width Modulation (PWM). For the time interval the IGBTs are open, we get a pulse at power circuit, which has the same amplitude of source. The RMS time integral give us the output values. The on-off is determined by a control unit which is analyzed below. The modulation factor can be used as a parameter for the dynamic control of the system.

5.15. Generator types

5.15.1. Permanent magnet generator

An induction generator with wound rotor and slip rings is one of the possible generator configurations used in a wind turbine system. Such generators are also called cascade generators because the electrical power is applied at the stator as well as at the rotor terminals. In all of the applications, the stator winding is connected to the grid. A three phase rotor-side converter is connected to the rotor windings through slip rings.

5.15.2. Generator equivalent circuit

The generator model in the doubly-fed induction generator control program is based on a single-phase equivalent circuit of the generator that is referred to a stator reference frame (rotor-side quantities are scaled to the stator reference frame). The figure below shows the generator equivalent circuit in the stator reference frame.

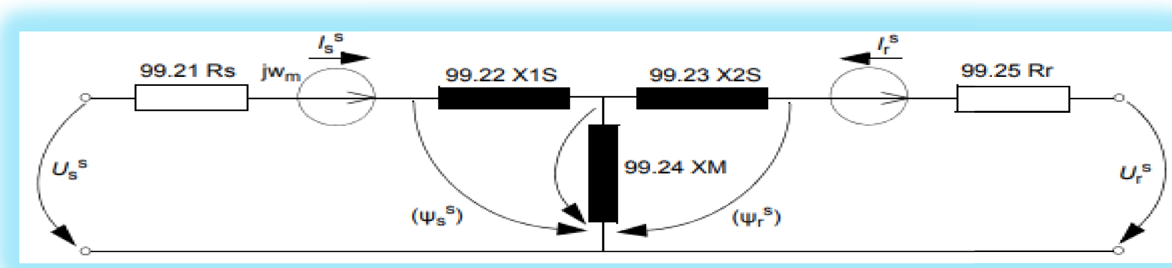


Figure. 5.26. Wind turbine equivalent circuit

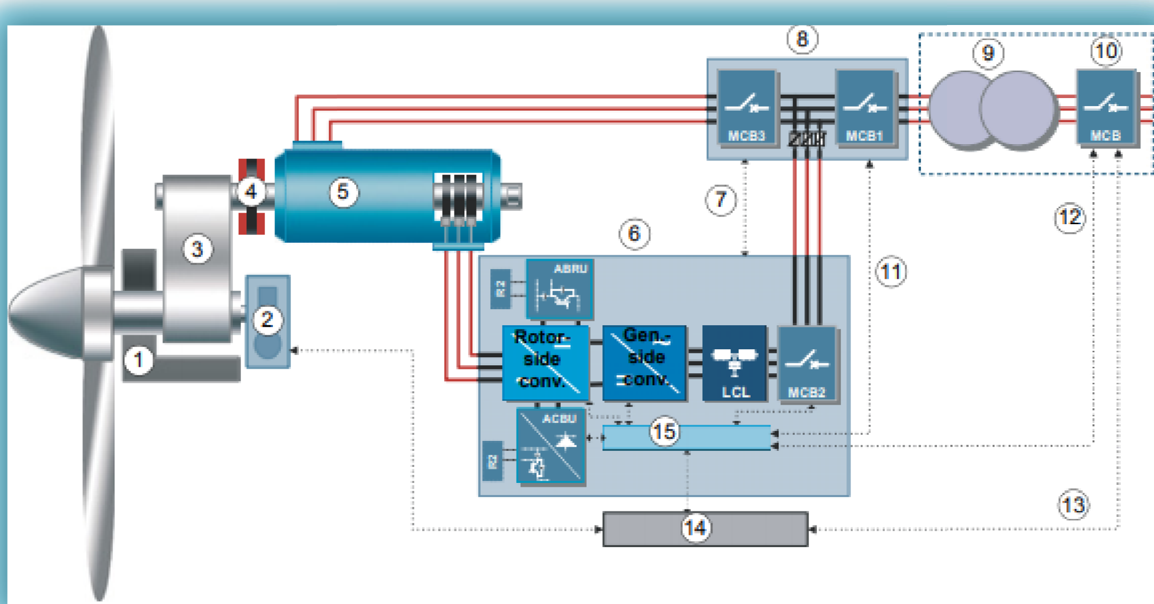
5.16. Wind turbine converter system and types

A block diagram of the wind turbine converter system is shown below. The stator is connected to the grid via MCB3 and the rotor is connected to the rotor-side converter. The ACS800-67(LC) controls the rotor-side voltage, current and frequency so that the desired torque and the desired power factor are available at the stator terminals. In normal operation, the rotor is rotating due to the wind within a certain speed range. Typical value for the operational speed range is ±30% around the synchronous speed, which (in rpm) is given by the following equation.

$$\frac{120 \times fn}{p}$$

p = number of generator poles
f_n = nominal frequency of the grid

If the mechanical speed of the rotor is lower than the synchronous speed, the torque controlled rotor-side converter supplies power to the rotor windings. If the mechanical speed of the rotor is higher than the synchronous speed, the rotor windings supply power to the rotor-side converter. Therefore, it is necessary to have a grid-side converter between the grid and the DC link of the converter. The grid-side converter is capable of handling the bidirectional power flow between the grid and the rotor-side converter. If the mechanical speed of the rotor is lower than the synchronous speed, the torque controlled rotor-side converter supplies power to the rotor windings. If the mechanical speed of the rotor is higher than the synchronous speed, the rotor windings supply power to the rotor-side converter. Therefore, it is necessary to have a grid-side converter between the grid and the DC link of the converter. The grid-side converter is capable of handling the bidirectional power flow between the grid and the rotor-side converter.



1	Rotor bearing	9	Turbine transformer
2	Pitch drive	10	Medium voltage switchgear
3	Gearbox	11	MCB1 ON/OFF ctrl
4	Brake system	12	MCB emergency open ctrl
5	Doubly-fed induction generator (DFIG)	13	MCB ctrl
6	Wind turbine converter	14	Wind turbine ctrl
7	MCB3 ON/OFF ctrl	15	Converter ctrl
8	Low voltage switchgears		

Figure.5.27. the grid-side converter is controlled with the grid-side control program. The rotor-side converter is controlled with the permanent magnet generator control program.

5.17. Specifications of variables used in the design

Table.5.11. specification of designing materials and wind power existing data

Semiconductor type	IGBT DIODE-4
Snuber resistance	5KΩ
Snubber capacitance	9.27m F
Internal resistance	1Ω
Carrier frequency	5kHz
Modulation index	0.85
Frequency of output voltage	60Hz
Input voltage	400V ± 5V
Power rate	10kw
Transformer	1
DC- Terminal voltage	400V
Rated terminal voltage	690V
Primary current	2000A
Secondary current	1A
Generato type	Permanent magnet generator
Generator capacity	1500KW
Turbine type	3-bald 35m radius
Rating capacity of Turbine capacity	1.5MW
Number of turbines in wind farm	102
Adama-II length nearby by substation	4.3km
PCC points	3-common node points
Number of blade	3 rotor
Rotor Diameter	77m
Swept area	4736m2
Cut in wind speed	3.5m/s
Rated wind speed	12m/s
Cut-out wind speed	25m/s-mean value in 10 minutes

Safe wind speed	59.5m/s-mean value in 3scond
Hub height	70m
Rotating speed	10.6-21.1rpm
Generator power factor	-0.95 to +0.95
Rated current	660A
Protection class	Ip23
Insulated level	F ($\leq 150C^o$)
Unit transformer	
Quantity	102
Type	1600KVA, $33\pm2.5\%/0.69kv$
230KV step up substation	
Main transformer	
quantity	2
Type	90MVA
	230±8*1.25%/33KV
Circuit number	1

5.18. Static converters and controllers

There are many strategies for controlling the switches. The most common control strategy is the interceptive PWM. Its principle is reminded in figure below. The switch control signals are generated by comparing three sinusoidal voltages (modulating) which are phase-shifted through $2\pi/3$ [rad] with a same triangular voltage waveform (carrier).
However, the large amount of power semiconductors as well as auxiliary components could largely reduce this converter's reliability and increase the cost. The total system weight and volume reduction in the wind turbine application still needs to be further investigated. The comparisons between the six solutions for full-scale power converter wind turbines are regarding to the performances of output voltage levels, power semiconductor numbers, maximum output voltage amplitude, fault tolerant ability, as well as filter and transformer size.

Nowadays there is also a trend to use the permanent magnet synchronous generator (PMSG) in the full-rated power converter wind turbines. Because there is no reactive power needed in such generator and active power flows one way-directionally from PMSG to the grid. A simple diode rectifier can be applied as the generator side converter to get a cost-effective solution. While for the grid side converter, some of the previously presented four-quadrant topologies, which will offer all the grid support features, can be directly used. These wind turbines with PMSG can have a gearbox or they can be direct-driven. In order to get variable speed operation and stable DC bus voltage, a boost DC-DC converter could be inserted in the DC-link.

Controlling a wind turbine involves both fast and slow control dynamics. Overall the power has to be controlled by means of the aerodynamic system and has to react based on a set-point given by a dispatched center or locally with the goal to maximize the power production based on the available wind power. The power controller should also be able to limit the power. An example of an overall control scheme of a wind turbine with maximum power production and the wind turbine will typically vary the speed proportional with the wind speed and keep the pitch angle θ fixed. At very low wind the turbine speed will be fixed at the maximum allowable slip in order not to have over voltage. A pitch angle controller limits the power when the turbine reaches nominal power. The generated electrical power is done by controlling cabinet and nacelle generator through the rotor-side converter. The control of the grid-side converter is simply just keeping the dc-link voltage fixed. Internal current loops in both converters are used which typically are PI-controllers, as it is illustrated in figure below. The power converters to the grid-side and the rotor-side are both voltage source converters.

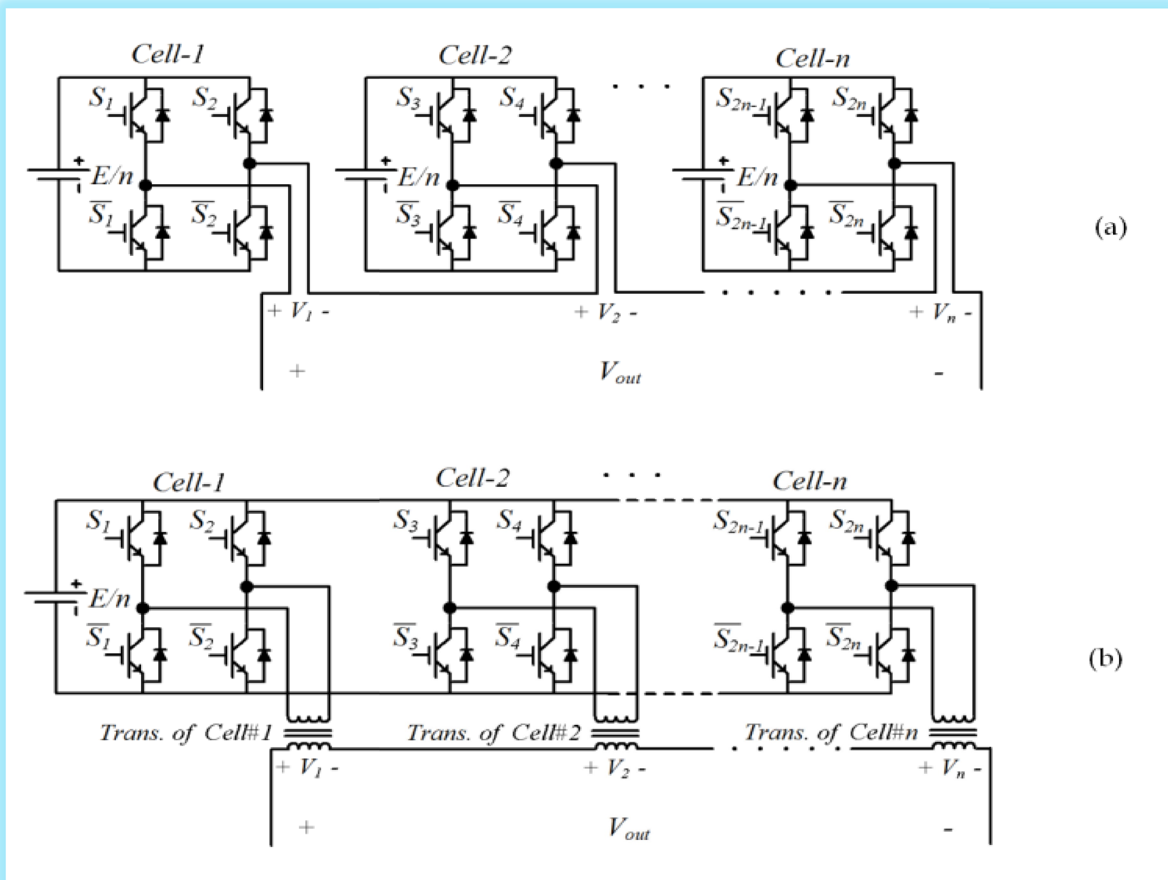


Figure .5.28. IGBT or DIODE static converter and circuit unit

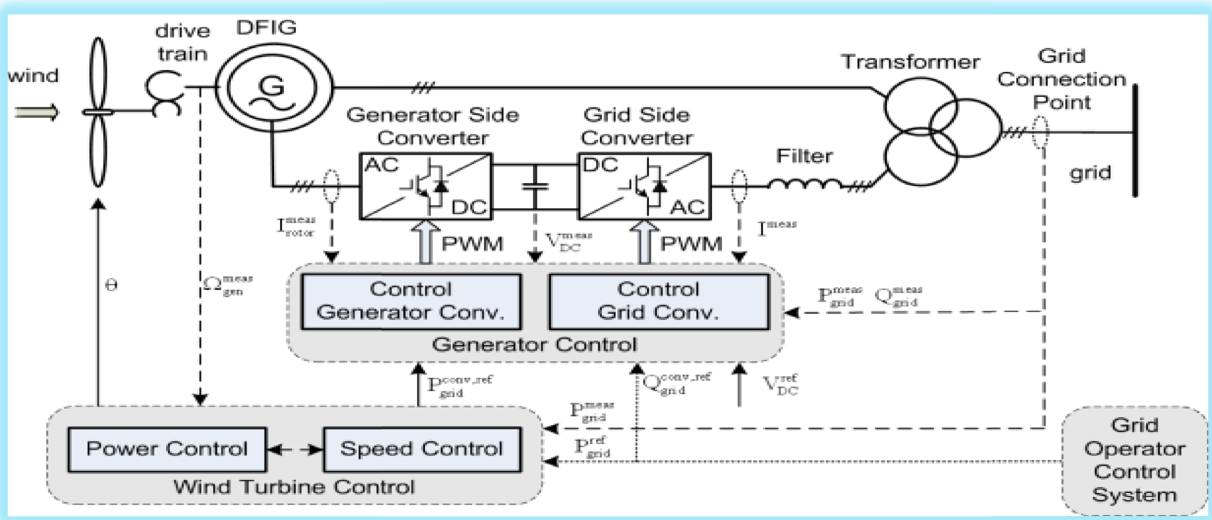


Figure .5.29. Wind turbine converter and controller circuit

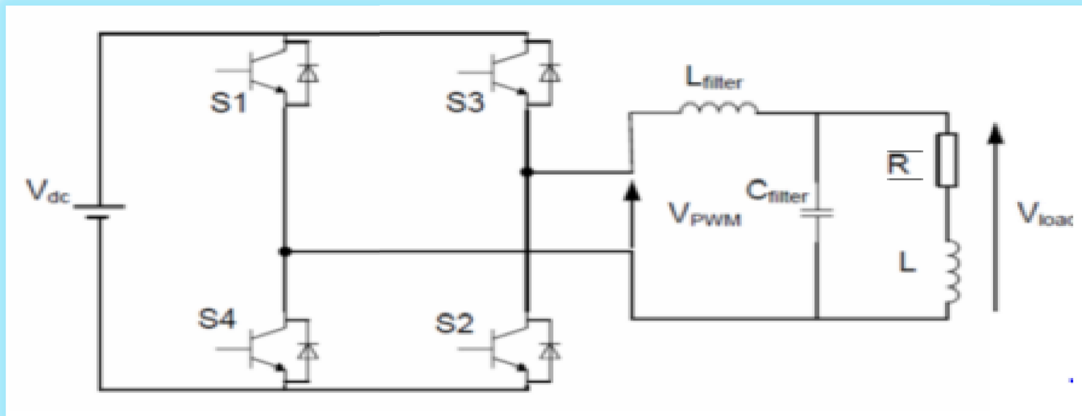


Figure. 5.30. Topology of a single-phase inverter with filter and load

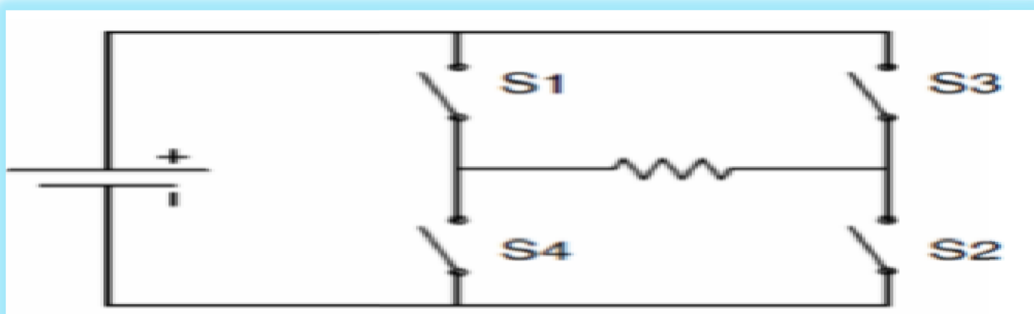


Figure .5.29. Single phase full bridge DC/AC inverter

The above figure shows the equivalent circuit of single-phase inverter. This has four switches that turn on and off to obtain a sinusoidal output. To generate an AC waveform in single-phase inverter, the switches S1, S2 ON and S3, S4 off for period and as shown in figure (3.3). For that period, the output is a positive voltage.

5.18. Semiconductors Selection of interrupters

Power semiconductors are the main part of the switching cell. The inverter's features depend largely on their performance and characteristics. Basically, all semiconductors consist of PN junctions. Those are achieved doping silicon with boron (P layer) or phosphorus (N layer). When a certain voltage is applied to the junction, the internal charges move, letting the current flow through it. If the voltage is not enough, the charges do not flow and therefore the semiconductor acts like a blocker. An ideal semiconductor would perform as an ideal switch, being its main characteristics on- and off-control, instantaneous switching, null impedance in conducting and infinite impedance in cut-off. Also, reversibility regarding current and voltage and the voltage range in conducting are issues that define a semiconductor. Different semi-conductors are used for switching such as diode, BJT, MOSFET, power MOSFET and IGBTS but here we are using only IGBTS.

5.19. Inverter sizing

The inverter has to be capable of handling the maximum expected power of AC loads. The input of the inverter have to be matched with the battery block voltage which is 24V while its output should fulfill the specifications of the electric grid of the grid which is 220V, single phase ,50 Hz frequency the next figure shows the specifications of the inverter.

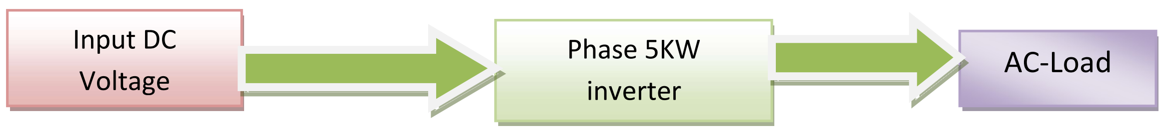


Figure .5.31. Block diagram of 5kw inverter

5.20. Inverter specifications

The specification of the electric grid of the household specified as: 220V ± 5% AC, three phase 50 Hz, sinusoidal wave voltage. The maximum inverter output current is found by dividing the total load power by the system voltage: Inverter to load current = 5kW / 220V =22.7A Let the efficiency the inverter to be = 90% - 95%.

5.21. Sizing of Transformer's Components

The power Rating for the Inverter transformer (KVA) =5KVA, V1=24V Assuming the efficiency of transformer =85%

$$The\ efficiency\ = \frac{output}{input}$$

$$then\ input\ rating\ = \frac{output}{efficiency} = \frac{5000VA}{0.85}\ = 5{,}882.35VA$$

The current on the primary side of a transformer is calculated as follows

Input rating power = primary current *primary voltage

From these

$$primary\ current\ = \frac{input\ rating\ power}{primary\ voltage}$$

$$I_p = \frac{p_i}{V_p} = \frac{5{,}882.35}{24} = 245.091A$$

And the output current is calculated as follows

$$I_s = \frac{P_0}{V_s} = \frac{5000}{220} = 208.33A$$

For practical design of inverter transformer number of turns per volt for both primary and secondary winding is given by;

$$N_T V^{-1} = \frac{7}{A}$$

Where A is the area of transformer in sq. meter transformer area A is 2.3m by 1.5m =3.45sq.meter

$$N_T V^{-1} = 3.45 = 2.03$$

$$N_T V^{-1} = 2$$

$$N_T V^{-1} = 2\ is\ approximate\ value$$

Primary winding

$$N_{p1} = 2 * 24 = 48 turns$$

Secondary winding

$$S_{s2} = 2 * V_2 = 2 * 220 = 440 turns$$

5.22. Filters

Attenuation is a reduction or loss in the magnitude of a voltage or current due to its transmission over a line. A filter is a network designed to pass signals having frequencies within certain bands (called pass bands) with little attenuation, but greatly attenuates signals within other bands (called attenuation bands or Stop bands). A filter is frequency sensitive and is thus composed of reactive elements. Since certain frequencies are to be passed with minimal loss, ideally the inductors and capacitors need to be pure components since the presence of resistance results in some attenuation at all frequencies. Between the pass band of a filter, where ideally the attenuation is zero, and the attenuation band, where ideally the attenuation is infinite, is the cut-off frequency, this being the frequency at which the attenuation changes from zero to some finite value. A filter network containing no source of power is termed passive, and one containing one or more power sources is known as an active filter network. Filters are used for a variety of purposes in nearly every type of electronic communications and control equipment. The bandwidths of filters used in communications systems vary from a fraction of a hertz to many megahertz, depending on the application [4]. A filter is basically a circuit which modifies frequency components between its input and output. It can be anagogic or digital and depending on its behavior, there are mainly four types.

Table.5.12.Type of filters and main features

Types of filter	feature
Low	The let pass low frequencies and attenuate the once over a cut point
High pass	They attenuate frequencies below a cut point
Band Pass	They let pass frequencies between a range
Band rejection	They block frequencies between a range
Single tuned filters	They passive filter the inductance reactance are equal value
C-type filters	They are high quality factor an comparatively high losses

Once the type of circuit is selected, the cut point and the ranges of frequencies can be chosen by modifying the components. As in this case the objective is to attenuate harmonics, a low pass filter will be selected. For a low pass filter, there are two options regarding circuitry: RC (resistor – capacitance) or LC (inductance – capacitance).

5.23. Low pass filter design

A low pass LC filter is required at the output terminal of Full Bridge VSI to reduce harmonics generated by the pulsating modulation waveform. While designing L-C filter, the cut-off frequency is chosen such that most of the low order harmonics is eliminated therefore, the capacitance value should be maximized and the inductance value should be minimized at the selected cut-off frequency of the low-pass filter. Each value of L and C component is determined to minimize the reactive power in these components because the reactive power of L and C will decide the cost of LC filter and it is selected to minimize the cost, then it is common that the filter components are determined at the set of a small capacitance and a large inductance and consequently the output

The filter output to input voltage harmonics must be less than 3%.So,

$$\frac{VC(j\omega)}{VA(j\omega)} = 3\%$$

$$\frac{1}{1 - L_F\, C_F\, \omega^2} = 0.03$$

$$\frac{|1|}{f^2\, \frac{XL}{XC}} \leq 0.03$$

$$\frac{XL}{XC} \geq \frac{34.2}{f^2}$$

$$\frac{XL}{XC} \geq \frac{34.2}{f^2}$$

Where f=corner or cutoff frequency so, that from this we can find the L C for the filter.

From these $XL = J\omega L$

$$XC = \frac{1}{J\omega C}\ so\ \frac{xl}{xc} = -\omega^2 LC$$

$$\omega^2 LC \geq \frac{34.2}{f^2}$$

From these f is our cut of frequency which is 50Hz

And $\omega^2 = 314 * 314 = 98596$

$$LC = \frac{34.2}{f^2\omega^2} = \frac{34.2}{60^2 * 314^2}$$

$$LC = \frac{34.2}{2500 * 98596} = \frac{34.2}{246{,}945{,}000}$$

$$LC = 0.139 * 10^{-6}$$

Then let say $L = 150\mu H$

Then $C = \frac{0.13910^{-6}}{150^{-6}} = 9.27 * 10^{-4} = 0.00927F = 9.27mF$

The parameters what I have been used to here in the simulation is as follows

Dc voltage source = 400V

Four IGBTs

1PWM with demuxing system

1Ttransformer

Low pass filter C = 9.27mF and L = 139μH

Modulation index for IGBTS = 0.8

- An over view of the voltage and current harmonic injection by static converters by the wind turbine generators without filter would be 0.506 or 50.6% of the total sum for each 102 wind turbines and the appearing odd harmonics are namely the third (3^{rd}) harmonic, fifth harmonics (5^{th}), seventh harmonics (7^{th}), elevens (11^{th}) harmonics, twenty one (21^{th}) harmonics and twenty three (23^{th}) harmonics. However the other odd harmonics thirteen (13^{th}) through nineteenth (9) harmonics are below of twenty five percent (25%).

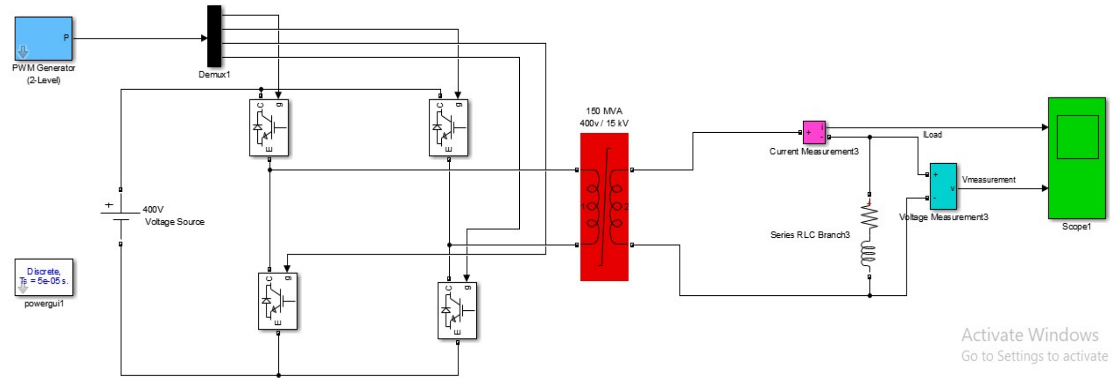


Figure .5.32. Circuit diagram of inverter without filter

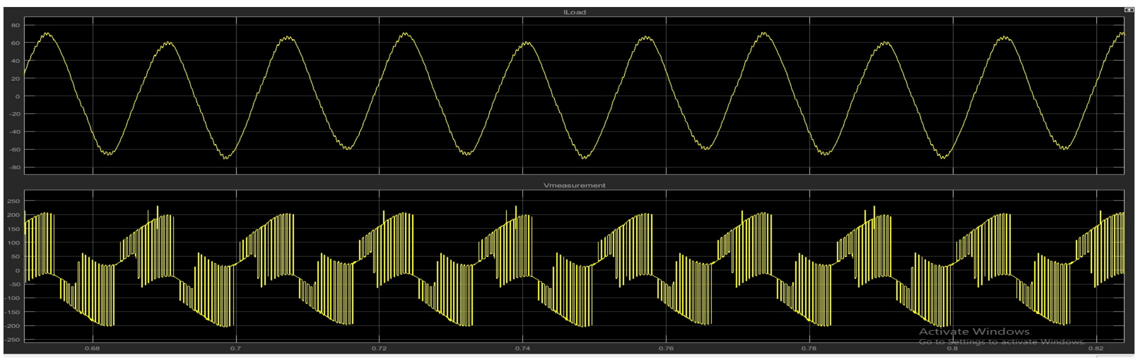


Figure.5.33. Output of inverter without filter

- An over view of below diagram of the voltage and current harmonic injection by static converters of the summation of all wind turbine generators without filter would be 0.506 or 50.6% of the total sum for each 102 wind turbines and types of harmonics appear would be odd harmonics of 3^{rd} ,5^{th}, 7^{th}, 11^{th}, 21^{th} and 23^{th} harmonic distortion.

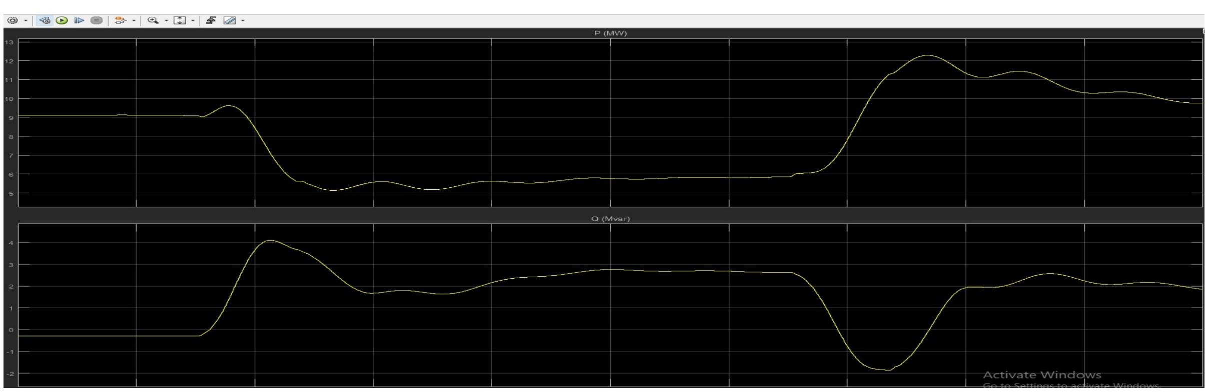


Figure.5.34.out put active and reactive power

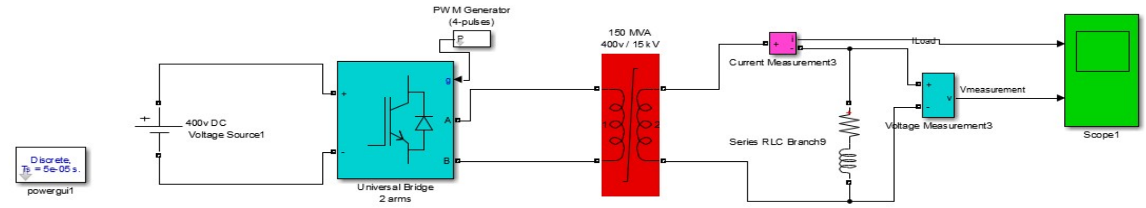


Figure.5.35. Output of inverter without filter

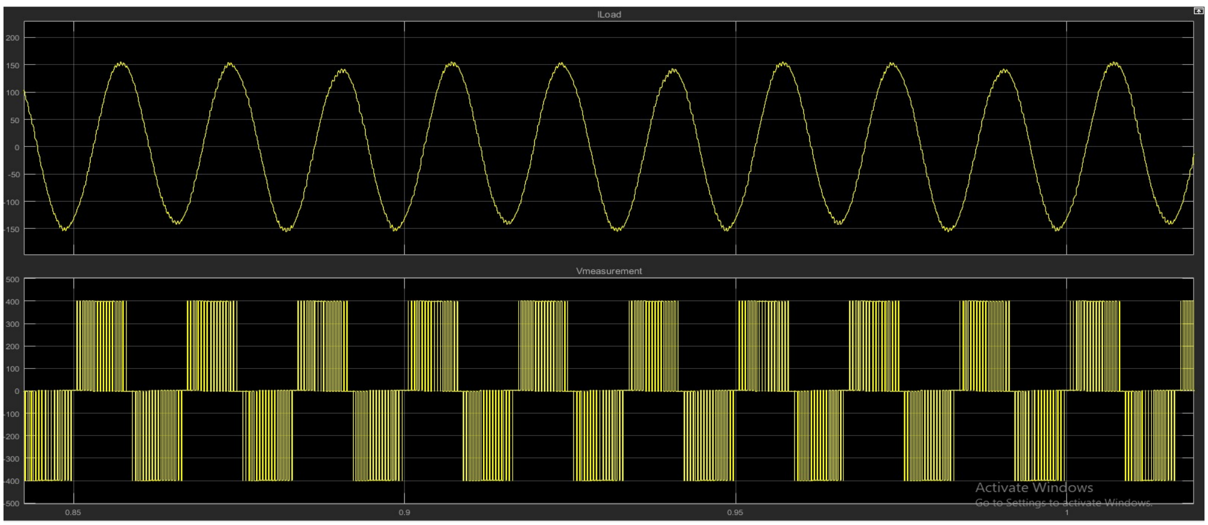


Figure .5.36. Voltage output and current output without filter

The below diagram represents the static inverter of the wind turbine within the single tuned filter ,the voltage and current output result of each individual of 102 wind turbine would 0.0299 or 2.99% of the total harmonic injection of system. So that as shown from voltage and current wave forms, the signals is true sinusoidal wave form output.

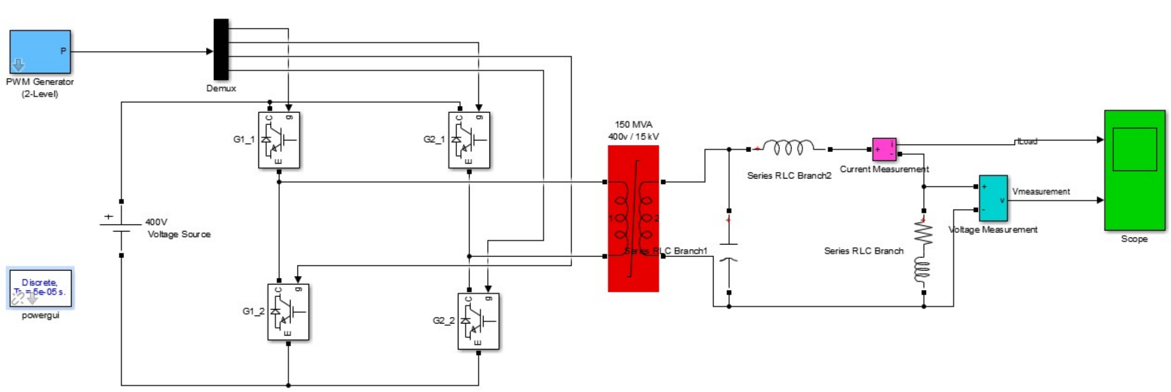


Figure.5.37. Circuit diagram with filter

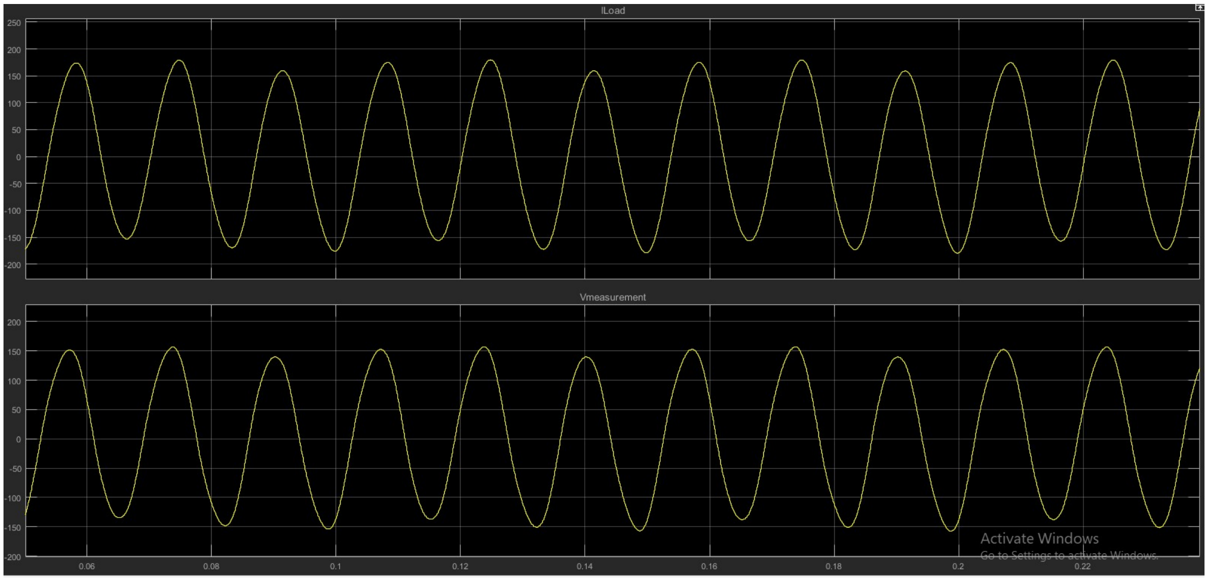


Figure. 5.38. Output of voltage and current inverter with filter

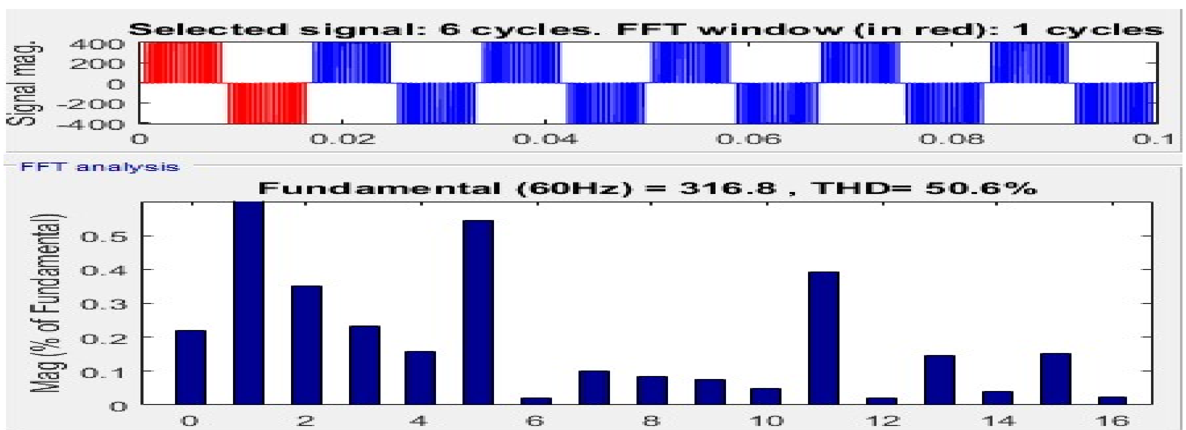


Figure .5.39. Harmonic distortion without filter

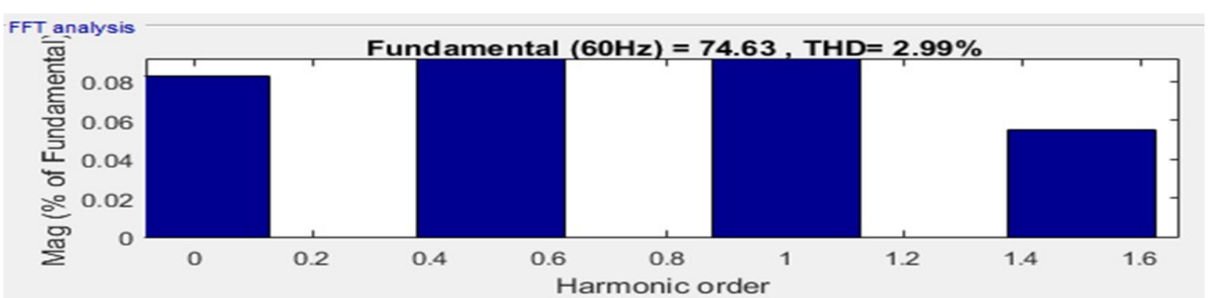


Figure.5.40. Voltage and current harmonic magnitude with filter

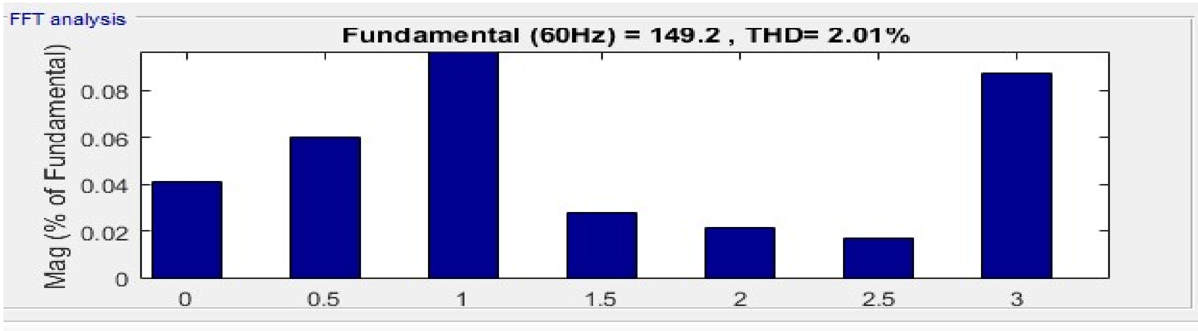


Figure.5.41. Current harmonic magnitude with filter

Summary

As I have understood from the simulation by using this device we can design an inverter with above specifications so accordingly my methodology the harmonic magnitude of the total harmonic distortion is 0.506 or 50.6% without harmonic filter and when I am adding the single tuned harmonic filter the harmonic magnitude is 0.020 and 0.0299 or 2.0%and 2.99% is shown in figure above respectively, so that, the goal has been succeed. With the conversion of 24V seventeen (17) terminal phase group of DC (400V) to 690 ac maximum value which has a frequency of 50 Hz. So when I used a low pass filter has been obtain a better output of modified sine wave these told me low pass filter is the necessary thing for inverter application. What I want to recommend here is that the design of filter for correct harmonic mitigation was for very difficult and for the future I will design for these inverter application a single tuned which is more efficient than low any other pass filter.

CHAPTER SIX

6. RESULT AND DISCUSSION

As the modeling or mathematical representation of the system under study goes well and presented above, operating equipment's integrations will be then triggered from parameters with various perspectives in this section of my study. However, many are available in my study, I had used MATLAB analysis tool as to simplify the modeling. The well-known IEEE 519 bus benchmark system was used as a base case and the 5 buses of Adama–II of power generation network and 10 bus distribution networks is modeled in detail.

6.1. BASE CASE

The conventional measurements are given in Fig.5.12. This optimal problem is modeled based on the algorithm proposed in section 5.8.

Table.6.1. VIHD (individual Harmonic Distortion) without filters

Bus		Voltage Distortion		
ID	KV	Fundamental%	VIHD%	Order
Bus1	0.97	147.84	3.23	3
Bus2	0.98	93.88	3.23	3
Bus4	2.20	29.41	3.23	3
Bus7	0.46	85.63	3.91	3
Bus10	2.50	149.25	3.22	5
Bus1	0.49	101.85	3.20	5
Bus13	0.45	87.53	3.22	5
Bus5	0.20	100.31	20.12	5
Bus6	0.110	99.74	6.18	7
Bus8	0.49	75.34	5.42	7
Bus9	2.20	100.33	5.23	7
Bus1	2.50	149.25	6.97	7
Bus2	0.12	99.73	6.00	7
Bus4	0.96	159.65	5.23	7
Bus5	0.96	159.65	6.18	7
Bus3	0.22	100.83	5.23	7
Bus1	0.97	147.84	6.10	7
Bus2	0.98	93.88	6.44	7
Bus4	2.20	29.41	3.23	7
Bus5	0.20	100.31	20.12	7
Bus7	0.46	85.63	3.91	7
Bus9	0.49	101.85	3.20	7

Bus3	0.22	99.83	57.23	7
Bus1	0.97	147.84	6.90	9
Bus2	0.98	93.88	6.99	9
Bus4	2.20	29.41	6.99	9
Bus7	0.46	85.63	7.61	9
Bus10	2.50	149.25	6.98	9
Bus1	0.49	101.85	6.95	9
Bus3	0.45	87.53	6.99	9
Bus1	0.97	147.84	31.69	11
Bus6	0.95	106.74	20.64	11
Bus2	0.98	93.88	32.34	11
Bus4	2.20	29.41	32.33	11
Bus5	0.20	100.31	6.60	11
Bus6	0.110	99.74	17.35	11
Bus7	0.46	85.63	3.91	11
Bus8	0.49	75.34	11.30	11
Bus9	2.20	100.33	12.97	11
Bus10	2.50	149.25	32.28	11
Bus1	0.49	101.85	32.22	11
Bus9	0.12	99.73	32.32	11
Bus8	0.45	87.53	32.33	11
Bus4	0.96	159.65	12.96	11
Bus5	0.96	159.65	17.35	11
Bus3	0.970	100.00	12.97	11
Bus1	0.97	147.84	23.75	13
Bus2	0.98	93.88	24.54	13
Bus4	2.20	29.41	24.63	13
Bus5	0.970	4.67	2.64	13
Bus6	0.110	99.74	11.51	13
Bus7	0.46	85.63	3.91	13
Bus8	0.49	75.34	8.08	13
Bus9	2.20	100.33	9.96	13
Bus10	2.50	149.25	24.49	13
Bus1	0.49	101.85	24.51	13
Bus2	0.12	99.73	24.62	13
Bus3	0.45	87.53	24.63	13
Bus2	0.96	159.65	9.95	13
Bus3	0.970	100.00	9.96	13
Bus1	0.97	147.84	6.41	17
Bus2	0.98	93.88	6.89	17
Bus4	2.20	29.41	6.92	17
Bus5	0.20	100.31	3.88	17
Bus6	0.110	99.74	18.96	17
Bus7	0.46	85.63	44.84	17
Bus2	0.49	75.34	12.77	17

Bus9	2.20	100.33	16.55	17
Bus10	2.50	149.25	6.38	17
Bus3	0.970	100.00	16.55	17
Bus1	0.97	147.84	4.55	19
Bus2	0.98	93.88	4.86	19
Bus4	2.20	29.41	4.88	19
Bus6	0.110	99.74	9.85	19
Bus7	0.46	85.63	3.91	19
Bus8	0.49	75.34	5.13	19
Bus9	2.20	100.33	7.56	19
Bus2	2.50	149.25	4.84	19
Bus3	0.970	100.00	7.56	19
Bus5	0.970	4.67	3.91	23
Bus6	0.110	99.74	27.26	23
Bus7	0.46	85.63	3.91	23
Bus8	0.49	75.34	15.75	23
Bus9	2.20	100.33	24.60	23
Bus3	0.970	100.00	2.4.60	23
Bus5	0.20	100.31	3.19	25
Bus6	0.110	99.74	23.35	25
Bus7	0.46	85.63	3.91	25
Bus8	0.49	75.34	13.35	25
Bus9	2.20	100.33	21.86	25
Bus3	0.22	100.83	21.86	25

Table.6.2. Individual Harmonic Distortion before adding filters

3rd	5th	7th	9th	11th	13th	17th	19th	23th	25th
0.0317	0.6611	0.6552	0.0681	0.3143	0.2345	0.0626	0.0454	0.0388	0.0317
0.0316	0.6590	0.6586	0.0690	0.3205	0.2422	0.0673	0.0485	0.2713	0.2326
0.0316	0.3672	0.2515	0.0690	0.3202	0.2431	0.0677	0.0486	0.0674	0.1275
0.0391	0.6817	0.3060	0.1760	0.0661	0.0521	0.0387	0.0992	0.1568	0.1330
0.0316	0.8519	1.1658	0.0761	0.1728	0.1146	0.1902	0.4584	0.2448	0.2178
0.0316	0.5540	0.2327	0.0689	0.9225	1.1177	0.5430	0.0518	0.2713	0.3326
0.3106	0.5721	0.2507	0.0686	0.1124	0.0805	0.1280	0.0762	0.2444	0.2173
	0.6591	0.658	0.0690	0.1290	0.0992	0.1660	0.0484	0.2444	0.2173
	0.6546	0.6569	0.0690	0.3199	0.2418	0.0668	0.0486	0.2444	0.2173
	0.6590	0.6579	0.0624	0.3194	0.2420	0.0668	0.0486	0.2444	0.2173
	0.7817	0.6578		0.3202	0.2420	0.0677	0.0486	0.2444	0.2173
	0.5721	0.3060		0.3202	0.2431	0.0677	0.0992	0.2444	0.2173
	0.5721	0.2507		0.1728	0.2431	0.1902	0.0762	0.2444	0.2173
	0.5721	0.2507		0.1290	0.1146	0.1658	0.0762	0.2444	0.2178
	0.5721	0.2507		0.1290	0.0991	0.1658	0.0762	0.2444	0.2178
	0.5721	0.2507		0.1290	0.0991	0.1658	0.0762		
	0.5721	0.2507		0.1290	0.0991	0.1658	0.0762		

	0.5721	0.2507		0.1290	0.0991	0.1658	0.0762		
		0.2507		0.1290	0.0992	0.1658	0.0762		
				0.1290		0.1658			

$$V_3(\%) = \frac{V_{3max}}{V_{Fundamental}} * 100$$

Where V fundamental is maximum value of 7th harmonics and V3max=0.3106

$$V_3max(\%) = \frac{0.3106}{1.1658} * 100 = 26.7\%$$

$$V_{5max}(\%) = \frac{0.7817}{1.1658} * 100 = 67\%$$

$$V_{7max}(\%) = \frac{1.1658}{1.1658} * 100 = 100\%$$

$$V_{9max}(\%) = \frac{0.1760}{1.1658} * 100 = 15.1\%$$

$$V_{11Max}(\%) = \frac{0.7822}{1.1658} * 100 = 67.1\%$$

$$V_{13mxa}(\%) = \frac{1.117}{1.1658} * 100 = 95.8\%$$

$$V_{17max} = \frac{0.543}{1.1658} * 100 = 46.9\%$$

$$V_{19max}(\%) = \frac{0.358}{1.1658} * 100 = 39.3\%$$

$$V_{23Max}(\%) = \frac{0.244}{1.1658} * 100 = 20.9\%$$

$$V_{25}(\%) = \frac{0.332}{1.1658} * 100 = 28.6\%$$

Now the total voltage harmonic distortion can be calculated by:-

$THDv(\%) =$

$$\sqrt{18.1^2 + 58^2 + 100^2 + 6.25^2 + 58^2 + 87.3^2 + 38^2 + 30.7^2 + 20.9^2 + 19.9^2}$$

$$THDv(\%) = \frac{\sqrt{39827.05}}{400}$$

$$0.4989 = 50\%$$

This result is compared with the standard of the IEEE-519 is high harmonics impact to the voltage and current injection of the power system.

Table.6.3. Total harmonic distortion of voltage without coupling filters

Buses		Voltage Distortion	
ID	KV	Fundamental%	VTHD%
Bus1	0.97	147.84	102.14
Bus2	0.98	93.88	102.66
Bus3	0.22	99.83	74.65
Bus4	2.20	100.32	102.73
Bus5	0.20	10031	28.33
Bus6	0.11	99.74	88.02
Bus7	0.46	85.63	74.65
Bus8	0.49	75.34	66.43
Bus9	2.20	100.33	74.65
Bus10	2.50	149.25	102.66

Table .6.4. Transmission line input data

Ohms or mhos/1000m per phase								
ID	TC^o	R_1	X_1	Y_1	R_0	X_0	Y_0	Adj.(m)
Line1	75	1.050378	0.309927	$3.8*10^{-6}$	1.535737	1.216918	$1.5*10^{-6}$	1000
Line2	75	1.050142	0.3310019	$3.8*10^{-6}$	1.506425	1.254328	$1.5*10^{-6}$	1000
Line3	75	1.050057	0.328131	$3.8*10^{-6}$	1.452591	1.298760	$1.5*10^{-6}$	1000
Line4	75	1.050125	0.353580	$3.8*10^{-6}$	1.452229	1.28281	$1.5*10^{-6}$	1000
Line5	75	1.050378	0.309926	$3.8*10^{-6}$	1.535415	1.216377	$1.5*10^{-6}$	1000

Table.6.5. Impedance input Data

Impedance	Positive sequence impedance			Zero sequence impedance			
ID	R	X	Y	R_0	X_0	Y_0	Unit
Z1	0.00008	0.0005	0.088	0.00008	0.0005	0.088	Ohm
Z2	0.00018	0.00018	0.3255209	0.00018	0.00018	0.3255209	Ohm
Z3	0.00018	0.00018	0.2170139	0.00018	0.00018	0.2170139	Ohm
Z4	0.00018	0.00018	1.08507	0.00018	0.00018	1.08507	Ohm

Table .6.6. Two winding transformer input data

Transformer	Rating			Type
ID	MVA	Primary. KV	Secondary. KV	
T1	40	0.110	0.970	D/Y
T2	20	0.100	0.970	D/Y
T3	20	0.970	0.970	D/Y
T4	50	0.970	0.050	D/Y
T5	20	0.860	0.050	D/Y
T6	10	0.970	0.100	D/Y

Table .6.7. Total harmonic distortion after harmonic filter design is used in limited place

VTHD (Total Harmonic Distortion)			
Number of Buses		Voltage distortion	
ID	KV	Fundamental %	VTHD%
Bus1	0.97	147.84	6.47
Bus2	0.98	93.88	6.76
Bus3	0.22	99.83	6.47
Bus4	2.20	100.32	6.76
Bus5	0.20	10031	7.23
Bus6	0.11	99.74	4.18
Bus7	0.46	85.63	7.03
Bus8	0.49	75.34	6.47
Bus9	2.20	100.33	6.69
Bus10	2.50	149.25	6.65

Table .6.8. Total harmonic distortion after harmonic filter design properly used

VTHD (Total Harmonic Distortion)			
Buses		Voltage distortion	
ID	KV	Fundamental%	VTHD%
Bus1	0.97	102.06	3.33
Bus2	0.98	101.47	3.50
Bus3	0.22	102.06	3.33
Bus4	2.20	101.47	3.50
Bus5	0.20	70.86	20.64
Bus6	0.11	60.05	10.34
Bus7	0.46	106.81	57.43
Bus8	0.49	101.55	3.11
Bus9	2.20	110.00	3.33
Bus10	2.50	102.69	3.45
Bus11	0.49	103.00	3.44
Bus12	0.12	101.42	3.48
Bus13	0.45	102.06	3.33
Bus14	0.45	60.05	10.34
Bus15	0.96	114.45	3.50
Bus16	0.95	102.06	3.33
Bus17	0.05	102.06	3.33
Bus18	2.50	102.06	3.33
Bus19	0.21	102.06	3.33
Bus20	0.05	141.43	3.33

Table.6.9. Voltage Internal harmonic distortion standardized of the 3%

VITHD (Total Harmonic Distortion)				
Buses		Voltage distortion		
ID	KV	Fundamental%	VTHD%	Order
Bus1	0.97	101.40	1.56	5
Bus2	0.98	82.40	1.53	5
Bus3	0.22	110.00	1.54	5
Bus4	2.20	102.65	1.55	5
Bus5	0.20	102.95	1.54	5
Bus6	0.11	101.34	1.56	5
Bus7	0.46	114.37	1.56	5
Bus8	0.49	102.06	1.54	5
Bus9	2.20	102.06	1.54	5
Bus10	2.50	102.06	1.54	5

Table.6.10. Individual Harmonic Distortion approach to the standard

5^{th}	7^{th}
0.0153	0.0174
0.0156	0.0390
0.0154	0.0174
0.0155	0.0173
0.0154	0.0174
0.0156	0.0174
0.0156	0.0174
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170
0.0154	0.0170

$$Fundamel\ Voltage(V_{fun}) = 0.4KV = 400V$$

$$\mathrm{V_5(\%)} = \frac{\mathrm{V_{3max}}}{\mathrm{V_{Fundamental}}} * 100$$

$$V_{5max}(\%) = \frac{0.0156}{0.0390} * 100 = 39\%$$

$$V_{7ma}\ (\%) = \frac{0.0174}{0.0390} * 100 = 44\%$$

$$V_{11\max}(\%) = \frac{0.0301}{0.0390} * 100 = 77\%$$

$$V_{13max}(\%) = \frac{0.0172}{0.0390} * 100 = 44\%$$

$$V_{17max}(\%) = \frac{0.0231}{0.0390} * 100 = 59\%$$

$$V_{19max}(\%) = \frac{0.0154}{0.0390} * 100 = 39\%$$

$$V_{23max}(\%) = \frac{0.0183}{0.0390} * 100 = 46\%$$

The total harmonic distortion at the filter size is designed to the harmonic size that can be appearing in the system can be calculated by:-

$$THDv(\%) = \sqrt{39^2 + 44^2 + 77^2 + 44^2 + 59^2 + 39^2 + 46^2}$$

$$THDv(\%) = \frac{\sqrt{1.844}}{49.57}$$

=0.027394=0.3%

Therefore, this result is compared with the standard of the IEEE-519 is also produce harmonic impact to the voltage and current injection of the power system is an acceptable.

Table 6.11. Total harmonic distortion below of the 3%

VTHD (Total Harmonic Distortion)			
Buses		Voltage distortion	
ID	KV	Fundamental%	VTHD%
Bus1	0.97	102.06	2.89
Bus2	0.98	101.40	2.78
Bus3	0.22	102.06	2.90
Bus4	2.20	101.40	2.78
Bus5	0.20	98.54	2.90
Bus6	0.11	82.40	1.91
Bus7	0.46	106.23	0.90
Bus8	0.49	101.81	2.17
Bus9	2.20	110.00	2.66
Bus10	2.50	102.65	2.78

Table.6.12. Individual Harmonic Distortion at the standard of the fifth order

5^{th}
1.99
1.97
1.98
1.96
1.99
1.99
1.97
1.97
1.97
1.97
1.97
1.97
1.97
1.97

$$V_{5max}(\%) = \frac{V_{3ma}}{V_{Fundamental}} * 100$$

Where, V fundamental is maximum value of summation of all harmonics and the total harmonic distortion at the filter size is designed to the harmonic size that can be appearing in the system can be calculated by taking the maximum and minimum values of the output:-

$$V_{5max} = \frac{V_{5max}}{Fundametal\ Voltage}$$

$$V_{5max}(\%) = \frac{0.0199}{0.0199} * 100 = 100\%$$

$$V_{5max} = \frac{0.0166}{0.0199} * 100 = 83\%$$

$$THD_v = \frac{\sqrt{1^2 + 0.83^2}}{49.7}$$

$$THD_v = \frac{\sqrt{1.6889}}{49.57}$$

$$THD_v = \frac{1.299576854}{49.57} = 0.02615 = 3.0\%$$

Table.6.13. Comparing the output voltage harmonic distortion of different filter types

Bus-ID	KV	Single tuned filter	By pass filter	Hay pass damped filter	Hay pass un damped filter	Third order damped filter	Third order C-type filter
		VTHD%	VTHD%	VTHD%	VTHD%	VTHD%	VTHD%
Bus-1	0.970	2.96	3.91	3.20	2.96	6.47	3.06
Bus-2	0.970	2.83	3.80	2.81	2.83	6.76	2.99
Bus-3	0.970	2.96	3.91	3.20	2.96	6.47	3.06
Bus-4	0.970	2.83	6.00	2.88	2.83	6.76	2.56
Bus-5	0.110	2.87	4.15	2.87	2.87	7.23	2.57
Bus-6	0.050	2.87	5.69	2.87	2.87	4.18	3.03
Bus-7	0.900	2.83	3.80	2.81	2.83	7.03	2.79
Bus-8	0.960	2.93	3.89	3.02	2.93	6.47	2.99
Bus-9	0.960	2.91	3.85	3.00	2.91	6.69	2.98
Bus-10	0.100	2.95	3.91	3.19	2.95	6.65	3.05

Therefore, the above table is shown the different output of the total harmonic orders of the single tuned filter, bay pass filter, hay pass damped filer, hay pass un damped filter, third order damped filter, and third order C-type filter. However, the effective filter with good quality factor and low impedance along the networks are single tuned filter, high pass damped filter, C-type filter and the bypass filter types are occasionally preferable.

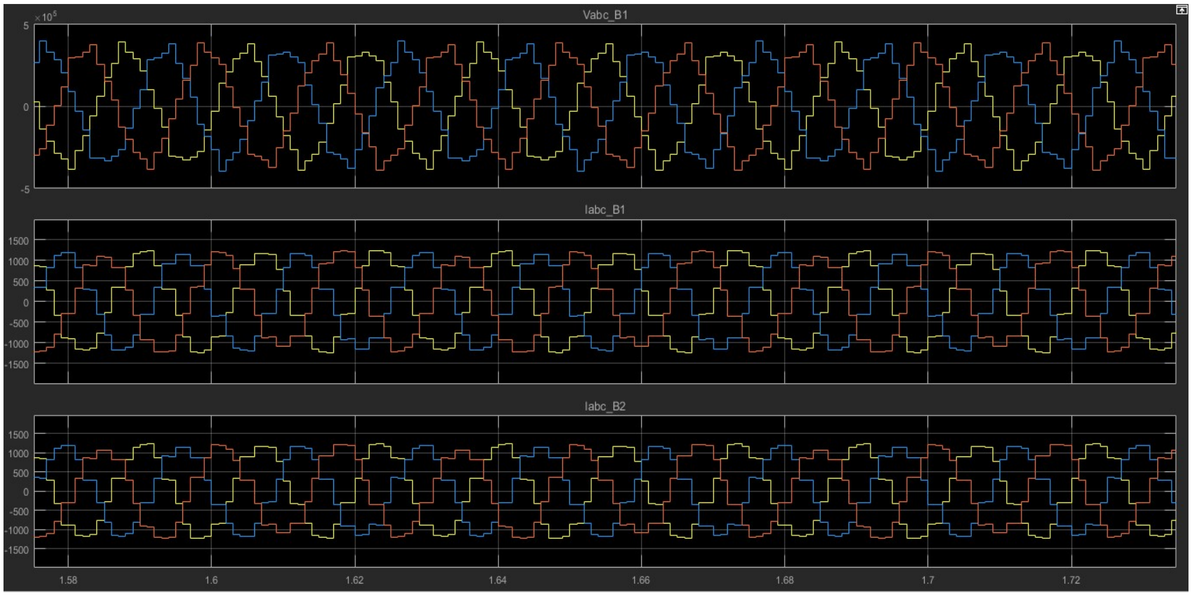


Figure.6.1. Current and voltage harmonic distortion of existing wave form

Figure .6.1.Indicates that the existing of Adma-II harmonic magnitude at the rage of (-5,5) of Vabc-B1, (-1500 to 1500) of Iabc-B1and (-1500 to 1500) Of Iabc-B2 are the negative and positive have cycle wave patterns have been explained the total harmonic distortion of voltage and current out puts are numerically about 50.6% would be distorted.

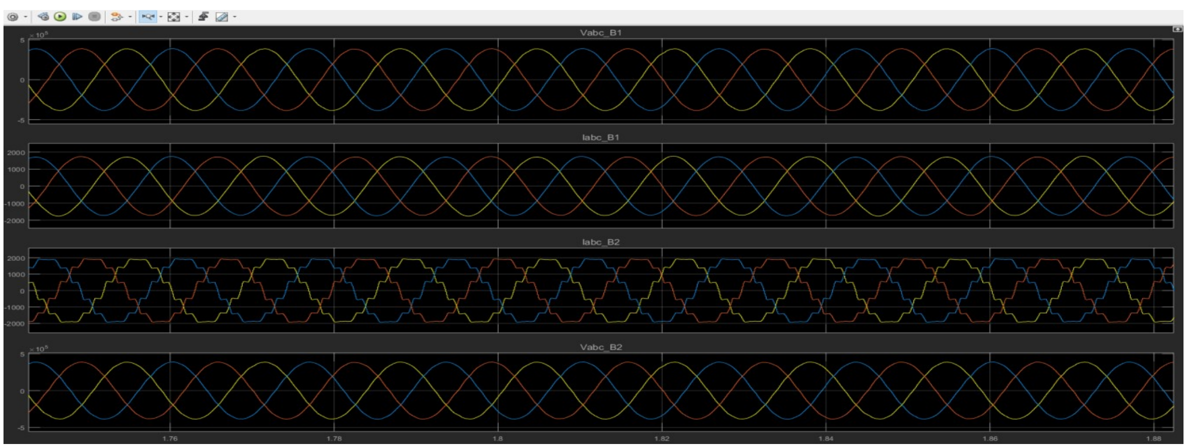


Figure.6.2. Existing wave form of current and voltage output in distribution network

Figure .6.2. Indicated that the current and voltage harmonic distortions of Vabc-B1 (-5, 5), Iabc-B1 (-2000, 2000) and Iabc-B2 (-2000, 2000) of a magnitude at the range of the wave patterns are shown that represents 30-43% harmonic magnitude of voltage and current output results.

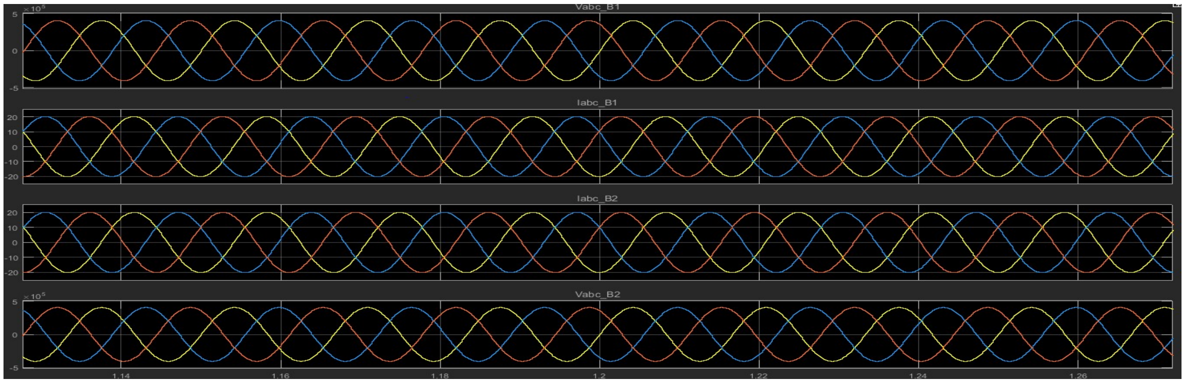


Figure .6.3.Voltage and current wave without harmonic filter and before inter connecting wind turbine

Figure .6.3. It is indicated that the I_{abc}-B_1, I_{abc}-B_2, V_{abc}-B_1 and V_{abc}-B_2 are shown that at the scale range of Iabc-B_1 is (-0.5,0.5) wave patterns, at Iabc-B_2 is (-0.5, 0.5) wave patterns, at Vabc-B1 is shown at the range of (-0.5,0.5) wave cycles, where as Vabc-B_2 is the same as the wave patterns of (-0.5,0.5) of the negative half cycle and the positive half cycle.

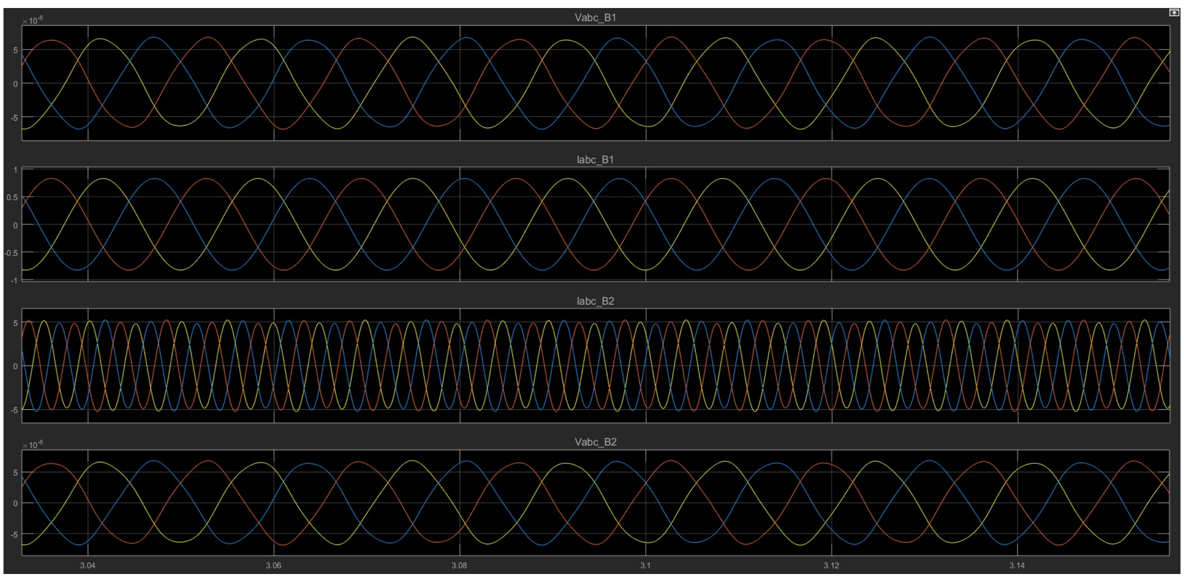


Figure.6.4. Voltage and current harmonic distortion with half filter

Figure .6.4.Voltage and current harmonic distortion with half filter, indicated that Vabc-B_2, Iabc-B1 and Iabc-B_2 is shown in the above wave patterns, so that the output wave patterns are not fully true sinusoidal wave form, because the true sinusoidal wave form of the IEEE standard is acceptable at Iabc-B_2 pattern is not true sinusoidal wave.

Figure .6.5. Wave form of voltage and current adding harmonic with filter

Figure .6.5. indicated that Iabc-B1 is the wave patterns shown that ,the magnitude of (-0.5,0.5) positive half cycle and the same as the Iabc–B_2 wave patterns also shown (-0.5 ,0.5) full cycles, where as the Vabc-B1 and Vabc-B_2 wave patterns also indicates the scale range magnitude of (-0.5 , 0.5) wave forms . In other hand the wave patterns of Iabc would be in the range scale of (-5, 5).

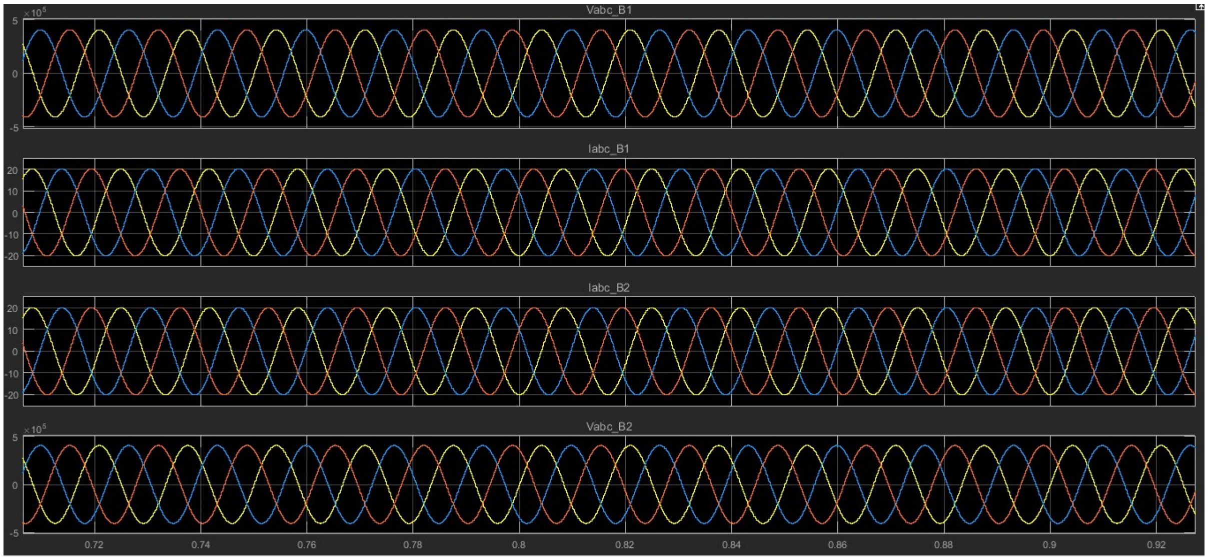


Figure.6.6. Current and voltage wave form out pout without wind turbine

Figure .6.6. Current and voltage wave patterns with connecting (adding) the filter had been indicated that , the magnitude of Vabc-B1 and Vabc-B2 is shown at the range scale of (-5 ,5) which implies that the harmonic distortion of the current and voltage magnitude would less or equal to three **(≤3%)**, where as the Iabc-B1 Iabc-B_2 are also shows that, the magnitudes of (-20 , 20) wave patterns of output result which verifies the amount of harmonic distortion of the current and voltage would be less or equal to three percent **(≤3%)**.

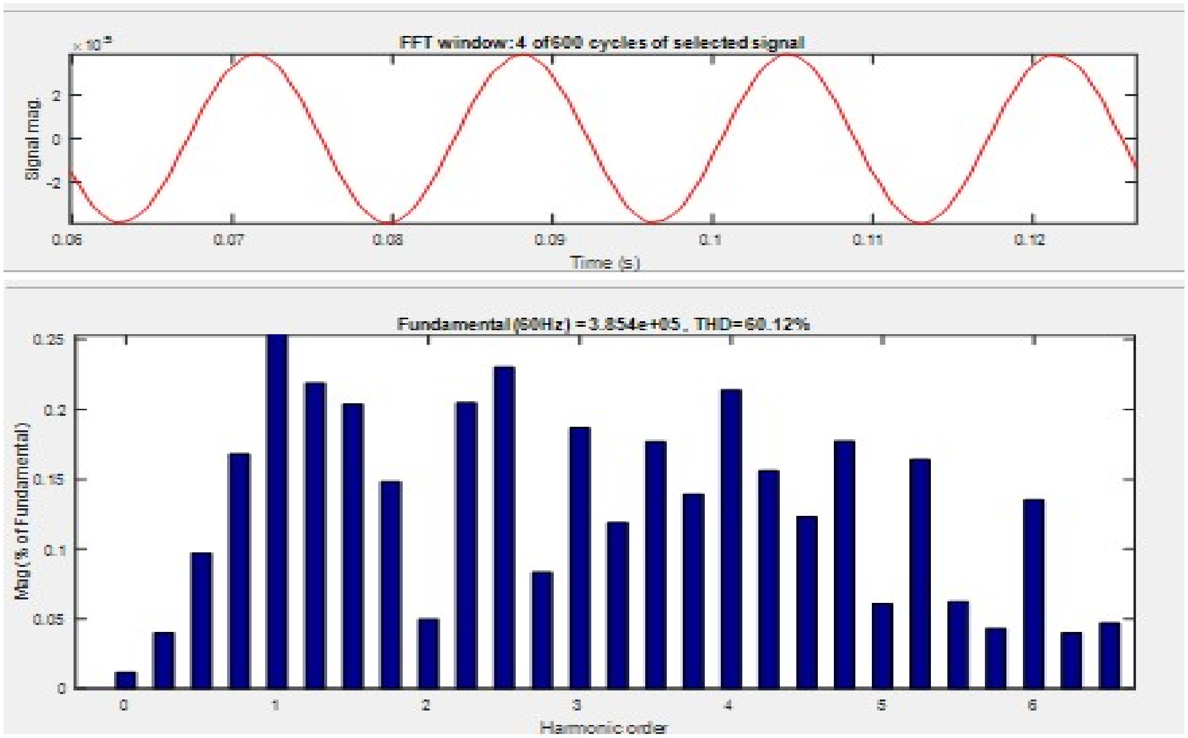


Figure 6.7.Harmonic distortion of the existing of wind power generation of harmonic order

Figure.6.7. The harmonic distortion of existing of wind power generation of harmonic order (without adding filters) indicated that the ordinal numbers (0 -1] is represents 3rd harmonic order, the ordinal number (1 - 2] is the 5th harmonic order, the ordinal numbers (2-3] is indicated the 7th harmonic order, the ordinal numbers (3-4] indicates 11th harmonic order, the ordinal numbers (4-5] indicate the 13th harmonic order, the ordinal number (5-6] and above are all indicates 17th , 19th, 21th and 23th harmonic order.

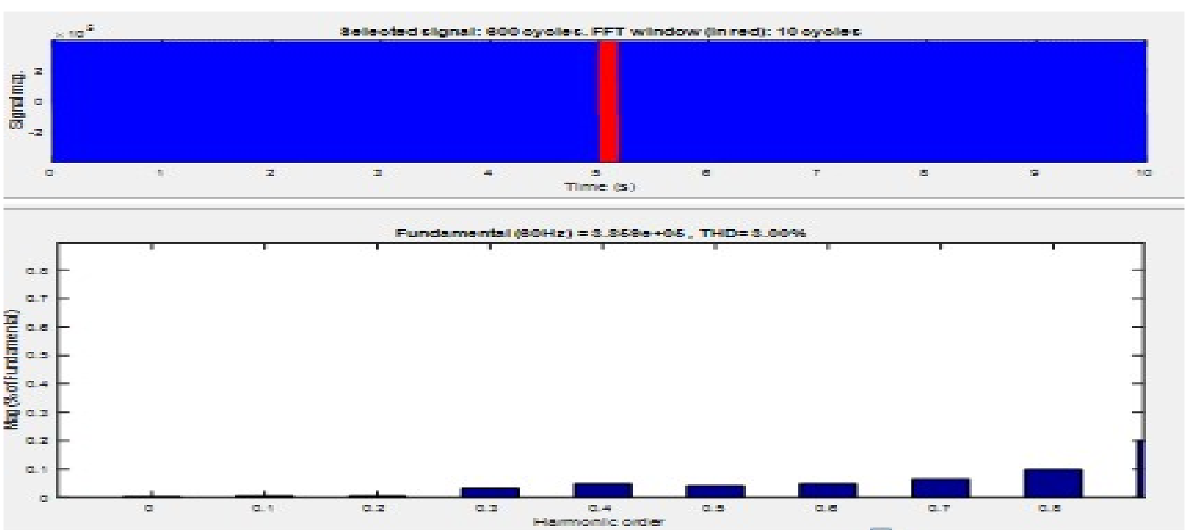


Figure 6.8. Harmonic order by adding filter into wind power generation

Figure.6.8. Harmonic order by adding filters into wind power at the terminal out going feeders have indicated that the ordinal number represent by (0) is 3rd harmonic order, the ordinal number represent by (0.1) is 5th harmonic order, the ordinal number (0.3) represents by the 11th harmonic order, the ordinal number (0.4) represents the 13th harmonic order, the ordinal number (0.5) represents 17th harmonic order, the ordinal number (0.6) 19th harmonic order, the number (0.7) represents 21th harmonic order . Finally the harmonic distortion is of the THDV and THDI is completely controlled by adding the above mentioned filters are success fully work.

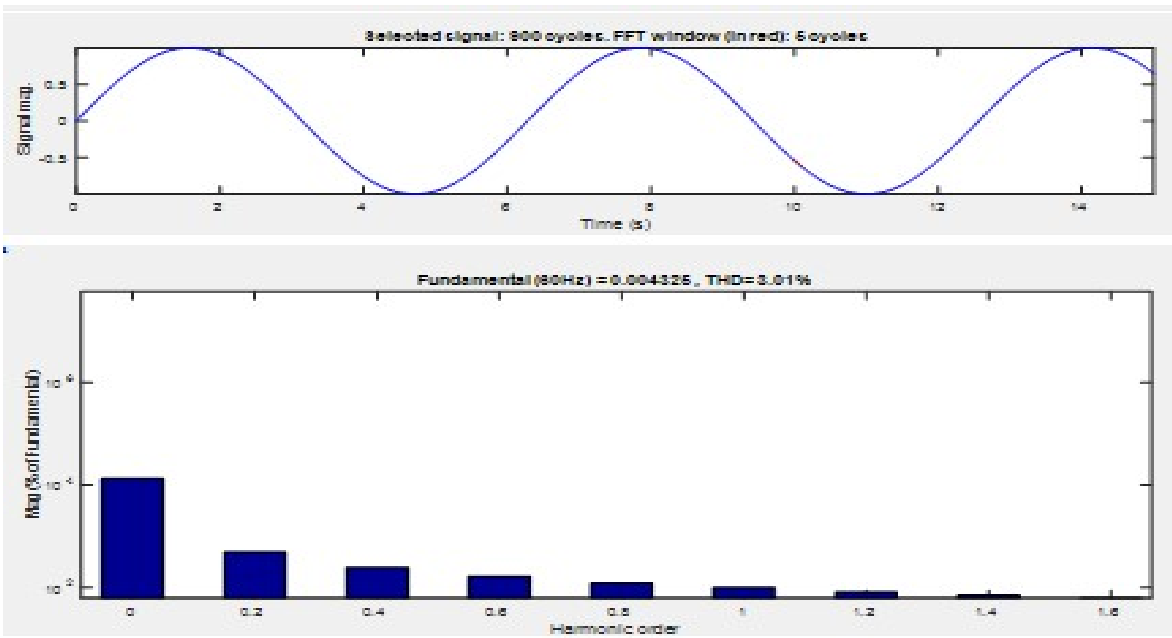


Figure 6.9.Harmonic distortion by adding filter of FFT of wind power generation

Figure.6.9. Harmonic distortion by adding filters of FFT wind power generation indicated that the harmonic orders of 3rd, 5th, 7th, 11th, 17th, 21th, and 23th harmonic plots.

CHAPTER SEVEN

7. CONCLUSION & RECOMMENDATION

7.1. CONCLUSION

Portion of Ethiopian Electric utility distribution network in south eastern of Addis Ababa around Adma-II wind power had been studied to investigate amount of harmonic distortion injected in to the network due to integration of synchronizing with hydro power generation, and under this study existed and identified particular harmonic level is able to be mitigated. Harmonic distortion has a harmful effect on both distribution system equipment and loads that the system supplies. It is a main cause of supply quality degradation. Analysis and calculations had been done considering the different transformers and feeders at distribution system which supplies power to the customer loads through the different network systems. The Total Harmonic Distortion of voltage (THDv) and Current (THDi) has been the main focus for the study and it is compared with the power quality standards stated on IEEE-519 and IEC-61000.

The impact of harmonics is occurring in the system. The analyzed field measurements in system analysis section show that the overall total harmonic voltage and current distortion is high in the area of special loads like, factory, commercial and all individual customer loads and power network with reference to IEEE-519 and IEC-61000 standards. Simulation result shows that the numerical output obtained in the result and analysis for both voltage and current with the addition of filters is good, that is almost equal or less IEEE-519($\leq 3\%$). The simulation results for the voltage and current without the addition of designed filters is lead to the real power injection and the power quality deterioration.

The set of equations for calculating the values required for modeling the utility network, and the wind power generation of 150MW, and inductance values of the filter to reduce harmonic distortion are presented in analysis section. It would be beneficial for the real power injection to minimize or reduce to the standard of the harmonic level on the network to avoid equipment failure and a major loss of production. As the number of non-linear load wind power generation increases, the level of distortion would extremely increase. But it is difficult to notice the effects of harmonic currents on equipment until equipment failure occurs. To overcome the power quality problems, one should make use of harmonic filters, which will not only suppress harmonics, but also supplies the reactive power for the improvement of power factor. In addition to this the wind supplies highly impact of harmonics on the distribution networks, in order to this the wind power generation is preferable to use independently or auxiliary purpose and vital loads.

7.2. RECOMMENDATIONS

After doing all the evaluation and analysis of data from those targets electric power generating elements, I have reached at a mechanism to improve operation at this location or able to avoid the impact due to harmonics from those mentioned sources. As I had identified all the effects from the injected harmonics and a causative level of harmonics within the system, finally I had developed and model a module to filter this harmonic in each case. With all my findings, I would like to forward my recommendation to this wind farm studied in this paper in particular, and proposed type of power generation based on wind energy sources at large.

For those wind power farm studied in this research work, I strongly recommend respected individuals to implement or integrate my specific filters design as I develop a model and simulated each modules for this type plant, correspond rating, and experience all the benefits as we as save and prolong life of equipment’s, suffering from the distortion.

Future expansion of the wind power generation, it is recommended that the designers utilize the proposed adaptation to indicate the ability of all power devices such as transformer, cables, invertors, transmission lines and switching devices are to handle harmonic loads.

7.3. FUTURE WORK

- A complete power quality study of the distribution network and micro-grid power generation should be done with the aid of Power quality analyzer (PQA), which is very important device nowadays for engineers in monitoring power quality problems. This device has the capability of measuring and displaying the standardized harmonics of the current, voltage, power, power factor, THDv and THDi. Therefore, it is recommended that PQA should be available in the utility distribution system.
- The research results in this thesis point to several issues where future research can be done in some other issues of large industry, geothermal power generation diesel generation and thermal power generation system.

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APPENDEX A – WIND POWER DATA COLLECTION AND SOLAR FARM DATA COLLECTION

Table.2.1. Technical parameters of WTGS

WTGS Model	GW66/1500KW	GW70/1500 KW	GW77/1500 KW	GW82/1500 KW	GW87/1500 KW
Security level	IECIA	IECIA/IECI IA	IECIA/IECI IIA	IECIA/IECI IIA	IECIA/IECI IIB
Rated Power	1500KW	1500KW	1500KW	1500KW	1500KW
Inverter output Voltage	620V	620V	620V	620V	620V
Diameter of Rotor	66m	70.34m	76.84m	82.34m	86.6-88.3m
Swept area	3421m^2	3885.9m^2	4637.3m^2	5324.9m^2	5874-611m^2
Hub height	65m	65/85m	65/85m	70m	70/75/85m
Scope of rotation speed of rotor	10.6-20.5rpm	8.8-19rpm	8.8-17.3rpm	8.8-17.3rpm	8.8-17.3rpm
Rated speed	20.5rpm	19rpm	17.3rpm	17.3rpm	17.3rpm
Rated wind speed	13.1m/s	12m/s	11m/s	10.3m/s	9.9m/s
Cut-in Wind speed	3m/s	3m/s	3m/s	3m/s	3m/s
Cut out wind speed	25m/s	22m/s	22m/s	22m/s	22m/s
Maximum survival wind speed(3-second)	78m/s	70m/s	59.5m/s	52.5m/s	52.5m/s
Maximum allowable maintena. wind speed	11m/s	11m/s	11m/s	11m/s	11m/s
Scope of operating temperature	-30č-40č	-30č-40č	-30č-40č	-30č-40č	-30č-40č
Survival temperature of WTGS	-30č-40č	-30č-40č	-30č-40č	-30č-40č	-30č-40č
Design service life	$\geq 20\ years$	$\geq 20\ years$	$\geq 20\ years$	$\geq 20\ years$	$\geq 20\ years$
Lightening protection design standards	IEC61400-IEC62305	IEC61400-IEC62305	IEC61400-IEC62305	IEC61400-IEC62305	IEC61400-IEC62305

Table 4.5.GW I.SMW Blade Characteristics

Blade Type	Blade Length	Rotor Diameter	Swept Area
LM35P	35.0m	70m	3,846.50m^2
LM373P	37.3m	77m	4,654.27m^2
LM40P	40.3m	82m	5,278.34m^2
Lm42P	42.1m	86.6m	5,887.15m^2

Table.2.7. Wind Turbine Specification

Rated power(kw)	1800
Rotor dynamics(m^2)	90
Swept Area(m^2)	6362
Cut in Speed(m/s)	4
Rated Speed (m/s)	12
Cut out speed(m/s)	25
Hub Height (m)	100
Blade Length(m)	49
Variable Pitch Reduce (Ratio)	155
Variable Pitch Reduce (Number Of teeth)	15
Variable Pitch Slewing bearing (Number Of teeth)	139
Variable Pitch Slewing bearing (Ratio)	1154
Yaw Reducer (Number of teeth)	14
Yaw Slewing Bearing (Number of teeth)	128
Increasing gear box (Ratio)	94.7
Principal axis proximity switch input pulse	36

APENDEX B – IEEE Standards

Table 3.7 harmonic current distortion limits in % by IEEE-1159 [1]

I_{SC}/I_L	$h < 11$	$11 \le h < 17$	$17 \le h < 23$	$23 \le h < 35$	$35 \le h$	TDD
$V_n \le 69$ kV						
<20	4.0	2.0	1.5	0.6	0.3	5.0
20–50	7.0	3.5	2.5	1.0	0.5	8.0
50–100	10.0	4.5	4.0	1.5	0.7	12.0
100–1000	12.0	5.5	5.0	2.0	1.0	15.0
>1000	15.0	7.0	6.0	2.5	1.4	20.0
69 kV $< V_n \le 161$ kV						
<20*	2.0	1.0	0.75	0.3	0.15	2.5
20–50	3.5	1.75	1.25	0.5	0.25	4.0
50–100	5.0	2.25	2.0	0.75	0.35	6.0
100–1000	6.0	2.75	2.5	1.0	0.5	7.5
>1000	7.5	3.5	3.0	1.25	0.7	10.0
$V_n > 161$ kV						
<50	2.0	1.0	0.75	0.3	0.15	2.5
≥50	3.0	1.50	1.15	0.45	0.22	3.75

Table 3.6 Maximum Current Distortions in % at PCC

Bus Voltage	Maximum Individual Harmonic Component (%)	Maximum THD(%)
69 KV and below	3	5
115KV-161KV	1.5	2.5
Above 161KV	1	1.5

Values shown are in % of "average maximum load current".

Table3.9. Harmonic Current limits according to IEC 61000-2-4 [12]

Harmonic order *h*	Max. permissible harmonic current* (%)	Harmonic order *h*	Max. permissible harmonic current* (%)
3	21.6	19	1.1
5	10.7	21	0.6
7	7.2	23	0.9
9	3.8	25	0.8
11	3.1	27	0.6
13	2	29	0.7
15	0.7	31	0.7
17	1.2	33	0.6

*Percent of the fundamental input current.

APENDEX C – Matlab output functions

```
function updateDisplayLayoutDimensions(this)
%updateDisplayLayoutDimensions   React to change in layout dimensions

%   Copyright 2012-2015 The MathWorks, Inc.

sendEvent(this.Application, 'LayoutDimensionsChanging');
prepareForLayoutChange( this );
destLayoutDims = this.getPropertyValue('DisplayLayoutDimensions');
destNumDisplays = prod(destLayoutDims);
% Get number of inputs and displays
source = this.Application.DataSource;

% Update the IOSignals. For Floating block and Viewers, we need to update
% the IOSignals to be consistent with the new number of displays. Also,
% floating scope and scope viewers should not hide the axes, i.e.,
ShowContent
% property should be true.
source.updateIOSignals(destNumDisplays);
isFloating = source.Floating;

numInputs = source.getNumInputs;
srcDisplays = this.Displays;
srcNumDisplays = length( srcDisplays );
srcNumDisplaysWithData = min( srcNumDisplays, numInputs );
destNumDisplaysWithData = min( destNumDisplays, numInputs );
% Get whether to defer moving content, which occurs if the simulation has
% not yet run or if inputs have been updated.  In this case, ensure
% DisplayContentCache is populated for later use.
% Update source - needed for TimeScopeSLA since source is not in sync
% while updates are being made in C++
if ~isempty( source ) && isa( source, 'Simulink.scopes.source.WiredSource'
)
    requestUpdate( source );
end
[~,deferContentMove] = isDataAvailable( this );
if deferContentMove && isempty( this.DisplayContentCache )
    srcContent = cell( 1, srcNumDisplaysWithData );
    for displayInd = 1:srcNumDisplaysWithData
        srcContent{ displayInd } = srcDisplays{ displayInd
}.getContentProperties;
    end
    this.DisplayContentCache = srcContent;
end
% Set ReshapingLayout so that calls to update are dropped while the layout
% is being updated.
this.ReshapingLayout = true;
restoreReshapingLayoutOnDelete = onCleanup( @() setReshapingLayout( this )
);
    function setReshapingLayout(this)
        this.ReshapingLayout = false;
    end
% Set layout grid invisible until update is complete
```

```
set( this.LayoutGridContainer, 'Visible', 'off' );
% There are three cases for reshaping dimensions:
% 1. Same number of populated displays as before
% 2. Fewer populated displays, in which case we need to consolidate
displays
% 3. More populated displays, in which case need to break up displays
newDisplays = {  };
if isequal( srcNumDisplaysWithData, destNumDisplaysWithData )
    % No work necessary on existing displays that have data, but trim or
    % create empty displays as needed.
    if destNumDisplays>srcNumDisplays
        % Create new "empty" displays
        for displayInd = (srcNumDisplays + 1):destNumDisplays
            destDisplay = cloneDisplay( this, displayInd, srcDisplays{ end
} );
            destDisplay.ShowContent = false || isFloating;
            newDisplays{ end + 1 } = destDisplay;  %#ok<*AGROW>
            this.Displays{ end + 1 } = destDisplay;
        end
    elseif srcNumDisplays>destNumDisplays
        % Trim old "empty" displays
        oldDisplaysToDelete = srcDisplays( destNumDisplays + 1:end );
        this.Displays( destNumDisplays + 1:end ) = [  ];
        cellfun( @delete, oldDisplaysToDelete );
    end
elseif destNumDisplaysWithData<srcNumDisplaysWithData
    % With fewer displays with data, two or more old displays will be
    % joined into a single new display.  If no data is available, just
    % trim the old displays to get the correct layout.
    if ~deferContentMove
        % Join old source displays into last display
        destDisplayContentInd = 1;
        for displayInd = destNumDisplaysWithData:srcNumDisplaysWithData
            hDisplay = srcDisplays{displayInd};
            destDisplayContentInd = hDisplay.joinContent(hDisplay, ...
                srcDisplays{destNumDisplaysWithData},
destDisplayContentInd);
        end
    end
    % Trim obsolete displays
    oldDisplaysToDelete = srcDisplays( destNumDisplaysWithData +
1:srcNumDisplays );
    this.Displays( destNumDisplaysWithData + 1:srcNumDisplays ) = [  ];
    cellfun( @delete, oldDisplaysToDelete );
else
    % With more displays with data, the last old display must be split
    % into two or more new displays.
    srcDisplay = srcDisplays{ srcNumDisplaysWithData };
    % Create new displays
    newDisplaysWithData = {  };
    newDisplaysWithNoData = {  };
    for displayInd = srcNumDisplaysWithData + 1:destNumDisplays
        if displayInd>destNumDisplaysWithData
            % Create empty display with default properties
            destDisplay = createDefaultDisplay( this, displayInd );
            destDisplay.ShowContent = false || isFloating;
```

```
            newDisplaysWithNoData{ end + 1 } = destDisplay;
        else
            % Clone display from source display
            destDisplay = cloneDisplay( this, displayInd, srcDisplay );
            newDisplaysWithData{ end + 1 } = destDisplay;
        end
        newDisplays{ end + 1 } = destDisplay;
    end
    if ~deferContentMove
        % Split source display into corresponding new displays.  Map one
        % input to each new display until the last display is reached,
        % which gets all remaining inputs.  Splitting content from source
        % display will also remove content from the display so that it
        % will be left with just the first input's data.
        numSrcInputs = size( srcDisplay.NumberOfChannels, 1 );
        destDisplays = [ { srcDisplay }, newDisplaysWithData ];
        for displayInd = 1:numel( destDisplays ) - 1
            srcDisplay.splitContent(srcDisplay, destDisplays{displayInd},
displayInd);
        end
        srcDisplay.splitContent(srcDisplay, destDisplays{end}, ...
            numel(destDisplays):numSrcInputs );
    else
        srcDisplay.onDeferredSplit( srcDisplay );
    end
    % Add new displays
    this.Displays = [ srcDisplays, newDisplaysWithData,
newDisplaysWithNoData ];
end
% If the new layout is a single display, then update default properties to
% be in sync with that display's values
if prod( destLayoutDims )==1
    hDisplay = this.Displays{ 1 };
    this.DisplayPropertyDefaults = hDisplay.getCloneProperties;
end
matlabshared.scopes.visual.Displayable.tile(this.Displays{1},
this.LayoutGridContainer, ...
    this.Displays, destLayoutDims);
% Push source data to displays
% if ~deferContentMove
    updateDisplays( this );
% end
% Set ReshapingLayout to false, since it should now be safe to call update
delete( restoreReshapingLayoutOnDelete );
% Perform visual specific work to update displays
onLayoutChange( this, newDisplays );
% Update and re-apply SelectedDisplay to guarantee that values shown in
the
% properties dialog are current.  If the selected display was one that was
% consolidated into a new display, update selectedDisplay to point to the
% new display.  In addition, updating SelectedDisplay results in the
% properties dialog being refreshed, which updates the list of displays to
% select from.
selectedDisplay = this.SelectedDisplay;
if (destNumDisplays<srcNumDisplays) && (str2double( selectedDisplay
)>=destNumDisplays)
```

```
    selectedDisplay = num2str( destNumDisplays );
end
this.SelectedDisplay = selectedDisplay;
% Set visible again
sendEvent(this.Application, 'LayoutDimensionsChanged');
set( this.LayoutGridContainer, 'Visible', 'On' );
end
```

```
function updateIOSignals(this,newNumAxes)
%UPDATEIOSIGNALS Update the IOSignals/IORec for Floating/Viewer Scopes
%   Update is done to respond to changes in the number of displays.

%   Copyright 2015 The MathWorks, Inc.

if this.Floating
   ioSignals = get(this.BlockHandle,'IOSignals');
   % Each cell of ioSignals represents an axes and it contains a list of
   % signals connected to that axes.
   currNumAxes = length(ioSignals);
   % Reformat the IOSignals to match the number of axes
   if currNumAxes == newNumAxes
        % Nothing to be done
        return;
   elseif currNumAxes > newNumAxes
        % Shrink the ioSignals reasonably. Append excess signals on the
        % last cell. A particular cell of the ioSignal cannot have a mix of
        % valid and invalid signals. So eliminate invalid signals.
        newIOSignals = ioSignals(1:newNumAxes);
        % Before appending the last cell, eliminate any invalid handles due
        % to no signal connection.
        if (newIOSignals{newNumAxes}(end).Handle == -1)
           newIOSignals{newNumAxes}(end) = [];
        end
        for indx = newNumAxes+1:currNumAxes
            currIOSignal = ioSignals{indx};
            for kndx = 1:length(currIOSignal)
                % The signal we are adding should not be invalid and also
                % not already existing on the last axes.
                if (currIOSignal(kndx).Handle~=-1) &&
~(any([newIOSignals{newNumAxes}.Handle] == currIOSignal(kndx).Handle))
                    newIOSignals{newNumAxes} =
[newIOSignals{newNumAxes}(:);currIOSignal(kndx)];
                end
            end
        end
   else
        % Expand the ioSignals by adding empty connections to match the
        % displays.
        newIOSignals = ioSignals;
        for indx = currNumAxes+1:newNumAxes
            newIOSignals{indx} = struct('Handle',-1,'RelativePath','');
        end
```

```
    end
    set(this.BlockHandle,'IOSignals',newIOSignals);
end

end
```

```
classdef Extension < matlab.mixin.Heterogeneous & handle
    %Extension   Define the Extension class.

    %   Copyright 2012 The MathWorks, Inc.

    properties (SetAccess = 'private')

        %Application Handle to the extensible application object
        %
        %   See also extmgr.Extension
        Application;

        %Configuration Handle to the configuration object
        %
        %   See also extmgr.Extension
        Configuration;

        %Registration Handle to the registration object
        %
        %   See also extmgr.Extension
        Registration;
    end

    properties (SetAccess = private, Hidden, Dependent)
        Config;
        Register;
    end

    properties (Access = protected)
        UIMgrGUI;
        PropertyListener;
    end

    methods
        function this = Extension(hApplication, hRegistration,
hConfiguration)
            %Extension   Construct the Extension class.

            this.Application   = hApplication;
            this.Registration  = hRegistration;
            this.Configuration = hConfiguration;
```

```
            this.PropertyListener =
event.listener(hConfiguration.pPropertySet, ...
                'PropertyChanged', @this.localPropertyChanged);
        end

        function convertObsoleteProps(~)
            % NO OP
        end

        function propValue = getPropertyValue(this, propName)
            %GETPROPVALUE Get the propValue.

            pSet = this.Configuration.pPropertySet;
            propValue = getValue(pSet, propName);
        end

        function setPropertyValue(this, varargin)
            %SETPROPVALUE Set the PropValue.
            %   setPropValue(H, PROP1, VALUE1) Set the property specified
by PROP1 to
            %   value specified by VALUE1.  Multiple P/V pairs can be
specified.
            %   propertyChanged will only fire for the last pair.

            % Disable the listener so that it doesn't fire for every
single property.
            this.PropertyListener.Enabled = false;

            % If we were passed a trailing input, it is the 'noResponse'
flag.
            noResponse = false;
            if rem(nargin, 2) == 0
                noResponse = varargin{end};
                varargin(end) = [];
            end

            propSet = this.Configuration.PropertySet;

            % Loop over and set all of the properties except the last one.
            for indx = 1:2:length(varargin)-2
                setValue(propSet, varargin{indx}, varargin{indx+1});
            end

            % If we want a response, turn the listener back on so that
setting the last
            % property will fire it.
            if ~noResponse
                this.PropertyListener.Enabled = true;
            end

            % Set the last property.
            setValue(propSet, varargin{end-1}, varargin{end});
```

```
            % If we do not want a response, turn the listener back on here
so that we
            % return the object back to its normal state.
            if noResponse
                this.PropertyListener.Enabled = true;
            end
        end

        function updatePropertySet(~, ~)
            % NO OP
        end

        function config = get.Config(this)
            config = this.Configuration;
        end

        function register = get.Register(this)
            register = this.Registration;
        end
    end

    methods (Sealed)
        function disp(this)
            if numel(this) == 1
                s.Type = this.Config.Type;
                s.Name = this.Config.Name;

                disp(s);

                disp@handle(this);

                disp(this.Configuration.PropertySet);

            else
                cwSize = get(0, 'CommandWindowSize');
                for indx = 1:numel(this)-1

                    disp(this(indx));

                    % Separate each extension display by a line.
                    fprintf([repmat('-', 1, cwSize(1)) '\n']);
                end
                disp(this(end));
            end
        end

        function b = eq(this, that)
            b = eq@handle(this, that);
        end

        function b = ne(this, that)
            b = ne@handle(this, that);
        end
    end
```

```
    methods (Static)
        function hPropSet = getPropertySet()
            hPropSet = [];
        end

        function obj = getDefaultObject
            obj = extmgr.Extension([], [], []);
        end
    end

    methods (Access = protected)
        function hInstaller = createGUI(~)
            hInstaller = [];
        end

        function hProp = findProperty(this, propName)
            hProp = findProperty(this.Configuration.PropertySet,
propName);
        end
    end

    methods (Hidden)

        function disable(~); end
        function enable(~);  end

        function localPropertyChanged(this, ~, ev)
            propertyChanged(this, ev);
        end

        function disableExtension(this, varargin)
            disable(this);
            uninstallGUI(this, varargin{:})
        end

        function enableExtension(this, varargin)
            installGUI(this, varargin{:});
            enable(this);
        end

        function varargout = evalPropertyValue(this, property)

            string_value = getPropertyValue(this, property);
            [varargout{1:nargout}] = uiservices.evaluate(string_value);
        end

        function optionsDialogTitle = getOptionsDialogTitle(this, hSystem)
            hRegister = this.Registration;
            type = hRegister.Type;
            optionsDialogTitle = sprintf('%s - %s %s', ...
                hSystem.findType(type).Label, ...
                hRegister.Label, ...
                getString(message('Spcuilib:scopes:TitleOptDlg')));
```

```
        end

        function propsSchema = getPropsSchema(~, ~)
            propsSchema = [];
        end

        function h = findProp(this, tag)
            h = this.Configuration.PropertySet.findProperty(tag);
        end

        function installGUI(this, allowRender)
            %INSTALLGUI If extension has a GUI, install and render it now.
            %   INSTALLGUI(H) installs the GUI aspects of the extension as
specified by
            %   the uimgr.Installer object returned from createGUI.
            %
            %   INSTALLGUI(H, false) installs the GUI but suppresses
rendering until a
            %   later time.

            % If we have already created the GUI simply return early
            hUIMgr = getGUI(this.Application);

            % Return early if the application does not support a UIMgr-
based GUI.
            if isempty(hUIMgr)
                return;
            end

            if isempty(this.UIMgrGUI)
                hGUI = createGUI(this);

                % If the extension does not wish to add GUI components,
return early.
                if isempty(hGUI)
                    return;
                end
                this.UIMgrGUI = hGUI;

                install(hGUI, hUIMgr);
            end

            % Must call render() manually after install() method.  This
provides
            % efficiency during startup phases (e.g., for our case when
allowRender =
            % false).
            if nargin < 2 || allowRender
                render(hUIMgr);
            end
        end

        function onOptionsDialogClose(~, ~)
            % NO OP
```

```
        end

        function [success, msg] = postOptionsDialogApply(~, ~)
            %POSTOPTIONSDIALOGAPPLY Called as the post action to the
OptionsDialog

            success = true;
            msg = '';
        end

        function propertyChanged(~, ~)
            % NO OP
        end

        function uninstallGUI(this, allowRender)
            %UNINSTALLGUI If extension has a GUI, uninstall it now.
            %   UNINSTALLGUI(H) uninstall the GUI if it exists.

            hInstall = this.UIMgrGUI;
            if ~isempty(hInstall)

                hUIMgr = getGUI(this.Application);
                uninstall(hInstall,hUIMgr);  % un-renders as well
                this.UIMgrGUI = [];

                if nargin < 2 || allowRender
                    render(hUIMgr);
                end
            end
        end

        function updatePropertyDb(this, varargin)
            updatePropertySet(this, varargin{:});
        end

        function varargout = validate(~, ~)
            %VALIDATE Returns true if this object is valid

            if nargout
                varargout = {true, MException.empty};
            end
        end
    end
end

% [EOF]
```