ANALYZING POWER QUALITY ISSUES OF WIND POWER PLANTS IN PUTTALAM

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Degree of Master of Science

Department of Electrical Engineering

University of Moratuwa
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Dissertation submitted in partial fulfillment of the requirements for the degree Master of Science

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DECLARATION

I declare that this is my own work and this dissertation does not incorporate without acknowledgement any material previously submitted for a Degree or Diploma in any other University or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgement is made in the text.

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Date: 19/12/2014

Dr. H.M. Wijekoon

ABSTRACT

Wind Power development has become a booming industry due to its advantages over conventional thermal power sources. However, wind is considered as an intermittent source in terms of power quality as wind turbines have an uneven power generation following natural variations of wind. Power quality (PQ) is an important issue for electricity consumers at all levels of usage, particularly industrial sector as PQ disturbances ultimately lead to huge economic losses and safety concerns.

The research objectives are; to study on major power quality issues associated with four wind plants in Puttalam, propose suitable PQ improving methods and to identify the most suitable wind technology in view of power quality. Project scope includes measurement of electrical parameters at each plant, analysis of parameters based on “IEC 61400-21” and “Grid Connection Requirement” published by Ceylon Electricity Board, study on mitigation techniques, computer modeling and simulation in MATLAB/SIMULINK environment to investigate harmonic mitigation. For each power quality aspect, a set of norms and marginal values were set to evaluate each wind plant’s performance. There are four distinct wind technologies and three of them are available in Sri Lanka. Out of these technologies, Wind Turbine type “C” which employs a Doubly-Fed Induction Generator with a partial scale power converter shows the best power quality characteristics.

From Measurements and Data Analysis it was concluded that, none of the investigated plants adhere to power quality requirements of the grid code. Neither the utility (CEB) nor the Wind Power Producers pay adequate attention on these violations. It is recommended to pay more attention on PQ deviations. Systems must be developed to continuously monitor PQ parameters and take necessary actions to keep them within specified levels. Further, hybrid filters to reduce harmonic distortion and Dynamic Voltage Restorers to mitigate voltage sags are proposed for WPPs under study.

Keywords: Power Quality, Wind Power, Harmonics, Active Filter

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TABLE OF CONTENTS

Chapters

LIST OF FIGURES

Page

LIST OF TABLES

LIST OF ABBREVIATIONS

Abbreviation	Description
AC	Alternating Current
AF	Active Filter
CEB	Ceylon Electricity Board
CSC	Current Source Converter
CSI	Current Source Inverter
DC	Direct Current
DFIG	Doubly-Fed Induction Generator
DSP	Digital Signal Processor
DVR	Dynamic Voltage Restorer
GIS	Gas Insulated Substation
GSS	Grid Sub Station
HV	High Voltage
IEC	International Electromechanical Commission
IEEE	Institute of Electrical and Electronic Engineers
IPP	Independent Power Producers
IT	Information Technology
LV	Low Voltage
LVRT	Low Voltage Ride Through
NCRE	Non-conventional Renewable Energy
NE	North East
NEMA	National Electrical Manufacturers Association
NREL	National Renewable Energy Laboratory
OP-AMP	Operational Amplifier
OPEC	Organization of Petroleum Exporting Countries
PCC	Point of Common Coupling
PF	Passive Filter
PMG	Permanent Magnet Generator

PQ	Power Quality
PSS/E	Power System Simulation for Engineering
PWM	Pulse Width Modulation
RMS	Root Mean Square
SCIG	Squirrel-Cage Induction Generator
STATCOM	Static Synchronous Compensator
SVR	Static Voltage Regulator
SW	South West
THD	Total Harmonic Distortion
VSC	Voltage Source Converter
VSI	Voltage Source Inverter
WPP	Wind Power Plant
WRIG	Wound Rotor Induction Generator

Principal Symbols

A	Ampere
GW	Giga Watt
H	Harmonic number
Hz	Hertz
I	Current
IGBT	Insulated Gate Bipolar Transistor
km	kilometers
kV	Kilo Volt
kVA	kilo volt ampere
kW	Kilo Watt
m	Meters
m/s	Meters per second
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
ms	Milliseconds
MVA	Mega volt ampere

MW	Mega Watt
MW	Mega Watts
P	Active Power
P_{LT}	Long Term Flicker Index
P_{ST}	Short Term Flicker Index
PU	per unit
Q	Reactive Power
R	Resistance
rpm	rounds per meter
s	Seconds
V	Volt

LIST OF APPENDICES

Chapter 01

INTRODUCTION

Electricity generation using wind energy has become a widely booming industry across the globe with an annual growth rate of 20%. A huge growth is observed in Asian region with the highest annual installing capacity. According to the Global Wind Energy Council, the global total of installed wind capacity at the end of year 2012 was 282.5 GW where 35% of them located within Asia. For the last few years, Asia was the world's largest regional market for wind energy. The increase of globally installed wind capacity is shown in Figure 1.1.

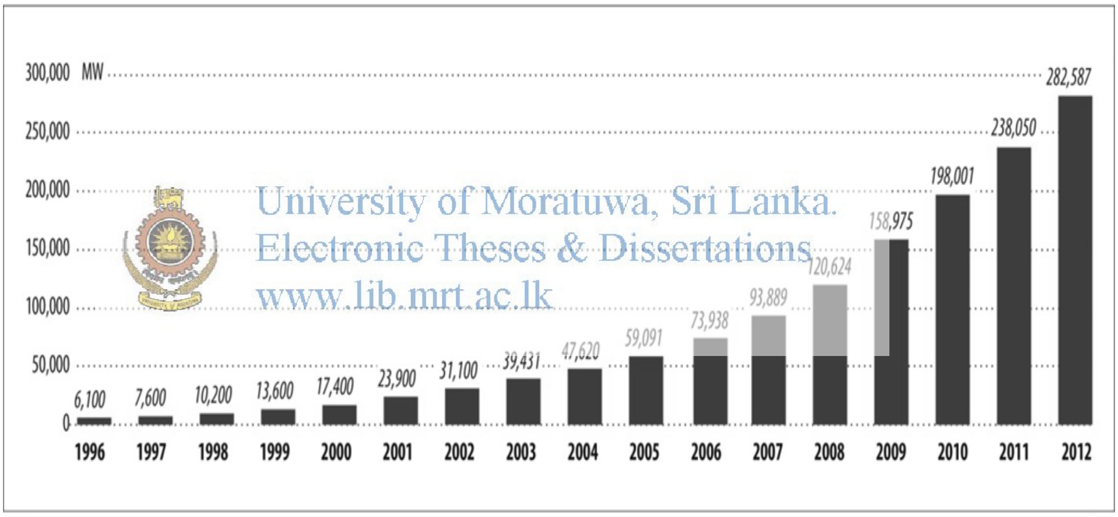


Figure 1.1 : Increase of Global Cumulative installed Wind Capacity in MW

Source : Global Wind Energy Council

Wind power has several advantages over conventional thermal power sources. Excessive heating of earth due to burning of fossil fuels have forced people to generate electricity through non pollutant energy sources like wind. It's the cleanest form of renewable energy that doesn't contaminate the environment at all. Further, the wind is free and wind turbines can be used to electrify remote areas that are not connected to the national grid.

Wind Power was introduced to Sri Lanka in 1999 by installing a 3MW Wind Power Plant (WPP) at Hambantota as a pilot project by Ceylon Electricity Board (CEB). This plant was intended to study the capability of harnessing wind energy into electricity and to get experience in integrating wind generators in to the system and get familiarize with the operation of wind turbines. According to the study "Sri Lanka Wind Farm Analysis and Site Selection Assistance" carried out by National Renewable Energy Laboratory (NREL) of USA in 2003, the country has a wind potential of 20,740 MW but only 200 MW of this is feasible to be developed due to system absorption limitations. However, CEB has not yet decided a limit on wind power absorption to national grid and will hold until carrying out a detailed study.

1.1 Power Quality Issues associated with Wind Plants

Wind turbines have an uneven power generation following natural variations of the wind. Operations of wind turbines have a significant impact on the Power Quality (PQ). Different power quality issues may arise depending on the type of the equipment used for the plant and the configuration of the connected Grid Sub Station. Major concerns associated with wind plants are;

i. Voltage changes and Fluctuations
ii. Voltage and Current harmonics
iii. Flicker
iv. Reactive power
v. Frequency variations
vi. Grid reconnection time

1.2 Motivation

The Government of Sri Lanka has declared development of renewable energy with high priority to reduce petroleum consumption for electricity generation and to ensure energy security by diversifying the energy mix. The National Energy Policy published in 2008 states, "The Government will endeavor to reach a minimum level of 10% of electrical energy supplied to the grid to be from Non-conventional Renewable Energy (NCRE) by a process of facilitation including access to green funding such as CDM. The target year to reach this level of NCRE penetration is 2015.” In order to achieve above target, Independent Power Producers (IPPs) are encouraged to invest in renewable energy sector like Small Hydro, Wind, Solar and Biomass including Dendro Power, Biogas and Waste. Several NCRE incentives like special standardized tariffs and a grace period free of resource cost (royalty) are offered to the developers.

As a result, a cumulative installed capacity of 95 MW of wind plants are integrated to the system at the moment, and Energy permits have been issued for another capacity of 30 MW by the Sustainable Energy Authority. Most of these plants are located in Puttalam area. In addition to that, a 200 MW wind park is proposed at Mannar region by 2017 and to be extended to 350 MW by 2021.

In Sri Lanka, wind generators are normally connected to 33 kV distribution feeders. These distribution feeders with a low fault level are not electrically stiff as transmission lines hence unable to operate firmly with the power quality disturbances mentioned in 1.1. Sometimes, consumers are directly connected to the same distribution feeder. In such situations, those consumers are directly exposed to power quality issues generated by the wind plants without an intervening of any Grid or Primary Substation, Gantry or Transmission Line.

As an Electrical Engineer working in the Distribution sector of Ceylon Electricity Board; I have come across several complaints regarding disturbances caused by wind plants from both utility side and consumer side. Therefore, in my opinion; we haven’t paid adequate attention on power quality issues generated by these wind plants. This research is mainly focused on analyzing power quality issues caused by wind plants located in Puttalam area.

1.3 Objectives of the Project

The main objectives of this research are,

i. To study about major power quality issues associated with four wind plants in Puttalam.
ii. To propose appropriate mitigation methods to rectify power quality issues.

1.4 Scope of the Project

The scope of the project includes the following.

- Measurement of Electrical Parameters of the Wind Plants from the Utility Side.
- Detailed Data Analysis.
- Study on Mitigation
- Computer Modeling and Simulation using MATLAB/SIMULINK environment to investigate harmonic mitigation.

With the analysis, I wish to propose suitable remedial measures to improve the quality of wind power in wind plants under study and to identify the most suitable wind technology for the National Grid as a recommendation for the upcoming wind plants on the view of power quality.

1.5 Overview of the Dissertation

This dissertation discuss on power quality issues related to wind power plants and different techniques available to mitigate them. The dissertation consists of nine chapters. Chapter 02 presents fundamentals of harnessing wind energy and describe available types of wind power plants with their advantages and disadvantages in brief. Basically, there are four types of wind plants and three of them are available in Sri Lanka. Further, a short description on world wind picture and its position in Sri Lanka are included under Chapter 02.

Chapter 03 contains the literature survey I have done on power quality of wind power plants and provides the basic definitions on power quality, different power quality issues, allowable limits, their causes and adverse effects.

Chapter 04 includes the research methodology followed, details on the measuring equipments used for data logging and main technical parameters of the four wind plants used for measurements.

Chapter 05 consists of the detailed Data Analysis. Power quality during steady state and voltage events are analyzed separately. Further details related to this chapter are provided as appendices.

Chapter 06 and Chapter 07 contain a comprehensive evaluation of the power quality of four wind plants taken for the study during voltage events and steady state operation respectively. Techniques available to improve the power quality are also discussed in detail under these two chapters and improvements are suggested where necessary.

Chapter 08 describes the computer modeling and simulation of a Shunt Hybrid Harmonic filter developed in MATLAB/SIMULINK environment along with the results of the simulation.

The dissertation concludes with Chapter 09, indicating the conclusions of the study, recommendations and provision for future research.

Chapter 02

FUNDAMENTALS OF WIND ENERGY CONVERSION

2.1 Historical Development

The history claims that harnessing power from the wind using man made machines date back beyond the time of the ancient Egyptians. The first wind turbine used to generate electricity was built by Charles F. Brush in Cleveland, Ohio in 1888. It was a direct current (DC) machine and had a rated power of 12 kW. [57] Afterwards, direct current electricity production continued to grow in the form of small scale and stand-alone. The first large scale alternating current (AC) wind turbine was produced in 1930's in USA and the grid connected wind turbines were introduced.

A strong interest in renewable energy sources was grown in mid 1970s when concerns on the environmental effects of fossil energy sources coincided with the Organization of Petroleum Exporting Countries' (OPEC) oil embargoes. From that time onwards, Wind turbine technology is developing continuously and now accounts for a global cumulative installed capacity of 282.5 GW at the end of year 2012 with an annual growth rate of 20%. Modern wind turbine and generators are highly sophisticated machines with advancing improvements in aerodynamics, structural design, materials technology and electrical and electronic controls.

2.2 Basics in Wind Power Generation

Wind turbines use the kinetic energy of air to generate electricity by converting it into rotating mechanical power. The most common type of wind turbine is the horizontal-axis turbine with two or three blades mounted on top of a tower. The power of the wind in an area, *A*, perpendicular to the wind direction is given by equation (1).

$$P = \frac{1}{2}.\rho.A.V^{3} \qquad \text{--(1)}$$

Where;

P = Power in watts (W)

ρ = density of air in kilograms per cubic meter (kg/m^3)

A = swept area perpendicular to the wind direction in square meters (m^2)

V = speed of the wind

But, it is impossible to harness whole amount of energy present in the wind. The actual power harnessing depends on several factors such as the type of machine and rotor used, the sophistication of blade design, friction losses, and losses in other equipment connected to the wind turbine. The fraction of power that can be captured by a wind turbine is given by a factor, C_p, called the power coefficient. C_p is a specific value to a wind turbine and is a measurement of efficiency of the turbine. The theoretical maximum coefficient of power for any wind turbine is 59.3% and referred as the Betz limit. In reality, this figure is usually around 45% (maximum) for a large electricity producing turbine. [5]

Therefore, the Power that can be harnessed by a wind turbine is given by;

$$P_{Tur} = ½. C_p.\rho.A.V^3 \text{ --(2)}$$

A typical wind turbine employs a rotor assembly with 2-3 blades and a low speed shaft to extract power from the wind, a gear system to step up the shaft speed of the rotor shaft to the higher speeds needed to drive the generator, and a generator to convert mechanical energy of the rotating shaft to electrical energy and a set of control and protection equipment. Power electronic converters may be used to regulate the power output of the turbine. Main components of a wind plant are shown in Figure 2.1.

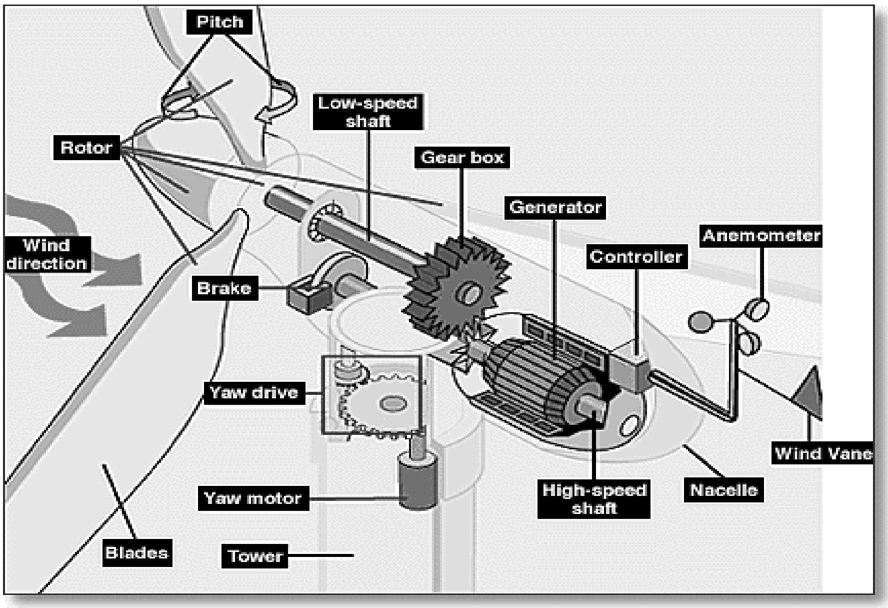


Figure 2.1 : Major components of a Wind Plant

Source : Wind Energy Development Programmatic EIS Information Center

2.3 Classification of Wind Turbines

Basically there are two types of wind turbines as fixed speed and variable speed. Modern wind turbines mainly employ four types of distinct technologies. They are,

i. Type A – Fixed Speed Wind Turbine
ii. Type B – Partial Variable Speed Wind Turbine with Variable Rotor Resistance
iii. Type C – Variable Speed Wind Turbine with partial-scale Power Converter
iv. Type D – Variable Speed Wind Turbine with full-scale Power Converter

2.3.1 Type A – Fixed speed Wind Turbine

Fixed-speed wind turbines are the most basic type of wind turbines in operation. They usually employ squirrel-cage induction generators (SCIGs) and operate with very little variation in rotor speed (approximately 1 - 2%). [5] The Induction Generator is directly connected to the Grid and the speed is almost fixed to the grid frequency, and not controllable. Basic components of a Type A wind plant is shown in Figure 2.2.

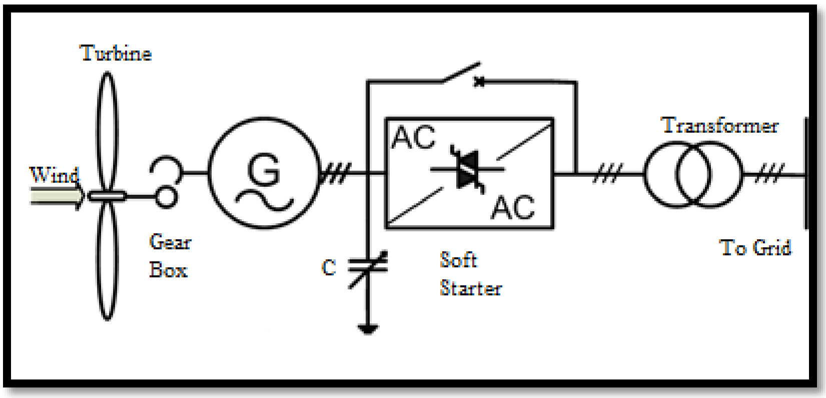


Figure 2.2: Basic components of a WPP employing Type A Wind Turbine

Advantages and Disadvantages of employing fixed-speed wind turbines with induction generators are given in Table 2.1.

Table 2.1: Advantages and Disadvantages of fixed-speed wind turbines

Advantages	Robust and Reliable.
	Economical and well proven technology.
	High mechanical compatibility with rapid wind variations.
	Do not generate harmonics other than the harmonics generated by a power factor correction capacitor bank if any.
	High Environmental Durability.
Disadvantages	Designed to obtain maximum efficiency at one specific Wind Speed.
	Uncontrollable Reactive Power Consumption.
	Poor wind energy conversion efficiency.
	Power Fluctuations that cause large Voltage Fluctuations.
	Do not contribute regulation of grid voltage or frequency.
	Limited Power Quality Control.
	High Mechanical Stress.
	Risk of self excitation during off-grid conditions

2.3.2 Variable-speed Wind Turbines

Variable-speed wind turbines; as the name implies, are designed to operate at a wide range of rotor speeds. It is possible to continuously alter the rotational speed of wind turbine according to the wind speed. Speed and power controls allow these turbines to extract more energy from wind than fixed-speed turbines. As the wind turbine operates at variable rotational speed, the plant is connected to the grid through a power electronic converter system placed between the generator (synchronous or asynchronous) and the grid. [5] Advantages and disadvantages of employing variable-speed wind turbines are given in Table 2.2.

Table 2.2: Advantages and Disadvantages of variable-speed wind turbines

Advantages	Improved System Efficiency & increased power capture form wind.
	Improved Power Quality.
	Reduced Mechanical Stress and Noise.
	Power electronic control provides the ability to meet high technical demands imposed by the connected grid substation.
	Controllable Active and Reactive Power.
	Quick response under transient conditions of the Power System.
Disadvantages	Harmonic Distortion due to presence of power electronic converters.
	Losses in power electronic elements.
	Higher cost.

2.3.2.1 Type B – Partial variable speed wind turbine with variable rotor resistance

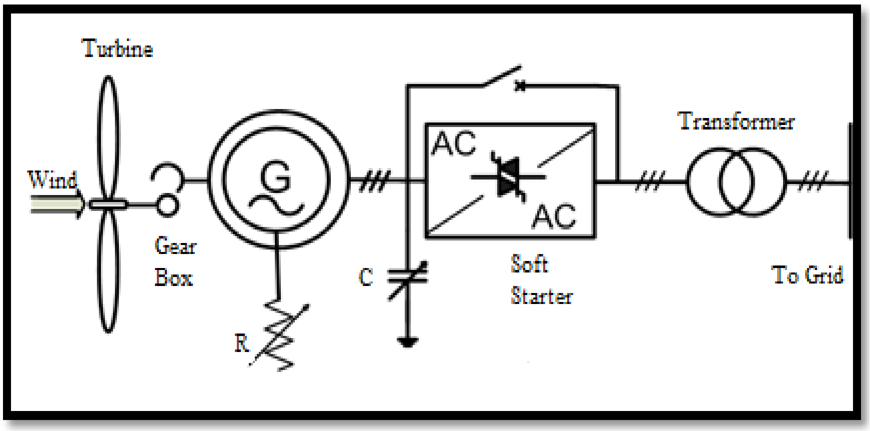


Figure 2.3: Basic components of a WPP employing Type B Wind Turbine

This method uses a wound rotor induction generator (WRIG), a capacitor bank for reactive power compensation and a soft-starter. The rotor resistance of the WRIG is variable hence the slip which controls the power output of the plant. The typical speed range is 0-10% above the synchronous speed. A major disadvantage of this type is, it has a High Reactive Power Consumption. [5], [14]

2.3.2.2 Type C – Variable speed wind turbine with partial-scale power converter

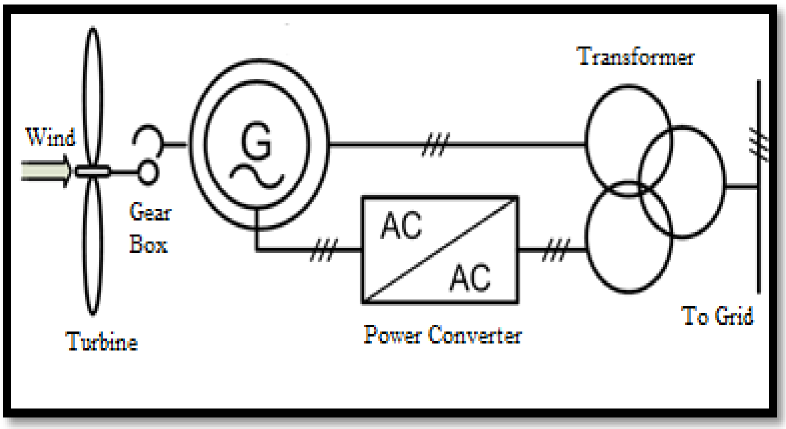


Figure 2.4: Basic components of a WPP employing Type C Wind Turbine

This configuration, which is commonly referred as Doubly-fed Induction Generator (DFIG) concept; employs a DFIG and a partial scale power converter. The stator circuit of the generator is directly connected to the grid while the rotor winding is connected to a three-phase variable frequency power converter which is normally rated at approximately 30% of nominal generator power. Therefore, the losses in the power electronic converter are less when compared with Type D mentioned below 2.3.2.3.

The DFIG system delivers power to the grid through the stator while the rotor either injects or absorbs power, depending on the rotational speed of the generator. If the generator operates above synchronous speed, rotor delivers power to the grid through the converter, and if the generator operates below synchronous speed, the rotor absorbs power from the grid. The partial-scale converter compensates reactive power and provides a smoother grid connection. The speed range is typically ±30% of Synchronous Speed. [32], [34]

DFIGs are one of the most common types of generator used to produce electricity in wind turbines because of following advantages over other types of generators.

i. DFIG allow the amplitude and frequency of the output voltages to be maintained at a constant value irrespective of the speed of the wind blowing on the wind turbine rotor. Because of this, doubly-fed induction generators can be directly connected and remain synchronized at all times with the ac power network.

ii. Ability to control the power factor (e.g., to maintain the power factor at unity), while keeping the power electronics devices in the wind turbine at a moderate size.

The main disadvantages of this configuration are the use of slip rings and high fault currents.

2.3.2.3 Type D – Variable speed wind turbine with full-scale power converter

This configuration has the liberty of employing either Synchronous Generators or Induction Generators with full variable speed wind turbines. The normal practice is using a Synchronous Generator / Permanent Magnet Generator (PMG) with a full power converter.

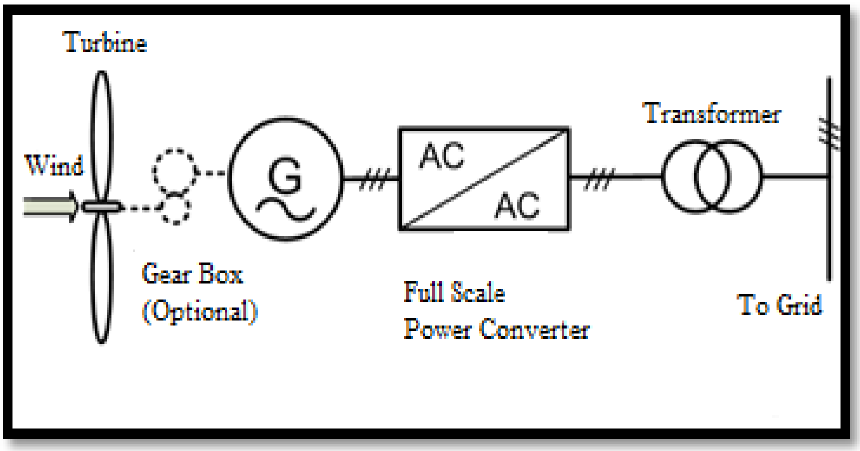


Figure 2.5: Basic components of a WPP employing Type D Wind Turbine

The only power flow path from wind turbine to the grid is the back-to-back AC/DC/AC converter. The converter enables independent real and reactive power control and provides a smoother grid connection. Type D configuration has gained popularity over other types in recent years because of its high efficiency, less complexity in electrical engineering perspective, wider range speed control and the ability to operate without a gear box in some cases. [5]

The excitation to the generators can be supplied electrically or by using permanent magnets. The use of Permanent Magnet Synchronous Generators does not require external excitation current, which reduces losses, eliminates mechanical complexities of gear boxes, compact size, improves efficiency and reliability.

From above four types of wind plants, three types; Type A, Type C and Type D are available in Sri Lanka.

2.4 Position of Wind Plants in Sri Lanka

Being an island, Sri Lanka possesses substantial wind energy resources. The wind pattern of the country is mainly supported by two Asian Monsoons; the South West (SW) and North East (NE).Wind Power was introduced to Sri Lanka in 1999 by installing a 3 MW Wind Plant (5 x 600 kW generators) at Hambantota as a pilot project by Ceylon Electricity Board. This plant was intended to get some hands on experience in integrating wind generators in to the system and harnessing the energy of the wind for local engineers. Thereafter, CEB carried out wind resource assessments in several areas of the country by installing wind masts during 2000 – 2002 period.

In year 2003, the National Renewable Energy Laboratory (NREL) of USA carried out an island wide full wind study for Sri Lanka using satellite mapping. The following areas were identified and evaluated for developing wind power plants in utility-scale.

i. Southeast Coast – From Hambantota to Buthawa
ii. West Coast – Kalpitiya Peninsula
iii. Northwest Coast – Mannar Island
iv. North Coast – Jaffna District
v. Central highlands in the interior of the country – Ambewela area

According to the study, nearly 5000 km^2 of the land of the country are windy areas with good-to-excellent wind resource potential. It’s around 8% of the total land area (65,600 km^2) of Sri Lanka. This huge wind resource can support around 20,740 MW of installed capacity. The windy lagoon areas are estimated to cover 700 km^2 of land with a potential installed capacity of 3500 MW. Kalpitiya Peninsula is the most potentially feasible site investigated for utility-scale wind power project development with excellent wind resources. However, wind capacity expansion is limited to 200 MW due to the absorption limitations of transmission infrastructure.

The present network cannot accommodate wind capacity more than 7% of the peak load and installing more than 20 MW of wind capacity in any given region will adversely impact local grid stability and power quality.

After these studies, in order to promote electricity generation based on non conventional renewable energy (NCRE), the Government of Sri Lanka introduced an Energy Policy in 2008 to achieve a minimum level of 10% of power generation through NCRE by year 2015. Based on this policy private sector investors were allowed to develop wind power plants with government incentives. As a result, a cumulative installed capacity of 95 MW of wind plants are integrated to the system at the moment. Most of these plants are located in Puttalam area.

Energy permits have been issued for another capacity of 30 MW by the Sustainable Energy Authority. In addition to that, a 200 MW wind park is proposed at Mannar region by 2017 and to be extended to 350 MW by 2021. Details of the commissioned wind plants in Sri Lanka by June 2014 are given in Table 2.3.

Table 2.3: Details of the commissioned wind plants in Sri Lanka by June 2014.

Sr. No	Name of the WPP	Location	Capacity (MW)	Type of Wind Turbine
01	Mampuri WPP	Kalpitiya	10.00	A
02	Vidathamunai WPP	Puttalam	10.00	D
03	Seguwantivu WPP	Puttalam	10.00	D
04	Nirmalapura WPP	Kalpitiya	10.00	D
05	Pavandanavi WPP	Kalpitiya	10.00	C
06	Uppudaluwa WPP	Puttalam	10.00	D
07	Madurankuliya WPP	Puttalam	10.00	D
08	Naladanavi WPP	Kalpitiya	5.00	C
09	Mampuri II WPP	Kalpitiya	10.00	C
10	Mampuri III WPP	Kalpitiya	10.00	C

But, integrating wind power does not significantly help mitigate capacity constraints in dry seasons where hydro generation falls because the maximum winds also occur during the wettest periods driven by two Asian Monsoons; the South-West monsoon from May till early October and North-East monsoon from December to February.

Chapter 03

POWER QUALITY AND LITERATURE REVIEW ON POWER QUALITY OF WIND POWER PLANTS

Power Quality is a set of parameters defining the properties of the power system as delivered to user in normal operating condition in terms of continuity of supply and characteristics of voltage & frequency. The definition for “Power Quality” in Institute of Electrical and Electronic Engineers’ (IEEE) Standard Terms is "the concept of powering and grounding electronic equipment in a manner that is suitable to the operation of that equipment and compatible with the premise wiring system and other connected equipment". Simply, Perfect power quality means that the voltage is continuous and sinusoidal with a constant amplitude and frequency. Deviations from this perfection are the power quality issues.

There are three main types of power quality disturbances.

i. Voltage Events
ii. Frequency Events – variations of the frequency outside the acceptable range.
iii. Waveform Events – unacceptable shaping of the waveforms.

PQ is an important issue for electricity consumers at all levels of usage, particularly industries and the services sector. Extreme use of sensitive power electronic equipment and non-linear loads in industry, commercial and domestic applications cause frequent disturbances to the quality of power nowadays. These disturbances ultimately lead to huge economic losses and safety concerns. A disturbance of few milliseconds to a power supply of complete continuous production lines where the process cannot tolerate any temporary shutdown of any element in the chain can stop the production line for hours with severe damage to material and equipment.

3.1 Voltage Events

Figure 3.1 shows the classification of voltage events linked with power systems according to the magnitude and duration of the event. [3]

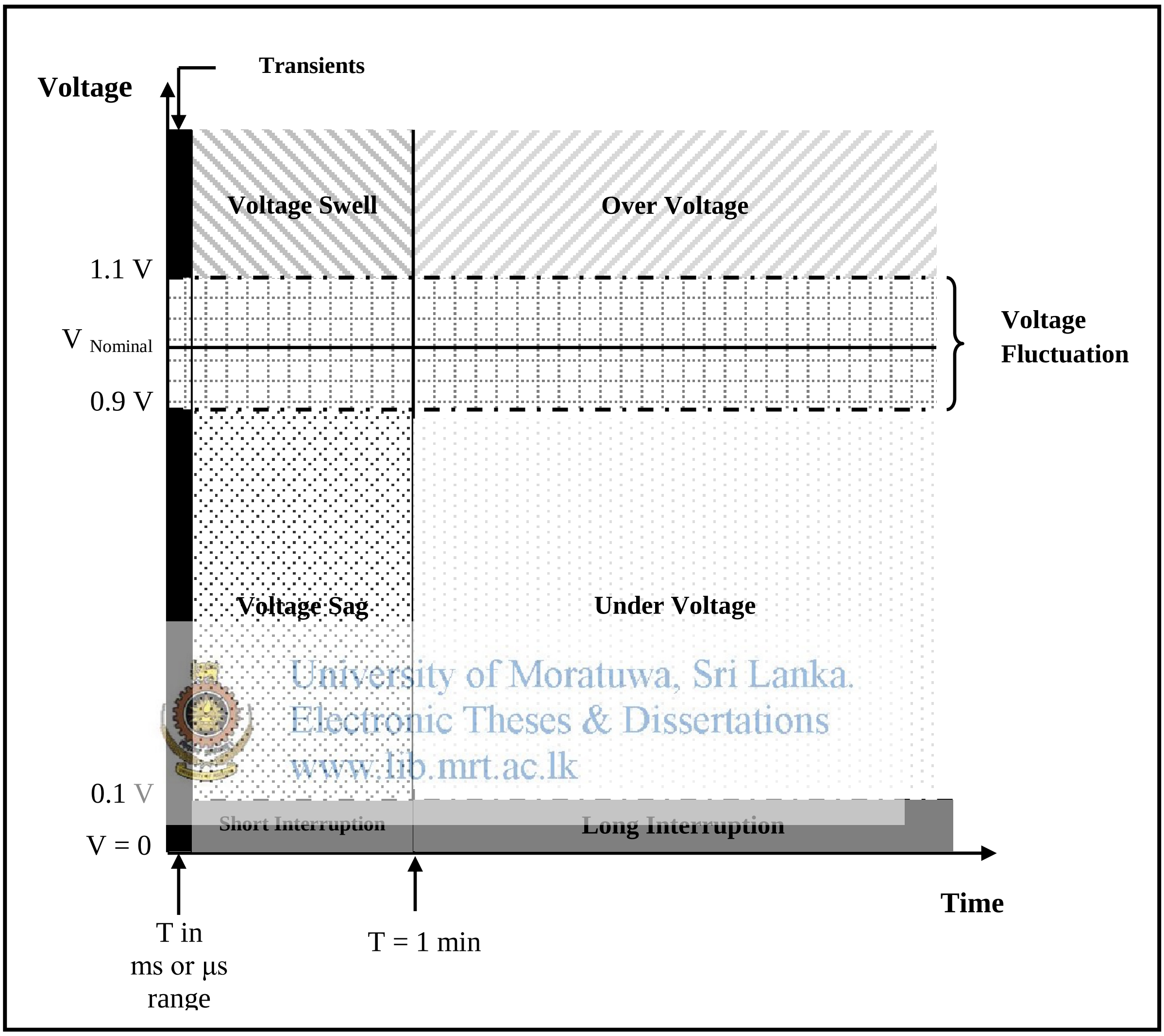


Figure 3.1: Classification of Voltage Events

3.1.1 Voltage Sag / dip

Voltage Sag is defined as sudden reduction in the voltage to a value between 0.1 pu – 0.9 pu in route mean square (rms) voltage for a duration conventionally 1ms to 1 min. Voltage Sags are the most common voltage event and can occur in any combination of phases. They are normally caused by system short circuit faults, earth faults, starting of heavy loads such as Induction Generator/Motors with high starting currents, bad weather conditions and sudden system overloads.

Voltage sags in higher voltages propagate to lower voltage levels via transformers. Voltage sag of few milliseconds may have damaging consequences for several hours. Sags result in tripping of control and protection equipment, sensitive power electronic devices and some motors. In order to mitigate sags, Automatic Voltage Stabilizers can be used.

3.1.2 Under voltage events

Under Voltages are sudden decreases of voltage to a value between 0.1 pu – 0.9 pu of rms voltage for a duration longer than 01 minute. Causes and unfavorable effects of Under Voltages are as same as voltage sags mentioned in above 3.1.1.

3.1.3 Interruptions

An Interruption occurs when the rms voltage falls less than 0.1 pu of nominal voltage. Interruptions that prevail less than 01 minute are defined as “Short interruptions” and interruptions that prevail longer than 01 minute are defined as “Long or Sustained interruptions”. Long interruptions may occur due to planned outages or as a result of isolation of a permanent fault. Interruptions are propagated from higher voltages to lower voltage levels via transformers. They require human intervention to resume power.

3.1.4 Over voltages

Over voltages are of three types as,

i. Temporary Power Frequency Over voltages
ii. Switching Over voltages
iii. Lightning

3.1.4.1 Power Frequency Over Voltages

An over voltage is an increase in rms voltage greater than 1.1 pu of nominal voltage. Over voltages prevail less than 01 minute are defined as “Voltage Swells”. This can occur in any combination of phases. The origins of over voltages are,

i. Insulation Faults - When an insulation fault occurs between a phase and earth, the voltage of the healthy phases to earth may reach the phase to phase voltage.
ii. System Faults
iii. Switching off of large loads
iv. Energizing of large capacitor banks
v. Incorrect settings on alternator regulators or transformer tap changers
vi. Overcompensation of reactive power

Over voltages on high voltage (HV) installation may propagate to low voltage (LV) installations via the earth of the HV/LV substation.

3.1.4.2 Switching over voltages

In a power system, switching operations are unavoidable. They particularly last for microseconds or milliseconds but the magnitude may raise to several times of nominal voltage.

3.1.4.3 Lightning over voltages

Lightning is a natural phenomenon that cannot be avoided.

The consequences of over voltages vary on magnitude, duration, repetition and frequency of the event. Transient over voltages cause premature ageing, permanent damage and destruction of equipment and dielectric breakdown of material.

3.1.5 Voltage fluctuations and flicker

Voltage fluctuations are variations in the rms value or the peak value of voltage with amplitude of less than 10% of the nominal voltage. Usually, fluctuations are a series of voltage changes within a voltage envelope as shown in Figure 3.2. These are characterized by the magnitude and frequency of the fluctuation.

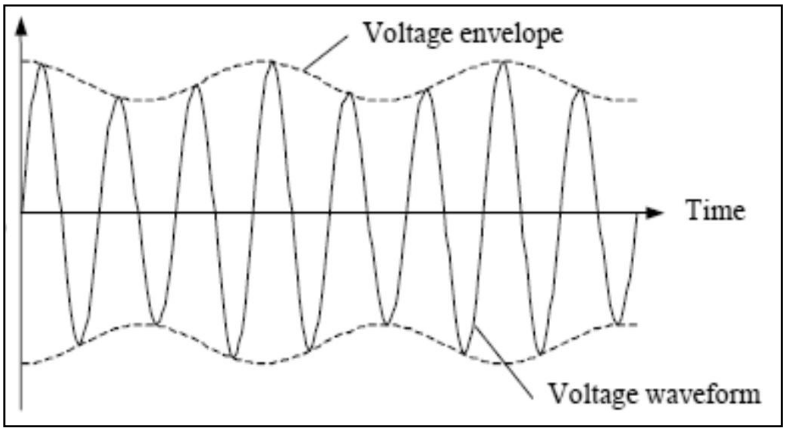


Figure 3.2: Voltage Envelope

The physiological effect of voltage fluctuation is referred as “Flicker”. Flicker is defined as “Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time”. [3]. Periodic fluctuation of voltage results in flicker of lighting, particularly in incandescent lamps. Flicker can be ignored or irritating depending on the flicker level - amplitude, shape and repetition frequency of the fluctuated voltage waveform. Flicker can cause annoyance to the human eye that result in fatigue and less concentration.

The magnitude of flicker depends upon following factors. [5]

i. Electrical Design of the Wind turbine
ii. The stiffness of the line
iii. Voltage level
iv. Distance from substation
v. Size of the Transformer

Two indices are typically used to measure flicker emission, Short-Term Flicker Index (P_{ST}) and Long-Term Flicker Index, (P_{LT}). P_{ST} is measure over a ten minute period and P_{LT} is a rolling average of P_{ST} values over a two hour period. Standard

IEC Characteristic for Flicker is shown in Figure 3.3. Maximum permissible compatibility levels and planning levels of flicker are given in Table 3.1. The usual threshold level for connecting wind turbines to grid is $P_{ST} \leq 1$.

Table 3.1: Maximum permissible Compatibility Levels and Planning Levels of Flicker

	Compatibility Level	**Planning Level**	
	LV & MV	MV	HV
P_{ST}	1.0	0.9	0.8
P_{LT}	0.8	0.7	0.6

The most preferable technique to mitigate the flicker is reactive power compensation. It can be adopted either by the grid-side converter of variable-speed wind turbines or by a static synchronous compensator connected at the point of common coupling (PCC).

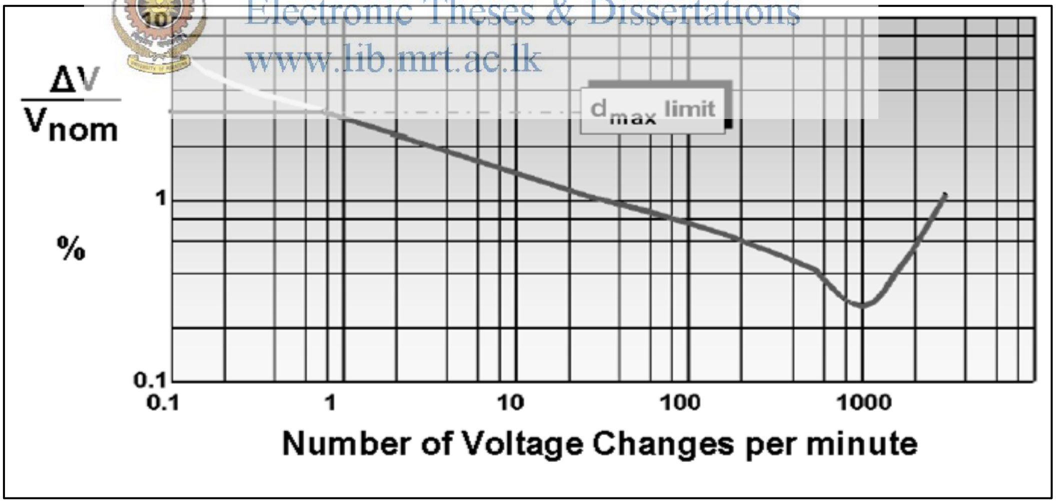


Figure 3.3: IEC Flicker Perception Curve for $P_{ST} = 1$

Source: IEC 61000-3-3

3.1.6 Voltage unbalance

A three phase system is called balanced if the three phase voltages and currents have same amplitude with a 120^0 phase shift with respect to each other. Any deviation from this condition results in system unbalance. According to National Electrical Manufacturers Association (NEMA), Voltage Unbalance is defined as follows.

$$\text{Voltage Unbalance} = \frac{\text{Maximum deviation from the mean of } \{V_{ab}, V_{bc}, V_{ca}\}}{\text{Mean of } \{V_{ab}, V_{bc}, V_{ca}\}} \qquad \text{------------------------------(3)}$$

Limits for unbalance factor in IEC standards are given as,

- < 2% for LV and MV systems
- < 1% for HV

In realistic situation, power systems are unbalanced due to unequal distribution of single phase loads, unbalanced three phase loads and differences in line impedances. Unbalance results in excessive heating of network components, degradation of insulation, reduced outputs, vibrations and noises.

3.2 Waveform Events

3.2.1 Harmonics

Harmonics are the waveforms whose frequency is an integer multiple of the fundamental frequency. Harmonics waveforms with odd harmonic numbers are referred as “Odd Harmonics” and harmonics waveforms with even harmonic numbers are referred as “Even Harmonics”.

A periodic waveform consisting of a DC component, fundamental and harmonics can be represented in Fourier series as in equation (4). Odd harmonics are additive. Even under balanced load conditions, neutral currents can reach magnitudes as high as 1.73 times the average phase current due to odd harmonics. Even harmonics cancel out in the neutral conductor.

$$F(t) = \underset{\substack{\downarrow\\ \text{DC}\\ \text{Component}}}{F_0} + \underset{\substack{\downarrow\\ \text{Fundamental}\\ \text{Component}}}{F_1\cos(\omega t+\theta_1)} + \underbrace{\sum_{h=2}^{h=\alpha}(F_h\cos(h\omega t+\theta_h))}_{\text{Harmonics}}$$

---------------------------------(4)

Where, h is the harmonic number

Harmonics are mainly produced by non-linear loads which draw non-sinusoidal currents from the supply voltage. In an ideal power system, voltage and current waveforms are pure sinusoidal. But in practical scenario, non-linear loads connected to power system introduce current and voltage harmonics into the system. Main sources of harmonics in power systems are,

i. Power Electronic Equipment: Static Power Converters, Drives, Rectifiers (diode or thyristor), Inverters and Switching Mode Power Supplies.
ii. Loads using electric arcs like arc furnaces, welding machines, lighting (discharge lamps, fluorescent tubes).
iii. Starting motors using electronic starters
iv. Domestic loads with power electronic devices such as Computers, Printers, photocopiers, Television sets, microwave ovens, fluorescent lamps etc.

Because of operating flexibility, high level of performance and high energy efficiency, the use of power electronic equipment is spreading extensively.

3.2.1.1 Harmonic distortion

Harmonic distortion is the change in the voltage or current waveform from the ideal sinusoidal waveform. “Total Harmonic Distortion (THD)” is used to calculate the distortion level of a given waveform as shown in equation (5).

$$THD = \sqrt{\frac{\sum_{h=2}^{\alpha} F_h^2}{F_1^2}} \times 100\% \qquad \text{---------------------------------(5)}$$

3.2.1.2 Adverse effects of harmonics

Harmonics in a power system cause severe degradation of power quality. Harmonics currents flow through the system impedance, results in non-sinusoidal voltage drops that can compromise network voltage quality. Most of the time, the impact of harmonics are not identified until the failure occurs. Equipment malfunctions are probable with a total harmonic distortion of greater than 8% of the voltage and between 5% - 8%, malfunctions are possible. Therefore as a global norm, THD has to be kept below 5% at the point of common couplings. [5]

Harmonics cause increased losses due to heating, mechanical stress, vibration, reduction of capacity at full load and acoustic noise in motors. They also cause destruction of capacitors by thermal overload and resonance, loss of accuracy of measurement instruments, unwanted operation of protective devices, increased I^2R losses in power cables, operational disturbances induced in computers, television sets, telecommunication systems and control systems. Harmonics increase overall reactive power demand of loads.

Harmonics affect transformers in multiple ways. High frequency harmonic voltages induce hysteresis loops that cause additional core losses. High frequency harmonic currents increase the rms current at the transformer windings and cause high I^2R losses. Eddy current losses are also increased. Another adverse effect is circulation of triple-N (integer multiples of third harmonic) harmonics in the delta winding of a transformer and add up in the neutral in case of a star connection. In addition to that, “Triplen Harmonics” (3^{rd}, 9^{th}, and 15^{th} harmonics) cause distortion of voltage waveforms.

Presence of harmonics ultimately cause high economic losses resulting from the additional costs linked to increased energy losses, over sizing of equipment, loss of productivity due to accelerated ageing of equipment and unwanted tripping. [48]

3.2.1.3 Harmonic Mitigation

Techniques used to mitigate harmonic voltages and currents in power systems mainly fall into three categories. They are, [48]

i. Filtering Harmonic Components
ii. Cancellation of Harmonic currents
iii. Design considerations of equipment

Details on harmonic mitigation are discussed in Chapter 07 of this dissertation.

3.3 Literature Review on Power Quality of Wind Power Plants

Studies already carried out related to power quality of wind plants were referred at the initial stage of the research and their methodologies and major identifications were taken into consideration.

3.3.1 Power Quality Issues associated with Wind Plants

Usually, wind energy is considered as a risky source in terms of power quality. Utilities across globe have identified adverse impacts of large scale integration of wind resources. [56] Wind turbines have an uneven power generation following natural variations of the wind. [5] Different power quality issues arise with operation of wind turbines depending on the type of the equipment used for the plant and the connected Grid Sub Station. Major concerns associated with wind plants are; [1]

i. Voltage changes and Fluctuations
ii. Flicker
iii. Frequency variations
iv. Grid reconnection time
v. Voltage and Current Harmonics
vi. Reactive power

In this dissertation, power quality aspects are discussed with reference to following base documents.

- Grid Connection Requirement for Wind Power Plants – Ceylon Electricity Board.
- International Electromechanical Commission’s (IEC) standard no 61400-21: Measurement and Assessment of Power Quality Characteristics of the grid connected wind turbines.
- Institute of Electrical and Electronics Engineers (IEEE) standard no 1159-2009: IEEE Recommended Practice for Monitoring Electric Power Quality.

When wind turbines are connected to a grid, its power quality highly depends on the interaction between the grid and the wind turbines. [56] The study is carried out based on IEC 61400-21 which has become the reference standard for the certification of the grid-connected wind turbines in terms of power quality. The researchers have recognized that, measurement and assessment procedure specified by the standard demands a deep knowledge and experience on power quality issues. Further, it requires storage and processing of a huge amount of data from voltage, current and wind time-series. To serve the above requirement, the research team has developed their own system to measure parameters; voltage, current and wind speed to assess power quality of grid-connected wind turbines.

3.3.2 Voltage variations and Fluctuations

The intermittent nature of the wind causes voltage variation. Uneven power production is common in both fixed speed and variable speed wind turbines. Fixed speed wind turbines connected to a grid show high fluctuations where variable speed turbines show a smoothed variation. In fixed-speed wind turbines, the tower shadow and gradient of the wind speed cause power fluctuations. Switching operations of wind turbine generating system also cause significant voltage variations. [5]

The variation of power is high during low winds and converges to a constant with the increase of wind. Uneven power production and power fluctuation results in voltage variations and flicker disturbances. [5] This documentation provides a comprehensive description on the power quality of wind turbines; organized in four major sections as;

i. Types of Electrical systems used in Wind Power Generation
ii. Measurements on Voltage and Frequency Variations, Transients & Harmonics.
iii. Standards for Measuring and Testing Power Quality of Wind Plants.
iv. Regulatory requirements concerning Power Quality of Wind Turbines

Proposed methods for assessing the power quality of wind turbines in the study are more appropriate to be used at wind plants having synchronous generators.

The main causes of voltage dips/sags at a wind turbine terminal are short circuits and earth faults. These faults can be either symmetrical (three-phase) or non-symmetrical (single phase, double phase or phase to earth). The magnitude of a voltage dip at the wind turbine terminals will depend on the type of faults, the distance to the fault and the fault impedance. [58]

The voltage dip will increase the current in the stator windings of the generator which in turn may lead to the destruction of the power converter. To avoid this, most wind turbines are automatically disconnected from the connected grid when a fault occurs and reconnected when the fault is cleared. But it is not possible to disconnect a wind plant from the grid without affecting the stability and reliability of the power system. The typical control strategy used in an event of a grid failure is to disconnect the wind turbines from the grid. But, when a significant amount of wind power is integrated to the grid, disconnecting the wind turbines result in voltage instability and collapse. [5]

3.3.3 Reactive Power

Fixed speed wind turbine units which employ induction generators require reactive power from the grid to operate. The reactive power requirement in an induction generator increases as the amount of power generation increases.

According to the grid code of CEB, Power Factor and Reactive Power Support from a Wind Power Plant shall be as follows.

“The recommended range for reactive power support by a wind farm is 0.80 lagging to 0.95 leading. The exact level of reactive power support required from a wind farm will depend on the outcome of grid interconnection studies. Therefore, unless specific reactive power support is requested in the grid interconnection proposal, the wind farm shall operate in the range of 0.98 leading to unity power factor. Failure to operate below 0.98 leading power factor (i.e. less than 0.98 leading) shall result in imposition of a penalty which shall be decided by CEB”.

Reactive power consumption is considerably high in wind turbines. It is identified as a major limitation when integrating a wind plant to a grid with a limited reactive power capability. [14], The study consists of observations made on measurements done at the 3 MW pilot wind plant in Hambantota, Sri Lanka and has concluded that, the power factor has fallen below 0.8 for 20% of the operating time of the wind plant.

In [14] and [37], conventional methods used for reactive power compensation are described and incorporating an Advanced Static Var Compensator (ASVC) is recommended for reactive power compensation.

3.3.4 Voltage Unbalance

Voltage Unbalance is a power quality problem observed mainly in distribution feeders where wind plants are connected. Using dedicated feeders to connect wind plants to the grid is recommended in order to avoid this unnecessary voltage unbalance. [14]

3.3.5 Flicker issue in wind plants

Flicker is considered as a major drawback and a limitation to integrate maximum possible amount of wind power to the grid. Flicker arises from wind power plants mainly due to variations in the wind speed, intermittent winds and tower shadowing effect. [5]

As per [15], Flicker emission of grid connected wind turbines depends on mainly on factors as,

i. Mean wind speed
ii. Turbulence intensity
iii. Short circuit capacity ratio
iv. Grid impedance angle

The specific goal of this research had been to investigate Flicker Emission and Mitigation of grid-connected wind turbines with Doubly Fed Induction Generators (DFIG) during continuous operation. The research concludes that, the Static Synchronous Compensator (STATCOM) is superior to the Static Var Compensator (SVC) for flicker mitigation which is commonly used in wind power generation.

A Reactive power compensator of appropriate rating could be employed to compensate the voltage changes and hence eliminate flicker in wind farms. [14], [37] However, for wind plants connected to the transmission system, voltage flicker is not a considerable issue. [5]

3.3.6 Harmonic issues associated with wind plants

In case of wind plants, current harmonics formed due to switching converters distort the supply current. According to IEC 61400-21: Measurement and assessment of power quality characteristics of grid connected wind turbines, harmonic measurements are not required for fixed speed wind turbines where the induction generator is directly connected to grid. Harmonic Measurements are required only for variable speed turbines equipped with electronic power converters.

Generally the power converters of wind turbines are pulse-width modulated inverters, with carrier frequencies in the range of 2-3 kHz.

Voltage and current harmonics should be limited to allowable level at the point of wind turbine connection to the system (PCC). Figure 3.4 shows the Instantaneous Voltage and Current of a wind plant connected to a distribution Feeder at Puttalam.

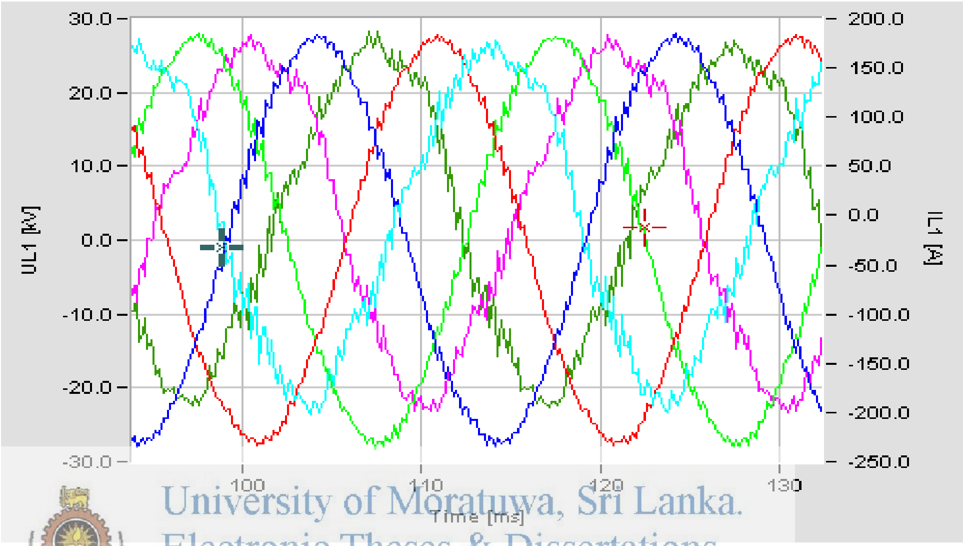


Figure 3.4: Distorted Voltage and Current waveforms of a wind plant directly connected to a distribution Feeder. (Original in Colour)

A typical bar plot of the amplitude of harmonics generated in a six-pulse converter with respect to fundamental is shown in Figure 3.5.

Active Harmonic Filters are a successful solution to mitigate harmonics in a power system. [48] A field survey on harmonic levels of different types of consumers had been carried out to investigate the possible contribution of harmonics to the power quality issues faced by them. A computer model of an active filter is also developed and simulation of its operation and control is carried out using the MATLAB/Simulink environment to analyze the harmonic mitigation capability.

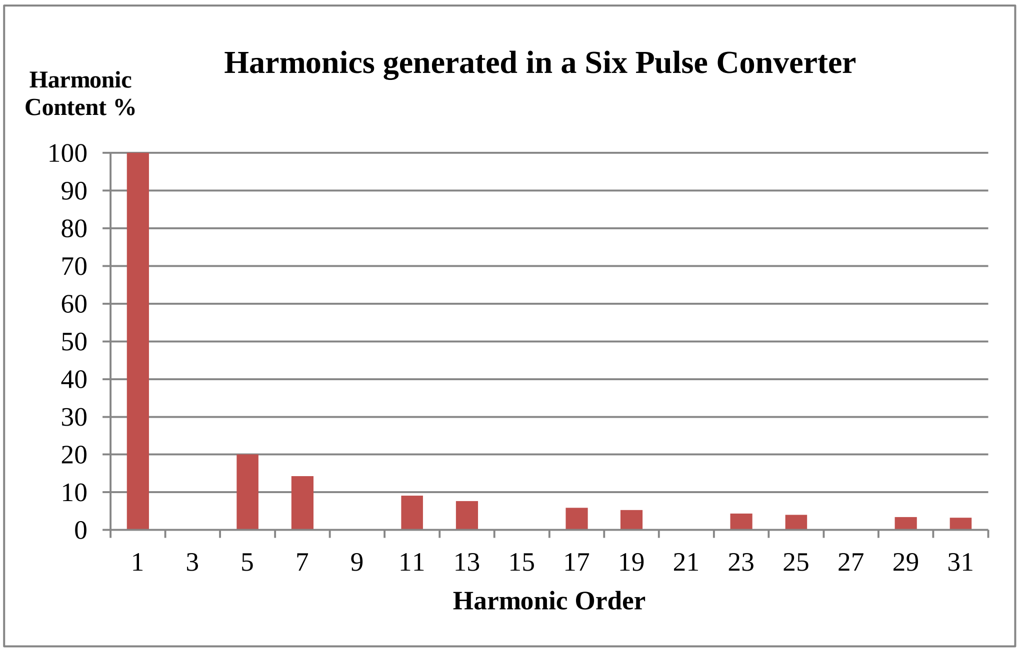


Figure 3.5 : Harmonics generated in a typical six-pulse converter

Chapter 04

METHODOLOGY AND MEASUREMENTS

4.1 Methodology

The Research methodology followed is illustrated in Figure 4.1.

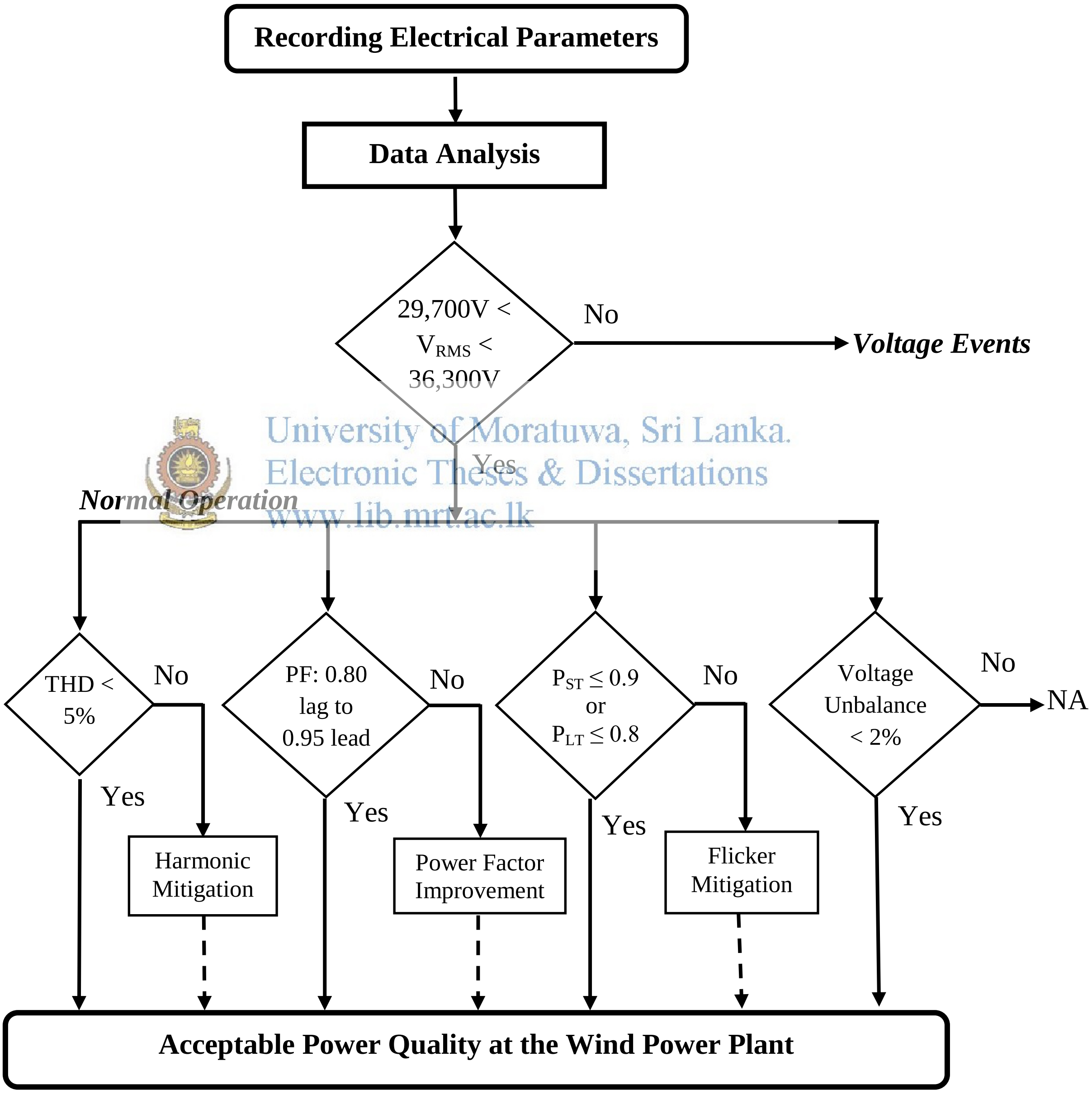


Figure 4.1(a): Research Methodology followed during Normal Operation of WPPs

Voltage Events

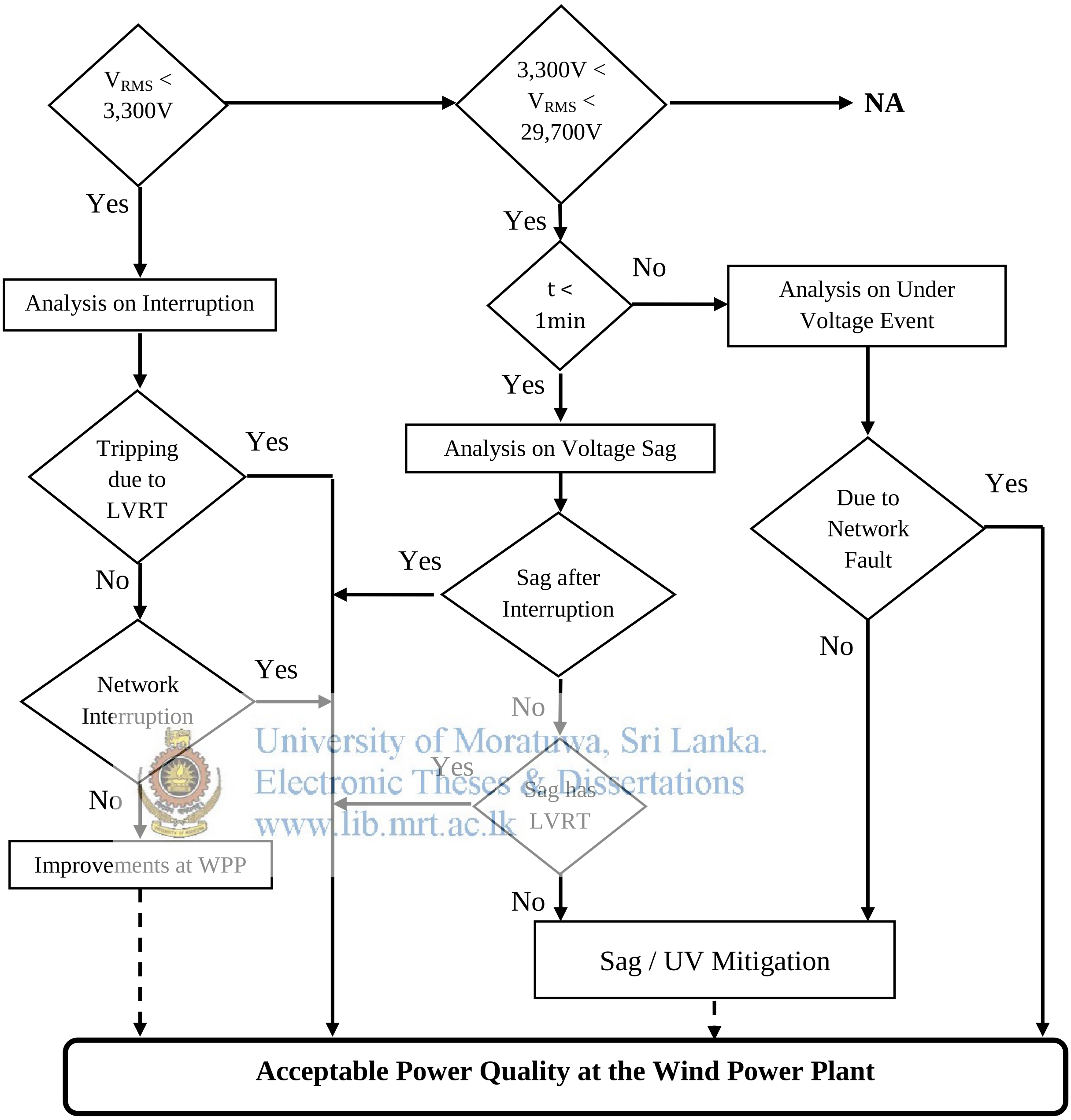


Figure 4.1(b): Research Methodology followed during Voltage Events

4.2 Measurements

In this research, measurements of electrical parameters were carried out in four wind plants located in west coast of Sri Lanka. Plants and their capacities are mentioned in Table 4.1.

Table 4.1: Wind Power Plants used for measuring purposes

Wind Power Plant		Location	Installed capacity (MW)
Plant 01	Seguwantivu WPP	Close proximity of Puttalam	10.00
Plant 02	Vidatamunai WPP		10.00
Plant 03	Nirmalapura WPP	Kalpitiya peninsula	10.00
Plant 04	Pavandanavi WPP		10.00

Figure 4.2 shows the seasonal wind pattern in Puttalam. Average wind speeds are high during May – September where the country's whether condition mainly depends on the South– West monsoon.

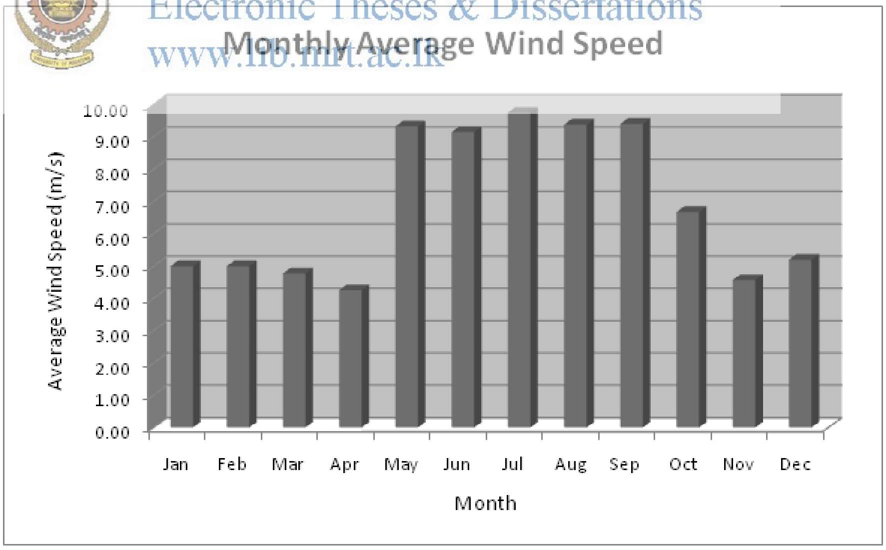


Figure 4.2: Seasonal wind pattern in Puttalam

4.2.1 Equipment used for Data Logging

Fluke 435 Handheld Three-Phase Power Quality Analyzer was used for the measurements. It complies with IEC standard 61000-4-30: Testing and measurement Techniques - Power Quality measurement methods – Class A. Key features of the analyzer are, [16]

- Maximum input current – 3000A
- Maximum input Voltage – 1000 V
- Harmonic measurements – up to 50th harmonic
- Accuracy – 0.1%
- Software - Fluke Power Log and FlukeView

The Power Quality Analyzer was installed at each WPP's point of connection with the national grid and parameters corresponding to the addition of all individual wind turbine units in a single plant were recorded. However, it was not possible to record parameters at all four WPPs under study simultaneously as only one Power Quality Analyzer was available; which was a limitation of the research. Sampling time was taken as 1 minute due to data storage limitations of the equipment. Recorded parameters are as follows.

i. Line to line rms, peak and fundamental voltages – minimum, maximum and average

ii. Line to line rms, peak and fundamental Currents – minimum, maximum and average

iii. Frequency – minimum, maximum and average

iv. Short Term Flicker Index (P_{ST})

v. Long Term Flicker Index (P_{LT})

vi. Active, Reactive and Apparent Power – minimum, maximum and average

vii. Power Factor

viii. Voltage unbalance (%)

ix. Total Harmonic Distortion – Voltage
x. Average Voltage Harmonics from H=2 up to H=50
xi. Total Harmonic Distortion – Current
xii. Average Current Harmonics from H=2 up to H=50

4.2.2 Plant 01 : Seguwantivu WPP

Seguwantivu and Vidatamunai plants are connected to Puttalam Grid Sub Station (GSS) through a 14.7 km 33kV dedicated feeder and a 31.5 MVA 132/33 kV transformer. The fault level of the 33kV bus is 11.2kA. The measurements were done from 12th July 2012; 18.29 hrs to 20th July 2012; 19.25 hrs at Seguwantivu. This plant falls to Type “D” of the classification of wind turbines. A block diagram showing main components of the plant is given in Figure 4.3.

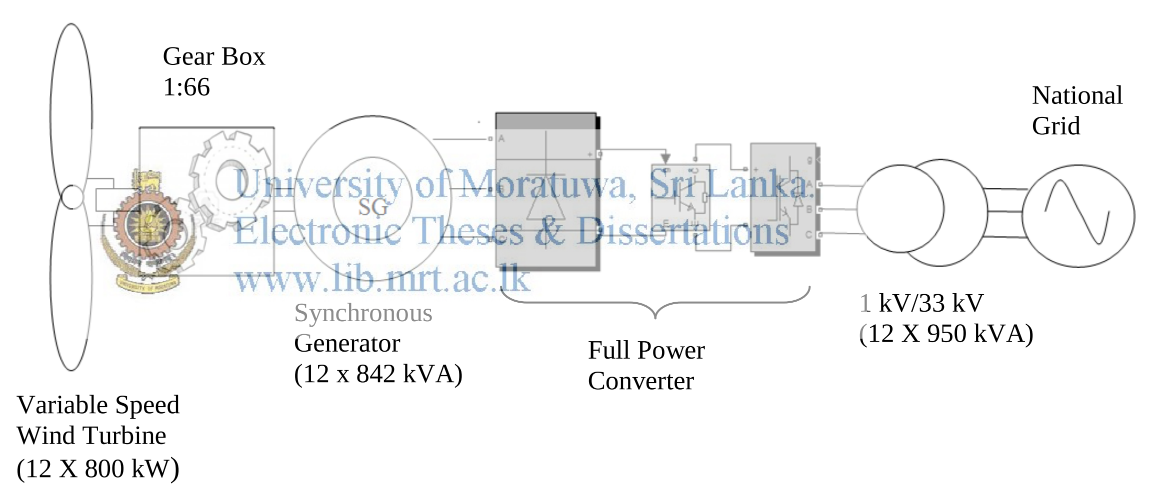


Figure 4.3: Major Plant Components at Seguwantivu WPP

Main technical parameters of Seguwantivu WPP are given in Table 4.2.

Table 4.2 - Major Technical Parameters of Seguwantivu WPP

Installed Capacity - 10 MW

Power Regulation - 100% variable speed

Average Wind Speed - 6.9 m/s (At 60m)

Expected Plant Factor - 30%

Turbine		
Make and Model	-	Gamesa AE-59
Turbine Capacity	-	800 kW
No of Turbine Units	-	12
Rotor Diameter	-	59 m
Tower Hub Height	-	60 m
Cut-in Wind Speed	-	3.5 m/s
Rated Wind Speed	-	11 m/s

Generator		
Type	-	Synchronous generator with independent excitation.
Generator Capacity	-	842 kVA
nominal speed	-	1500 rpm
No of Poles	-	04
Output voltage range	-	0-1000V
Output frequency range	-	0-50Hz

Grid connection	
	Through a Full Power Converter (850kW). Three Main parts; • 3 Phase Diode Rectifier to transform the variable voltage and frequency energy from the generator into DC energy. • DC Chopper for power control and voltage boost from 1000V to 1700V • 3 phase PWM Inverter for Power conversion from DC to AC and grid properties (V-f)

4.2.3 Plant 02 : Vidatamunai WPP

In design and technical configuration, Vidatamunai WPP is identical to Seguwantivu WPP. They are located in adjacent to each other and connected to Puttalam GSS through a common 33kV dedicated feeder as mentioned in above 4.2. Vidatamunai consists of 13 X 800kW turbine units. The measurements were done from 23rd July 2012; 14.11 hrs to 29th July 2012; 09.49 hrs at Vidatamunai.

4.2.4 Plant 03 : Nirmalapura WPP

Nirmalapura WPP is connected to the 220/33 kV Gas Insulated Substation (GIS) at Norochcholai through a dedicated 33kV feeder connecting all wind plants located in Kalpitiya peninsula. A 70 MVA 220/33 kV transformer is provided for connecting wind power at the Substation. The measurements were done from 16th August 2012; 16.59 hrs to 23rd August 2012; 02.58 hrs at Nirmalapura. This plant also falls to Type "D" of the classification of wind turbines. A block diagram showing main components of the plant is given in Figure 4.4.

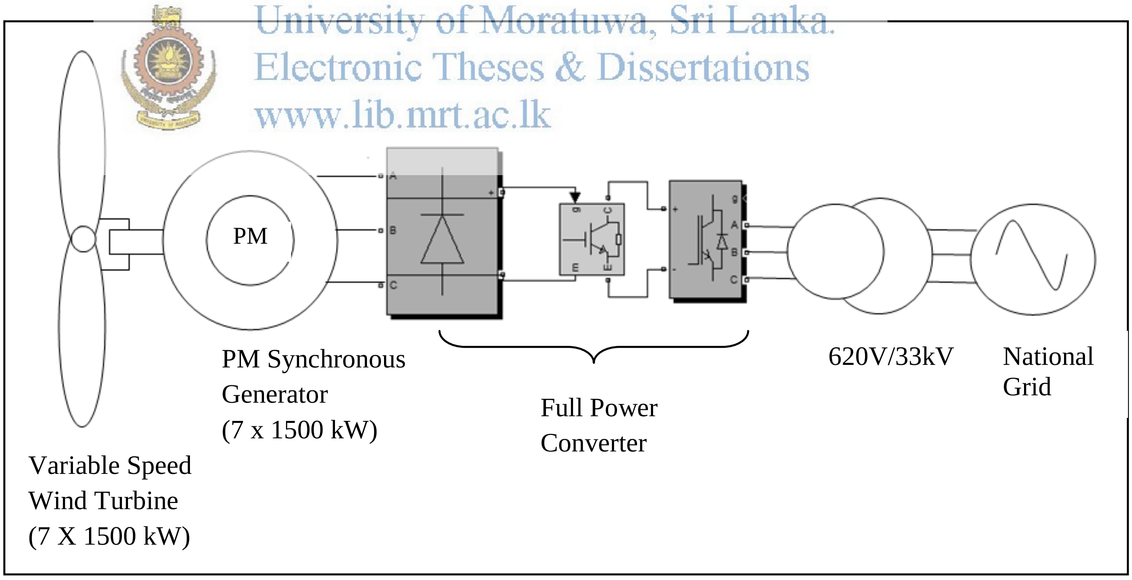


Figure 4.4: Major Plant Components at Nirmalapura WPP

Main technical parameters of Nirmalapura WPP are given in Table 4.3.

Table 4.3: Major Technical Parameters of Nirmalapura WPP

Installed Capacity	-	10 MW
Power Regulation	-	100% variable speed
Average Wind Speed	-	6.8 m/s
Expected Plant Factor	-	32 %

Turbine		
Make and Model	-	Vensys 77
Turbine Capacity	-	1500 kW
No of Turbine Units	-	07
Rotor Diameter	-	77 m
Tower Hub Height	-	85 m
Cut-in Wind Speed	-	3.0 m/s
Cut-out Wind Speed	-	22.0 m/s

Generator		
Type	-	Permanent Magnet generator
Generator Capacity	-	1500 kW
nominal speed	-	9-17.3 rpm (no Gear Box)
Output voltage	-	620 V

Grid connection	Through a Full Power Converter

4.2.5 Plant 04 : Pavandanavi WPP

Pavandanavi WPP is also connected to the 220/33 kV GIS Substation at Norochcholai through the dedicated 33kV feeder that connects all wind plants located in Kalpitiya peninsula. The measurements were done from 01st November 2013; 17.42 hrs to 08th November 2013; 02.12 hrs. This plant falls to Type “C” of the classification of wind turbines. A block diagram showing main components of the plant is given in Figure 4.5.

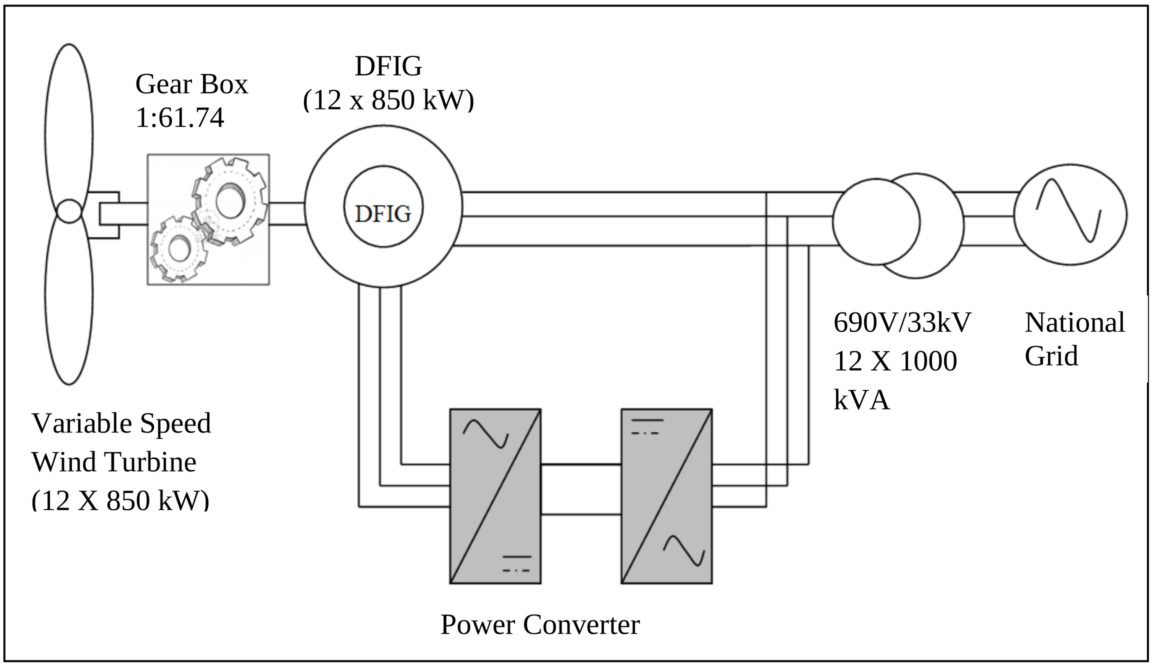


Figure 4.5: Major Plant Components at Pavandanavi WPP

Main technical parameters of Pavandanavi WPP are given in Table 4.4.

Table 4.4: Major Technical Parameters of Pavandanavi WPP

Installed Capacity	-	10 MW
Power Regulation	-	100% variable speed
Average Wind Speed	-	6.5 m/s
Expected Plant Factor	-	30%

Turbine		
Make and Model	-	Gamesa G58
Turbine Capacity	-	850 kW
No of Turbine Units	-	12
Rotor Diameter	-	58 m
Tower Hub Height	-	55 m
Cut-in Wind Speed	-	3.0 m/s
Cut-out Wind Speed	-	23.0 m/s

Generator		
Type	-	Doubly Fed Induction Generator
Generator Capacity	-	850 kW
nominal speed	-	1000: 1950 rpm
No of Poles	-	04
Output voltage	-	690V
Output frequency	-	50Hz

The detailed data analysis of above four case studies is presented in Chapter 05.

Chapter 05

DATA ANALYSIS

In this chapter, measured electrical parameters of the four wind plants are analyzed in detail. For each power quality aspect, a set of norms and marginal values were set to evaluate each wind plant's performance. Norms and margins were set mainly based on referring following documents.

- Grid Connection Requirement for Wind Power Plants – Ceylon Electricity Board (referred as "Grid Code" hereafter)
- IEC 61400-21: Measurement and Assessment of Power Quality Characteristics of the grid connected wind turbines.

5.1 Voltage Variations

According to the grid connection requirement, the behavior of voltage of the grid connected wind turbines should be as follows.

"The embedded wind plant shall operate though out the full range of voltages (+/-10%) with time base capabilities depicted below.

Over Voltage:	1.10 PU	- Continuously
	> 1.10 PU, 1sec	- Should remain connected to the grid for 1 second and trip.
Under Voltage:	< 0.90 PU, 3 sec	- If Low Voltage Ride Through (LVRT) capability applicable. Should remain connected to the grid for 3 seconds and trip.
Otherwise;	<0.90 PU, 1sec	- Should remain connected for 1s and trip"

Voltage variations of grid connected wind farms occur mainly due to faults at the grid side or during switching operations of the wind turbines.

5.1.1 Interruptions

Interruptions are the durations that $V_{L-L} < 3{,}300$ V. Norms used to analyze Voltage Interruptions are,

i. No of Interruptions
ii. Interruption Duration
iii. Reasons for the Interruption

Summary of Interruptions are given in Table 5.1 and duration of recorded events is illustrated in Figure 5.1.

Table 5.1: Summary of Interruptions

Wind Power Plant	Plant 01	Plant 02	Plant 03	Plant 04
No of Events	3	6	3	-
Total Duration (min)	612	206	3	-
As a % of total measuring interval	8.4 %	2.46%	0.03 %	0.00%
Remarks	-	03 interruptions have occurred within 40 minutes with less than 5 min durations.	All 3 events are associated with immediate voltage sags.	No Interruptions during measurement interval

No interruptions have occurred in Plant 04 during the measurement interval. Interruptions of grid connected embedded generators occur mainly due to network faults. Apart from that, plant has been tripped after immediate voltage sags in plants 01 and 02. In plant 02, most of the interruptions seem to have occurred due to internal faults of the WPP. Further details on each event are attached as Appendix A.

5.1.2 Voltage sags

Voltage sags are the durations less than 1 min that $3,300 < V_{L\text{-}L} < 29,700$ V. Norms used to analyze Voltage sags are,

1. No of Voltage Sags
2. Depth of the Voltage Drop
3. LVRT Capability
4. Time taken to recover voltage
5. Reasons for the sag

<u>Low Voltage Ride Through (LVRT) Capability</u>

According to the Grid Code, LVRT Capability is applicable for wind farms having installed capacities of 5 MW or above. The conditions are,

- The wind power plant shall be connected to the grid during voltage disturbances (Under voltage conditions) of the power system for a short period of time.
- If the grid voltage at the point of interconnection reduces to 40% of the nominal voltage and remain at 40% of nominal voltage for a period less than 100 ms and then recover to a voltage level of 90% or higher within 3 seconds, the wind farm shall remain connected to the grid.
- If the voltage during the disturbance reduces below the aforesaid voltage profile, the wind farm shall trip.

The sampling time of the measured data is 1 min. Therefore, to observe LVRT capability, following criteria was used.

- "If the grid voltage at the point of interconnection reduces to 40% of the nominal voltage and remain at 40% of nominal voltage for a period less than 1mins and then recover to a voltage level of 90% or higher within 1 min, the wind farm shall remain connected to the grid.
- If the voltage during the disturbance reduces below the aforesaid voltage profile, the wind farm shall trip."

Summary of Voltage Sags are given in Table 5.2. No Sags have occurred at Pavandanavi during the measurement interval. In 02 events at Seguwantivu, 03 events at Vidathamunai and 05 events at Nirmalapura; the sags are followed by an interruption. Further analysis on each event is attached as Appendix B.

Table 5.2: Summary of Voltage Sags

Wind Power Plant	Plant 01	Plant 02	Plant 03	Plant 04
No of Voltage Sags	3	3	9	-
No of Sags having LVRT capability	2	2	7	-
Depth of sag	0.3 – 0.8 $V_{nominal}$	0.41 – 0.83 $V_{nominal}$	0.31 – 0.85 $V_{nominal}$	-

5.1.3 Under voltage events

Under voltage events are the durations longer than 1 min that $3,300 < V_{L-L} < 29,700$ V. Norms used to analyze Under Voltage events are,

1. No of Under Voltage events and Duration
2. Voltage Drop
3. Time taken to recover voltage
4. Reason for Under Voltage event

Table 5.3: Summary of Under Voltage Events

Wind Power Plant	Plant 01	Plant 02	Plant 03	Plant 04
No of Under Voltage Events	-	2	2	-
Duration (min)	-	4	4	-
Depth of Under Voltage	-	0.78 – 0.87 $V_{nominal}$	0.57 – 0.68 $V_{nominal}$	-

No Under Voltages occurred at Plant 01 and Plant 04 during measurement intervals. Further analysis on each event is attached as Appendix C.

5.2 Frequency Variations

According to the grid code, the allowable frequency band is 0.94 PU - 1.04 PU (47 HZ to 52 HZ). Frequencies measured at WPPs are as follows.

Plant 01	-	48.978 - 50.556 Hz
Plant 02	-	48.859 - 50.687 Hz
Plant 03	-	49.032 - 51.376 Hz
Plant 04	-	49.208 - 51.238 Hz

As all four WPPs lies within the allowable range, there are no power quality issues regarding frequency events.

5.3 Behavior of WPPs during Normal Operation

Operations when nominal voltage is within 29,700 V – 36,300 V are considered as normal/ steady state operation. Following norms were used to analyze plant behavior during Steady State.

1. Harmonic content in Voltage & Current waveforms
2. Behavior of V_{THD}
3. Behavior of I_{THD}
4. Voltage Unbalance
5. Variation of Power Factor
6. Behavior of Short term Flicker Index

Embedded generators do not generate power at its full capacity all the time. In wind plants, power generation varies with the wind speed at site. Variation of Power Generation in one of case studies is shown in Figure 5.1.

Active power flow from all four plants varies from minus values (where the plant draws active power from the grid) to their maximum installed capacity except for Plant 03. In plant 03; the maximum active power generation had been 157.5 kW during the measurement interval. Therefore, for analytical purposes, steady state behavior of each wind plant was classified into five categories as follows.

i. Active Power (P) < 0
ii. Active Power = 0
iii. 0 < P < 850 kW
iv. 850 kW < P < 5 MW
v. 5 MW < P < 10 MW

The corresponding durations of these categories are given in Figures 5.2 (1) –5.2 (4).

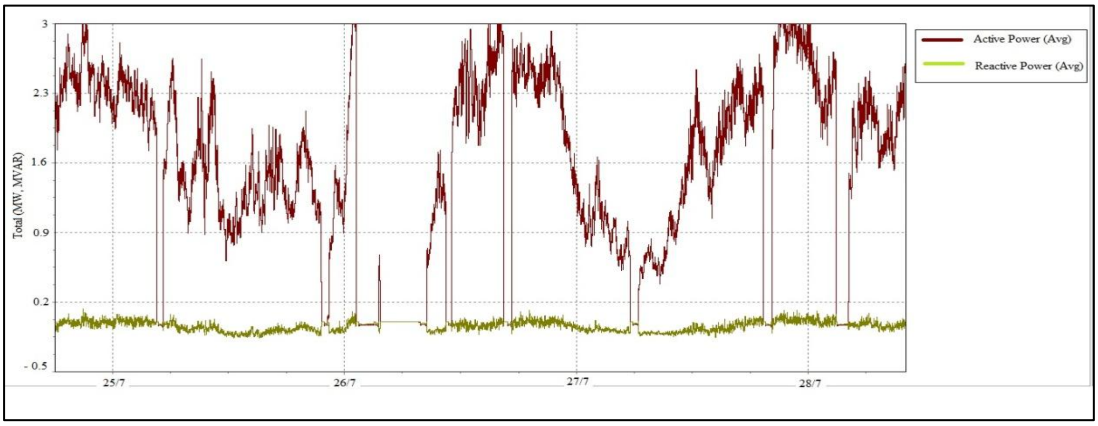


Figure 5.1: Variation of Active Power Generation in Plant 02 (Original in Colour)

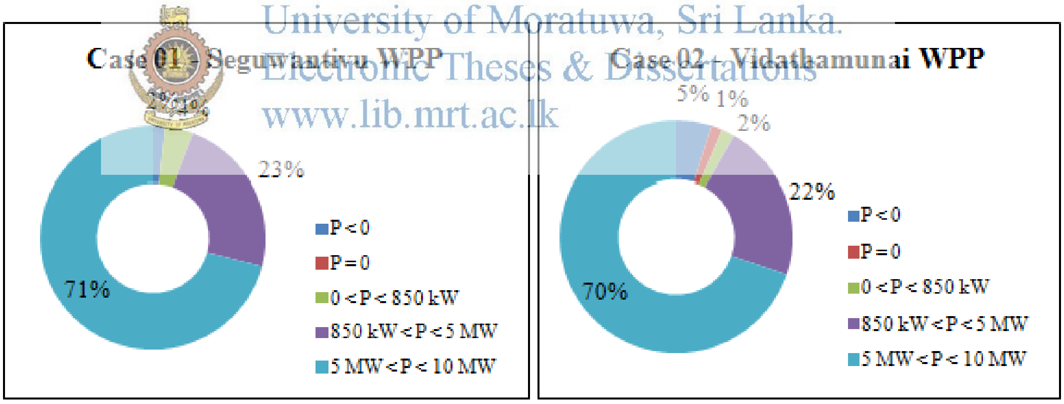


Figure 5.2 (1) - Seguwantivu WPP Figure 5.2 (2) - Vidathamunai WPP

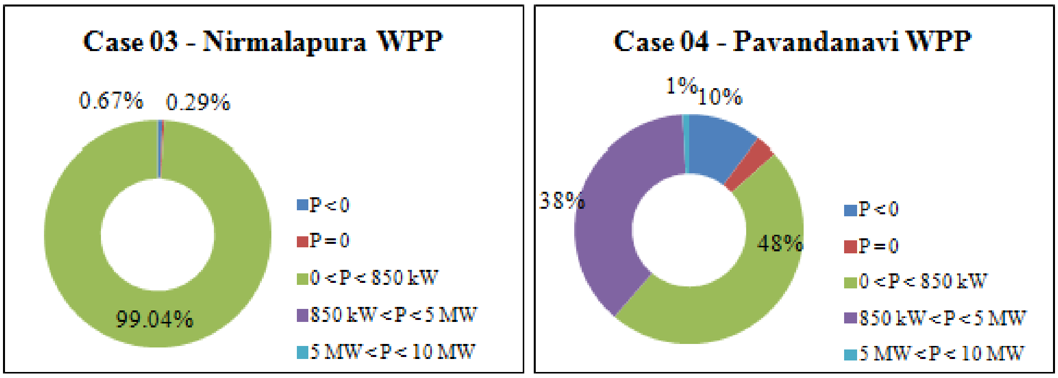


Figure 5.2 (3) - Nirmalapura WPP Figure 5.2 (4) - Pavandanavi WPP

Figure 5.2 : Durations of categories of power generation (Original in Colour)

5.3.1 Allowable limits for harmonic content

According to the grid code, Total Harmonic Distortion (THD) and emission of the individual harmonics has to be specified for frequencies up to 50 times the fundamental grid frequency. Further, Total Harmonic Distortion has to be less than 5% of the fundamental. The relevant emission limits for individual harmonics are given in Table 5.4.

Table 5.4 – Allowable Harmonic Limits in Grid Code

Harmonic order	**Odd harmonic Current (%)**	**Even harmonic current (%)**
n<11	4.0	1.0
11≤ n < 17	2.0	0.5
17≤ n < 23	1.5	0.4
23≤ n < 35	0.6	0.2
35≤ n ≤ 50	0.3	0.1

5.3.2 Harmonic spectrums

Harmonic Spectrums of the four plants obtained from the Analyzer are depicted in Figures 5.3(a) to 5.3(d). Values are given as a percentage of fundamental voltage and current. Maximum values are pointed with a red arrow and minimum values with a green arrow. Average values are indicated with a bar.

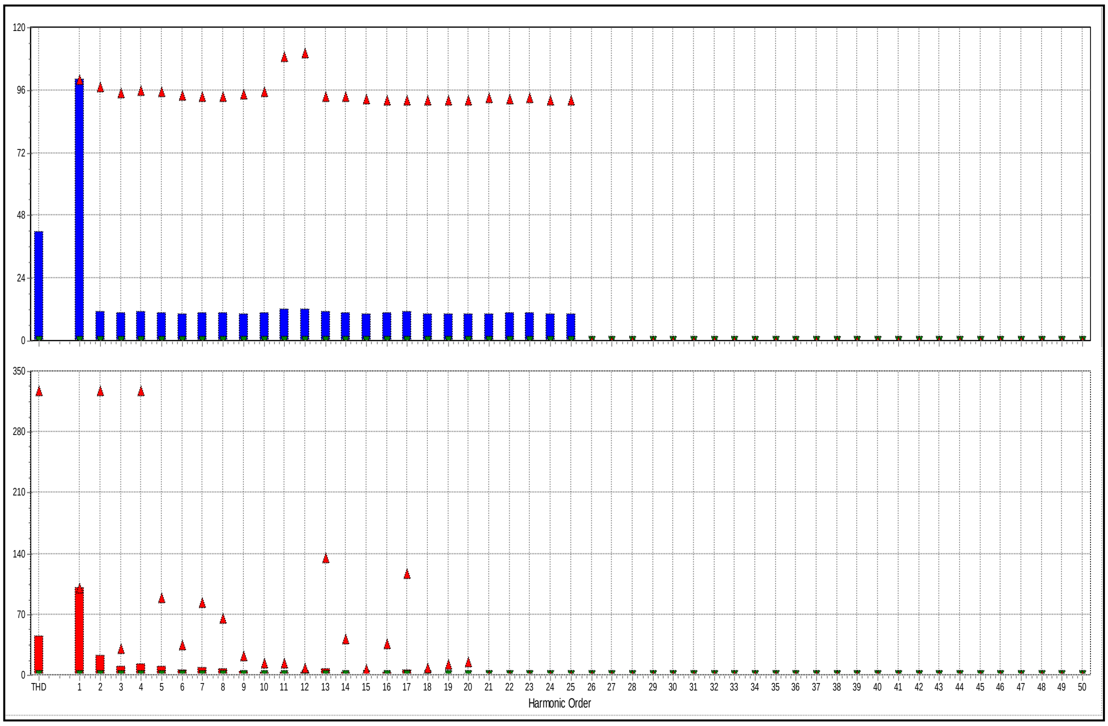


Figure 5.3(a) : Voltage and Current Harmonic Spectrum for Plant 01 (Original in Colour)

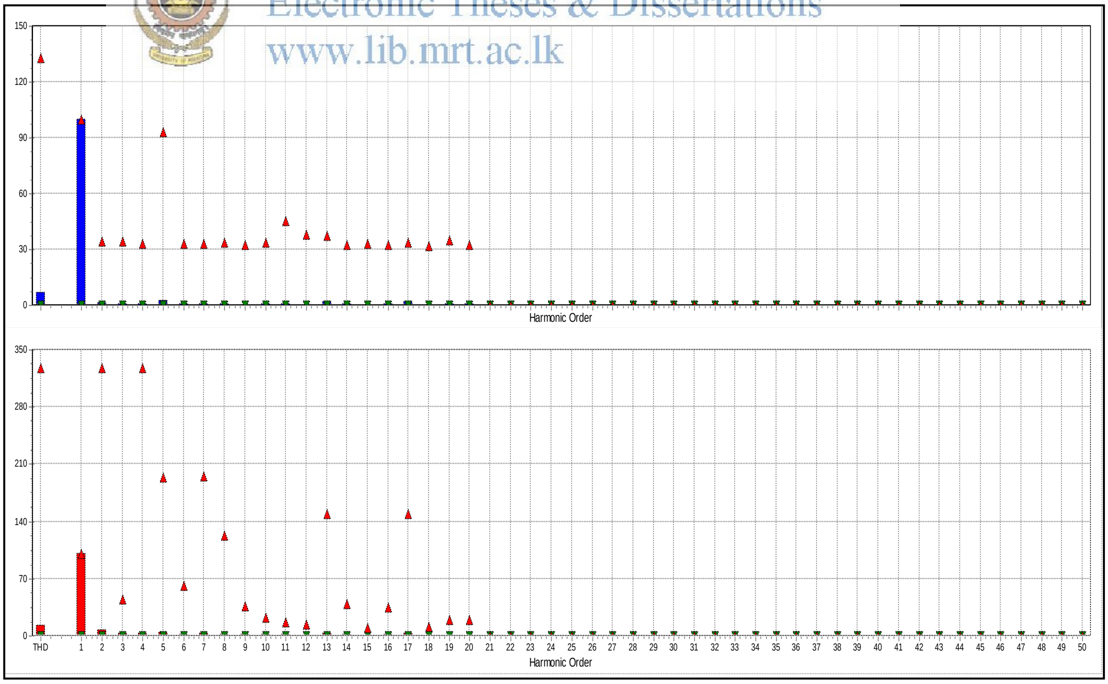


Figure 5.3(b) : Voltage and Current Harmonic Spectrum for Plant 02 (Original in Colour)

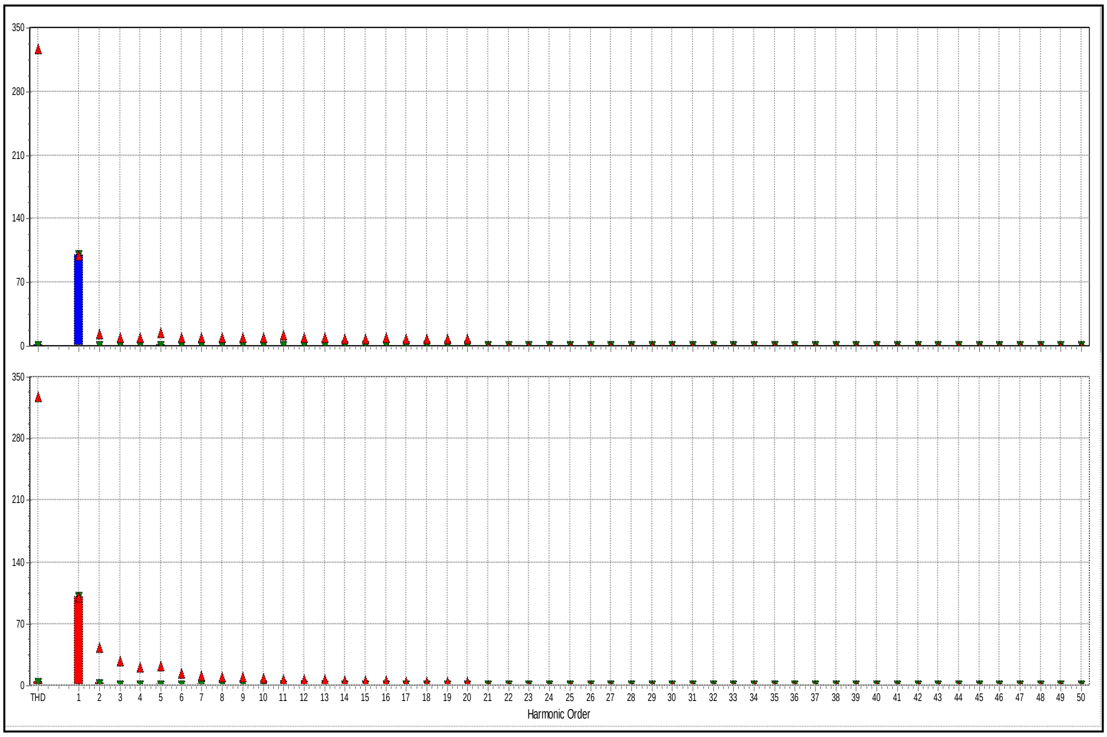


Figure 5.3(c) : Voltage and Current Harmonic Spectrum for Plant 03 (Original in Colour)

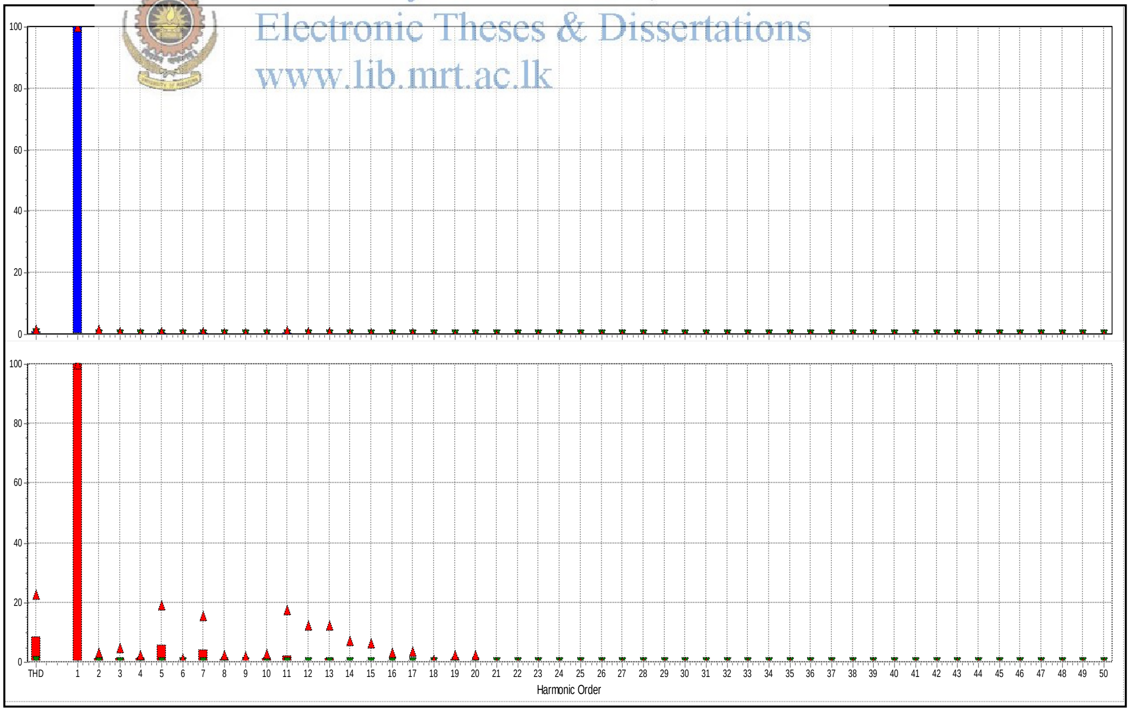


Figure 5.3(d) : Voltage and Current Harmonic Spectrum for Plant 04 (Original in Colour)

5.3.3 Harmonic content in voltage waveform

5.3.3.1 Harmonic content in voltage waveform when P<0

Figure 5.4 shows average harmonic voltages observed as a percentage of the fundamental voltage. In plants 01, 02 and 03, average harmonic voltages other than n > 23 are within allowable limits. The maximum percentages of harmonics in these 03 Plants have gone above 10%. In Plant 04, average harmonic voltages are well below allowable maximum limits for all categories. Harmonic voltages from n=23 to n=50 are not recorded in Plant 04. Minimum, maximum and average voltage harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix D (i).

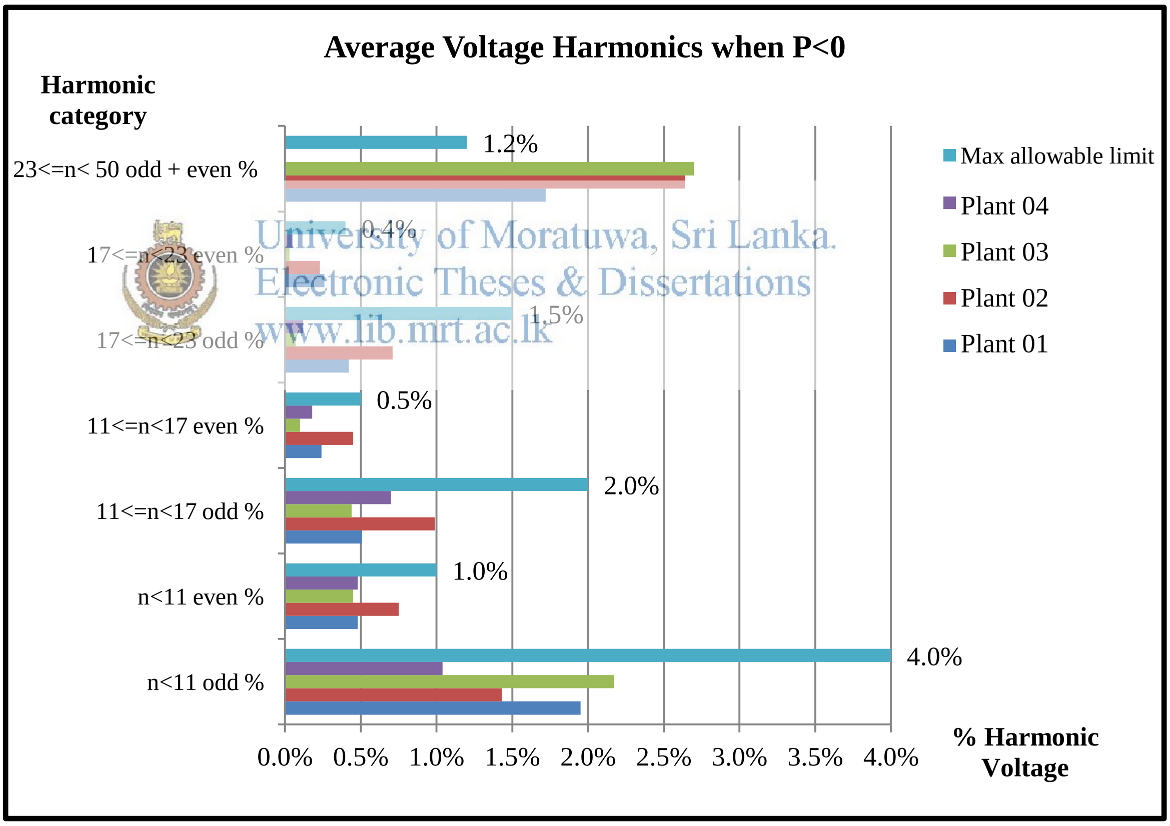


Figure 5.4 : Comparison of Average Harmonic Content in Voltage Waveform when P<0 (Original in Colour)

5.3.3.2 Harmonic content in voltage waveform when P=0

Figure 5.5 shows average harmonic voltages observed as a percentage of the fundamental voltage when P=0.

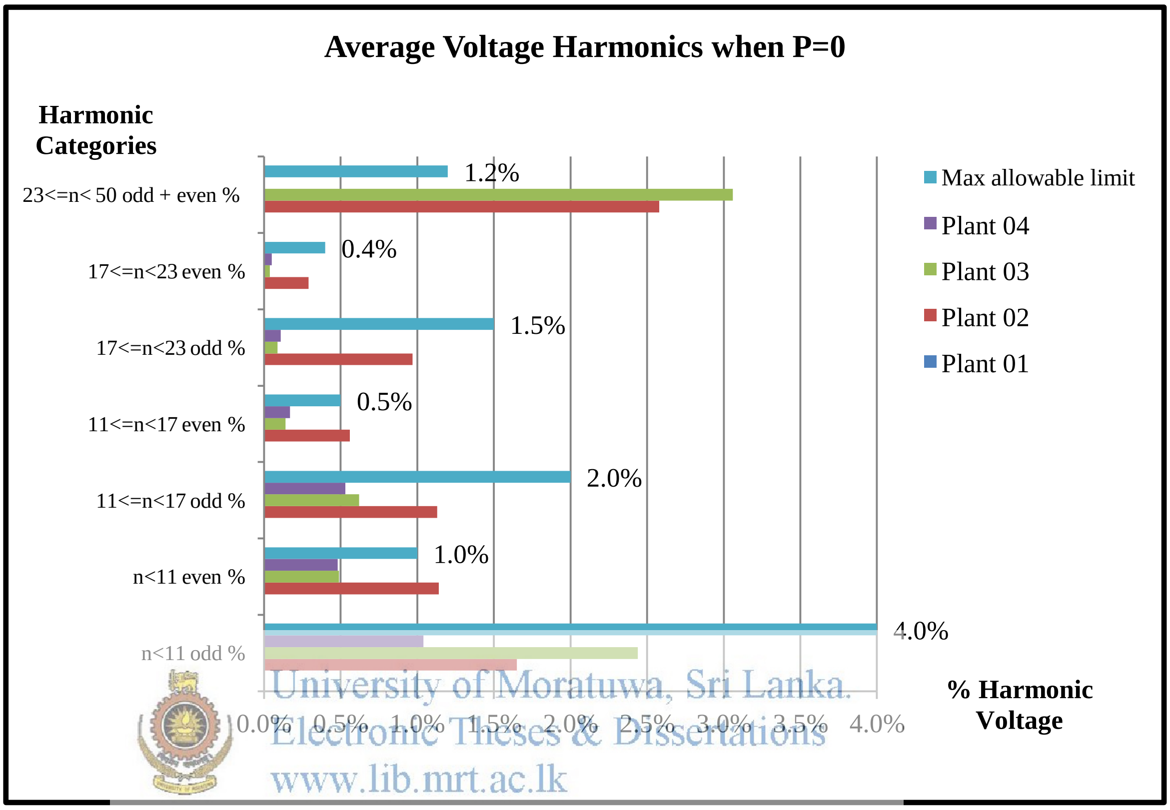


Figure 5.5 : Comparison of Average Harmonic Content in Voltage Waveform when P=0 (Original in Colour)

There are no records of P=0 events with respect to Plant 01. In Plant 02 and 03, average harmonic voltages when (23<=n< 50 odd + even %) have exceeded allowable limits. The maximum percentages of harmonics in these 02 Plants have gone above 10% as well. In Plant 04, average harmonic voltages are well below allowable maximum limits for all categories. Harmonic voltages from n=23 to n=50 are not recorded in Plant 04. Minimum, maximum and average voltage harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix D(ii).

5.3.3.3 Harmonic content in voltage waveform when 0 < P < 850 kW

Figure 5.6 shows average harmonic voltages observed as a percentage of the fundamental voltage when 0 < P < 850 kW.

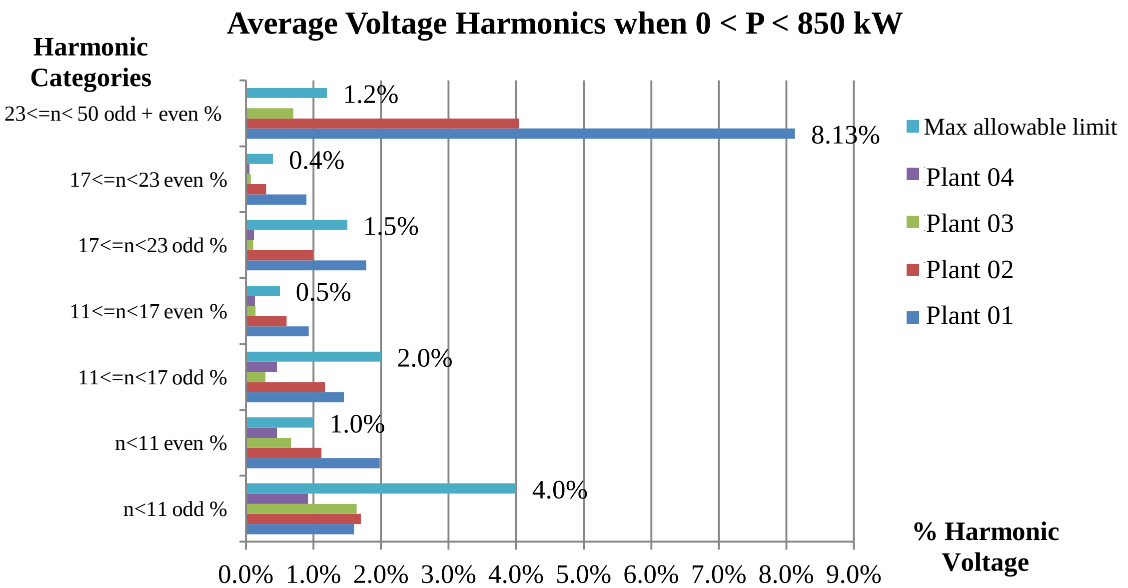


Figure 5.6 : Comparison of Average Harmonic Content in Voltage Waveform when 0 < P < 850 kW (Original in Colour)

In Plant 01, allowable limits of even harmonics have exceeded for (n<23). High harmonic voltages have been recorded for 02nd, 04th, 14th and 16th harmonics. For 80% of the measurement interval, harmonic level has exceeded the allowable limit. For harmonic order 23-50, average percentages of voltage harmonics is very high as 8.13% and maximum percentage has risen to 64.28% which is extremely unacceptable. For Plant 02, only harmonic contents of harmonic order 23-50 considerably exceeds the limit and maximum percentage has risen to 52.68%. For Plant 03 and 04, average harmonic voltages are below the allowable maximum limits for all categories. Harmonic voltages from n=23 to n=50 are not recorded in Plant 04. Minimum, maximum and average voltage harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix D(iii).

5.3.3.4 Harmonic content in voltage waveform when 850 kW < P < 5 MW

Figure 5.7 shows average harmonic voltages observed as a percentage of the fundamental voltage when 850 kW < P < 5 MW.

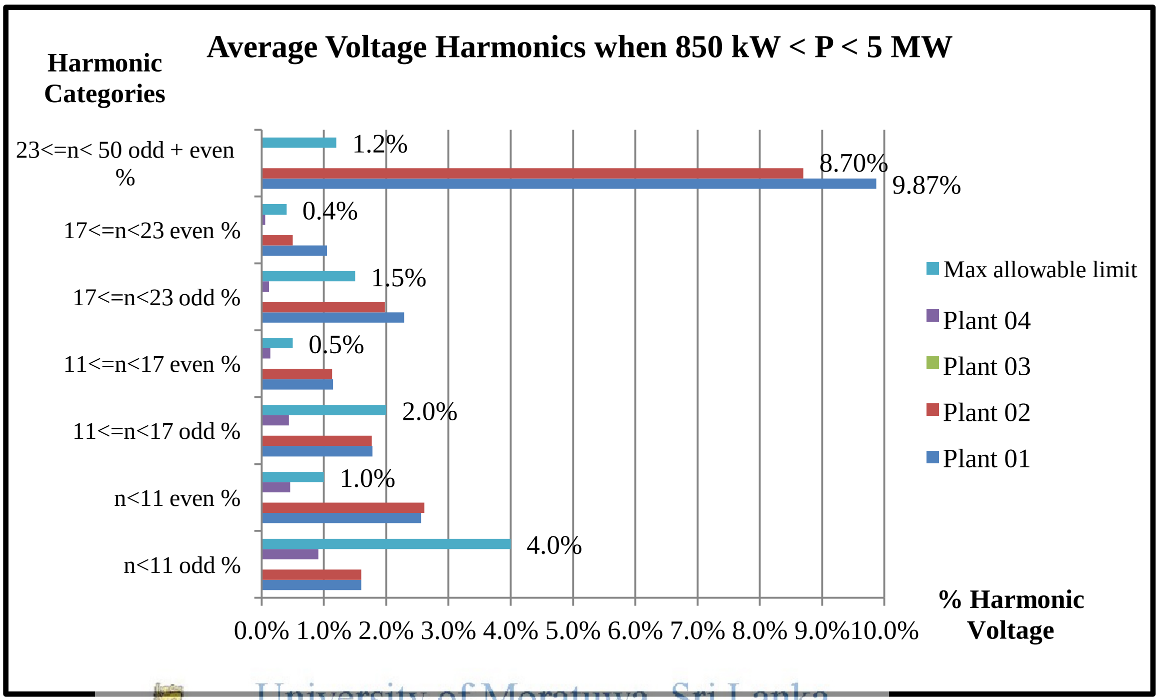


Figure 5.7 : Comparison of Average Harmonic Content in Voltage Waveform when 850 kW < P < 5 MW (Original in Colour)

In Plant 01, allowable limits of even harmonics have exceeded for (n<23) during the entire measurement interval. High harmonic voltages are recorded for 02nd, 04th, 8th, 14th, 16th and 22nd harmonics. For 84% of the time, (17<=n<23) odd harmonics has risen due to high 17th harmonic. For harmonic order 23-50, average percentages of voltage harmonics is very high as 9.87% and maximum percentage has risen to 29.11% which is extremely unacceptable. Harmonic behavior for Plant 02 is same as Plant 01. There are no records under this group for Plant 03 and in Plant 04, average harmonic voltages are below the allowable maximum limits for all categories. Harmonic voltages from n=23 to n=50 are not recorded in Plant 04.

Minimum, maximum and average voltage harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix D(iv).

5.3.3.5 Harmonic content in voltage waveform when 5 MW < P < 10 MW

Figure 5.8 shows average harmonic voltages observed as a percentage of the fundamental voltage when 5 MW < P < 10 MW.

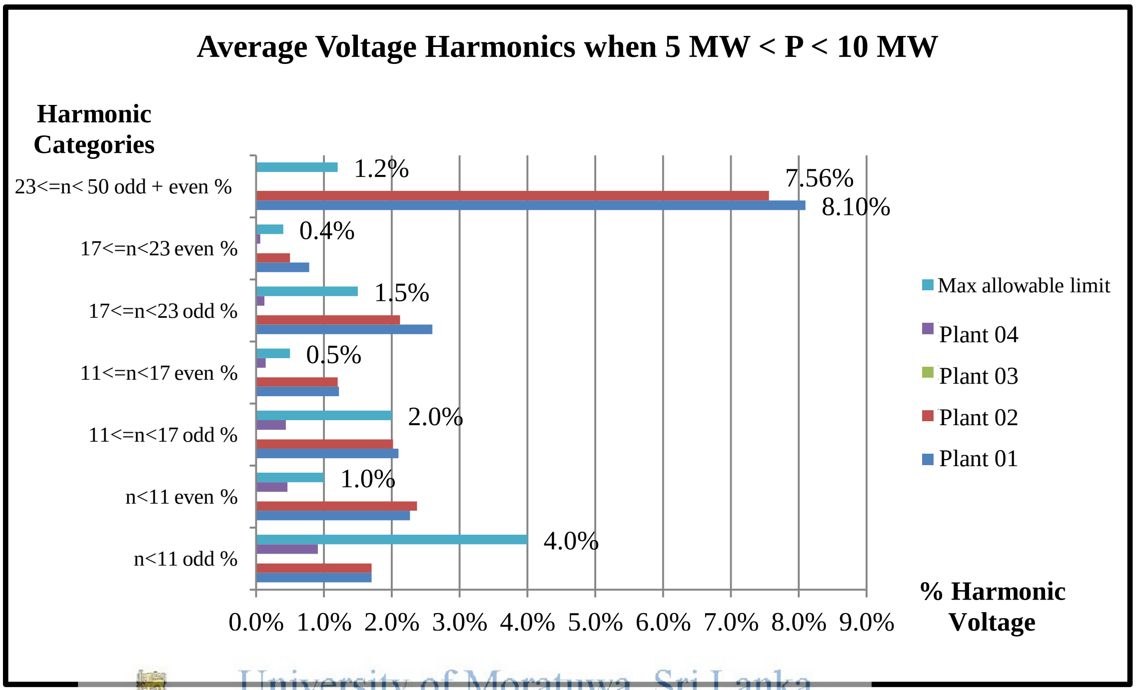


Figure 5.8 : Comparison of Average Harmonic Content in Voltage Waveform when 5 MW < P < 10 MW (Original in Colour)

In Plant 01 and Plant 02, all harmonic categories except (n<11) odd harmonics have exceeded allowable limits. High harmonic voltages are recorded for 02nd, 13th, 14th, 17th and harmonics from 23-50. For harmonic order 23-50, average percentages of voltage harmonics are very high as 8.1% and 7.56% respectively. Harmonic contents in all categories except (n<17) odd harmonics has violated allowable limits during entire measurement intervals.

There are no records under this group for Plant 03. In Plant 04, average harmonic voltages are below the allowable maximum limits for all categories. Harmonic voltages from n=23 to n=50 are not recorded in Plant 04. Minimum, maximum and average voltage harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix D(v).

5.3.3.6 Total harmonic distortion (THD) of voltage

Table 5.5 shows average and maximum THD values of voltage observed as a percentage of the fundamental voltage and the durations that V_{THD} exceeds its maximum allowable limit of 5%.

Table 5.5 : Behavior of V_{THD}

Harmonic Category	**V_{THD}**	**Plant 01**	**Plant 02**	**Plant 03**	**Plant 04**
P < 0	Average	2.51%	3.18%	3.90%	0.95%
	Maximum	10.13%	10.83%	11.65%	1.83%
	% Duration – V_{THD} exceeding 5%	18.8%	18.00%	27.69%	**0%**
P = 0	Average	NA	3.33%	4.58%	0.82%
	Maximum	NA	28.66%	12.06%	1.44%
	% Duration – V_{THD} exceeding 5%	NA	14.17	39.29%	**0%**
0 < P < 850 kW	Average	7.60%	4.66%	1.46%	0.79%
	Maximum	63.57%	52.83%	327.67%	3.23%
	% Duration – V_{THD} exceeding 5%	75.84%	20.55%	0.25%	**0%**
850 kW < P < 5 MW	Average	9.21%	9.22%	NA	0.79%
	Maximum	28.12%	15.00%	NA	4.34%
	% Duration – V_{THD} exceeding 5%	**98.17%**	**99.83%**	NA	**0%**
5 MW < P < 10 MW	Average	7.85%	8.20%	NA	0.83%
	Maximum	14.41%	19.00%	NA	1.36%
	% Duration – V_{THD} exceeding 5%	**98.70%**	**99.04%**	NA	**0%**

Figure 5.9 shows the behavior of average V_{THD} for above five harmonic categories.

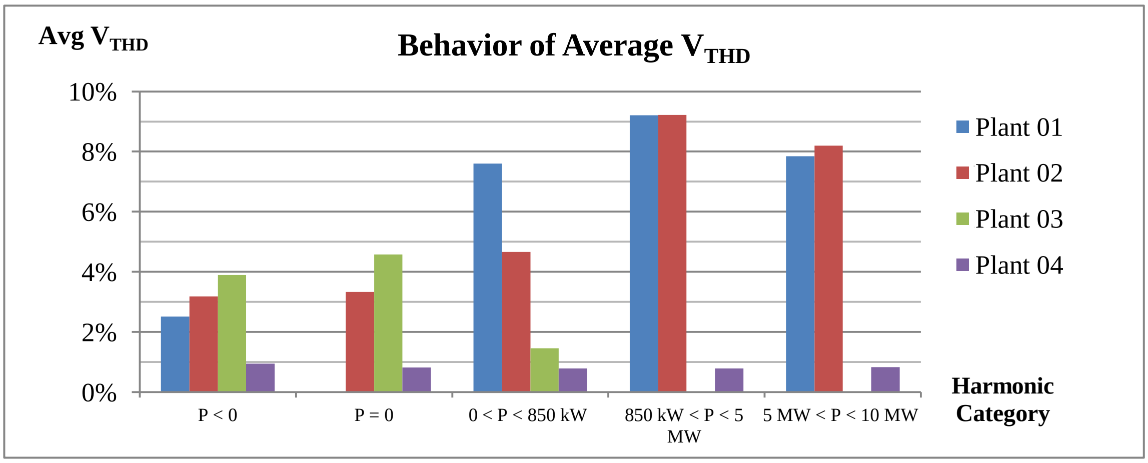


Figure 5.9 – Behavior of Average V_{THD} in four wind plants (Original in Colour)

During $P \leq 0$, average voltage THD levels are within the limit but except in Plant 04, maximum voltage THD levels have gone above 10%. During $P > 0$, following major observations are made.

i. Plant 01 – Average voltage THD levels have gone above 7.5% and highest when (850 kW < P < 5 MW). When active power generation is in MW range, THD levels have exceeded the maximum allowable limit of 5% for almost the entire period of measurement.

ii. Plant 02 – Average voltage THD levels have gone above 8% when P > 850 kW. As in Plant 01, when active power generation is in MW range, THD levels have exceeded the maximum allowable limit of 5% for almost the entire period of measurement.

iii. Plant 03 – Average voltage THD level is within the limit. But, for few times, V_{THD} has risen to very high values above 100%. The duration showing this abnormal behavior is negligible therefore, voltage harmonic distortion in this plant can be considered as satisfactory.

iv. Plant 04 – Even maximum voltage THD levels are within the limit during entire period of measurement. Average voltage THD level is below 1%. Therefore, voltage harmonic distortion in this plant can be considered as negligible.

5.3.4 Harmonic content in current waveform

5.3.4.1 Harmonic content in current waveform when P<0

Figure 5.10 shows average harmonic currents observed as a percentage of the fundamental current.

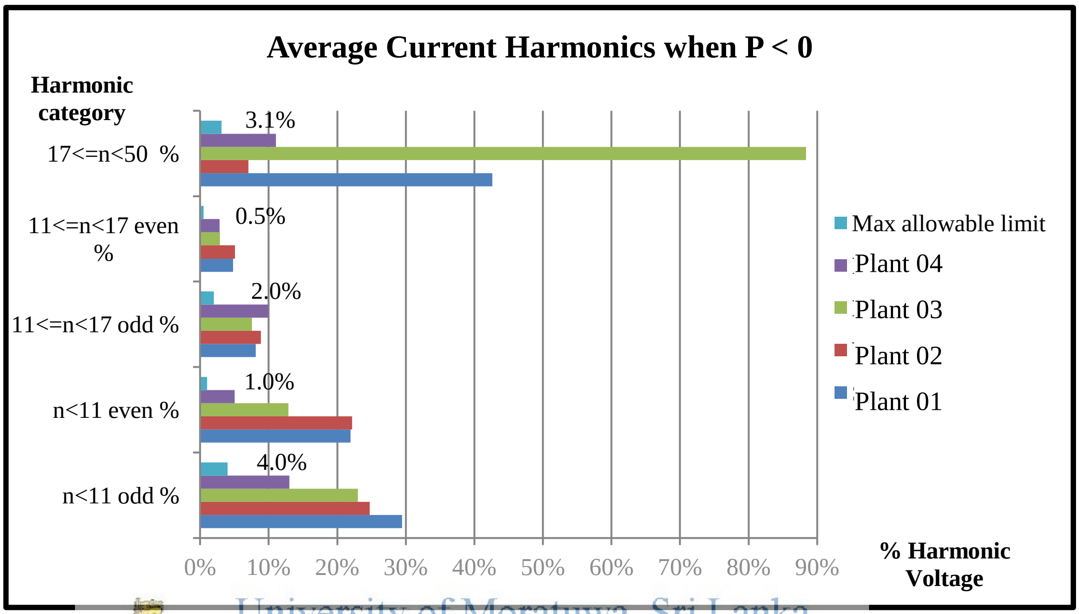


Figure 5.10: Comparison of Average Harmonic Content in Current Waveform when P<0 (Original in Colour)

In all four Plants, average harmonic currents exceed allowable limits for all five harmonic categories. Largest harmonic content of 88.4% is shown in Plant 03 when (17<=n<50 %). Of the four Plants, Plant 04 has the minimum harmonic content. Harmonic orders with high harmonic currents are given in Table 5.6 for each Plant.

Table 5.6: Harmonic orders with high harmonic content when P<0

Plant	High Odd Harmonics	High Even Harmonics
Plant 01	3, 5, 7, 13, 17, (27 – 49)	2, (26 – 50)
Plant 02	3, 5, 13, 17, (27 – 49)	(26 – 50)
Plant 03	3, 5, 11, 13, (21 – 49)	(22 – 50)
Plant 04	5, 11, 13	–

Minimum, maximum and average current harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix E(i).

5.3.4.2 Harmonic content in current waveform when P=0

Figure 5.11 shows average harmonic currents observed as a percentage of the fundamental current.

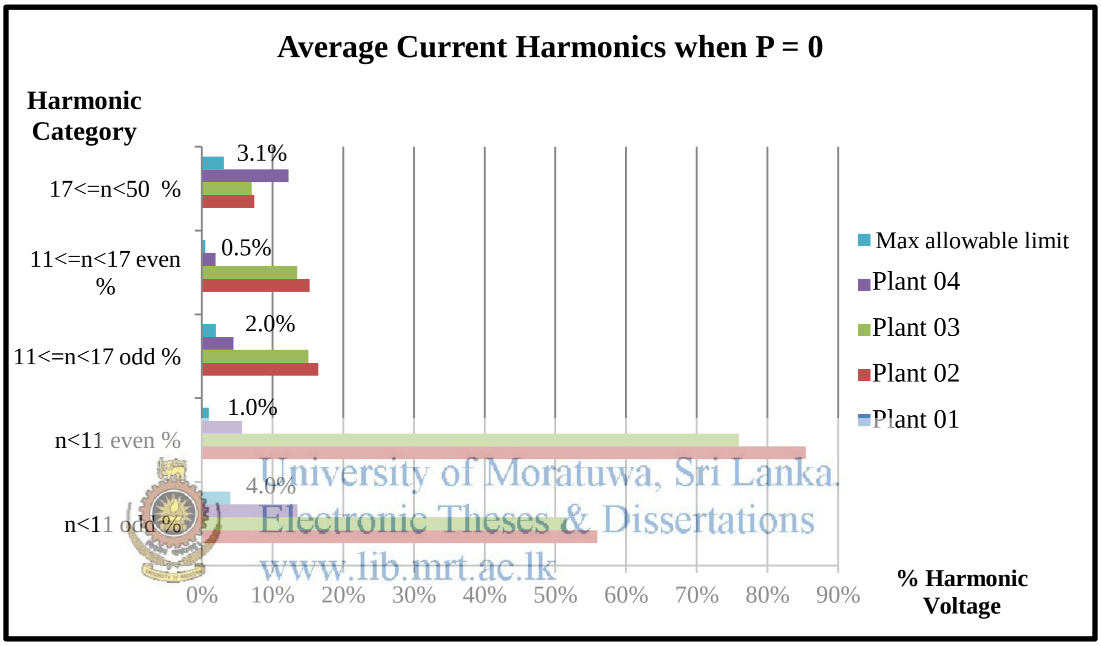


Figure 5.11: Comparison of Average Harmonic Content in Current Waveform when P=0 (Original in Colour)

There are no events recorded for Plant 01 when P=0. In other three Plants, average harmonic currents exceed allowable limits for all five harmonic categories where Plant 04 shows the minimum. For harmonic orders (2-10), average harmonic currents in Plants 02 and 03 are larger than 50%. Harmonic orders with high harmonic currents are given in Table 5.7 for each Plant.

Table 5.7: Harmonic orders with high harmonic content when P=0

Plant	High Odd Harmonics	High Even Harmonics
Plant 02	All current harmonics are comparatively high and gradually decreases from n=2 to n=50	
Plant 03	(3-49) except 19th harmonic	(2-50) except 18th and 20th harmonics
Plant 04	5, 7	–

Minimum, maximum and average current harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix E (ii).

5.3.4.3 Harmonic content in current waveform when 0 < P < 850 kW

Figure 5.12 shows average harmonic currents observed as a percentage of the fundamental current.

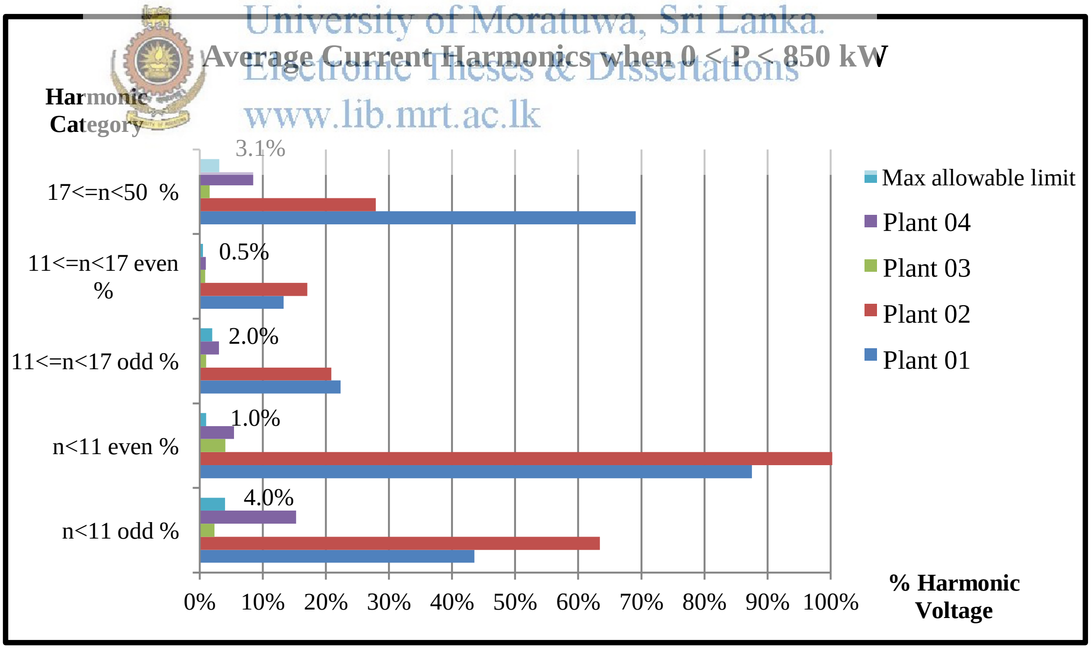


Figure 5.12: Comparison of Average Harmonic Content in Current Waveform when 0 < P < 850 kW (Original in Colour)

For Plants 01, 02 and 04, average harmonic currents exceed allowable limits for all harmonic categories where Plant 04 shows the lowest of them. For Plant 03, only n<17 even harmonic currents has gone above acceptable limits. Harmonic orders with comparatively high harmonic currents are given in Table 5.8 for each Plant.

Table 5.8: Harmonic orders with high harmonic content when 0 < P < 850 kW

Plant	High Odd Harmonics	High Even Harmonics
Plant 01	3, 5, 7, 13, 17, (27 – 49)	2, 4, 8, 16, (26 – 50)
Plant 02	All current harmonics are comparatively high and gradually decreases from n=2 to n=50	
Plant 03	3,5	–
Plant 04	–	–

Minimum, maximum and average current harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix E (iii).

5.3.4.4 Harmonic Content in Current Waveform when 850 kW < P < 5 MW

For Plants 01 and 02, average harmonic currents exceed permissible limits for all harmonic categories where Plant 01 shows the highest. There are no events recorded for Plant 03. For Plant 04, only harmonic currents less than harmonic order 11 has gone above acceptable limits. Harmonic orders with comparatively high harmonic currents are given in Table 5.9 for each Plant.

Table 5.9: Harmonic orders with high harmonic content when 850 kW < P < 5 MW

Plant	High Odd Harmonics	High Even Harmonics
Plant 01	5, 7, 13, 17, (27 – 49)	2, 4, (26 – 50)
Plant 02	5, 13, 17, (21 – 49)	2, 4, (22 – 50)
Plant 04	–	–

Figure 5.13 shows average harmonic currents observed as a percentage of the fundamental current.

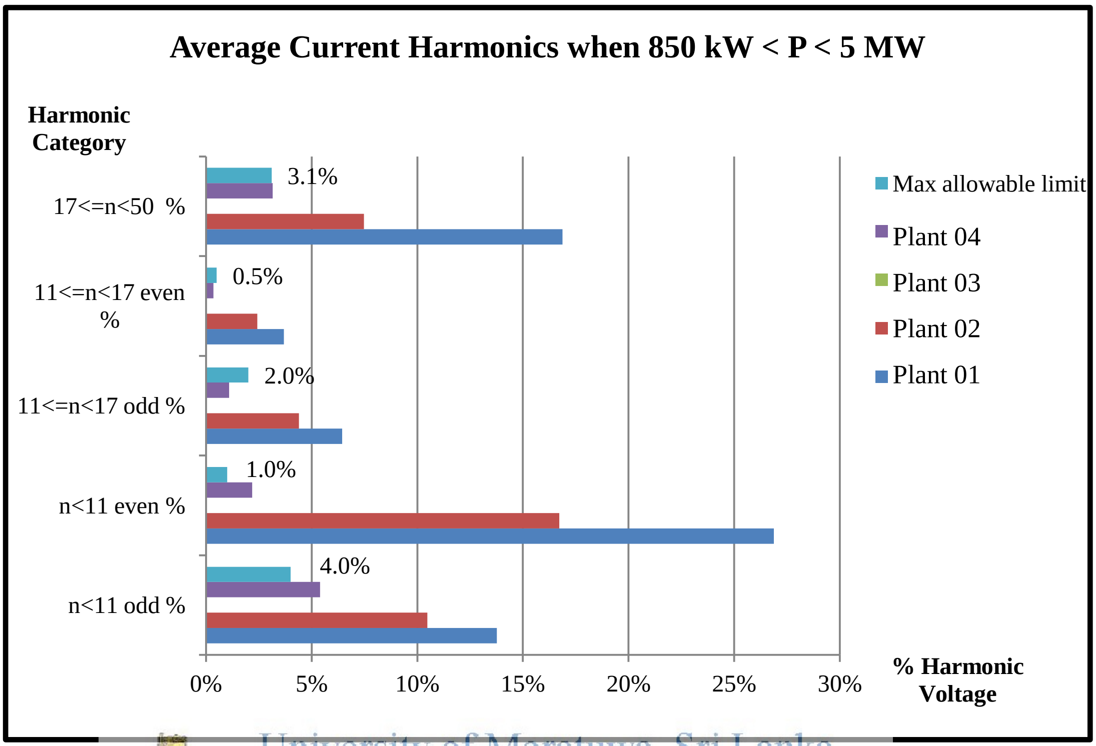


Figure 5.13: Comparison of Average Harmonic Content in Current Waveform when 850 kW < P < 5 MW (Original in Colour)

Minimum, maximum and average current harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix E (iv).

5.3.4.5 Harmonic content in current waveform when 5 MW < P < 10 MW

There are no events recorded for Plant 03. For Plants 01 and 02, average harmonic currents exceed permissible limits for all harmonic categories. For Plant 04, average harmonic currents are well below the maximum permissible limits. Harmonic orders with comparatively high harmonic currents are given in Table 5.10 for each Plant.

Table 5.10: Harmonic orders with high harmonic content when 5 MW < P < 10 MW

Plant	**High Odd Harmonics**	**High Even Harmonics**
Plant 01	05, 13	02
Plant 02	05	02
Plant 04	5, 7	02

Figure 5.14 shows average harmonic currents observed as a percentage of the fundamental current.

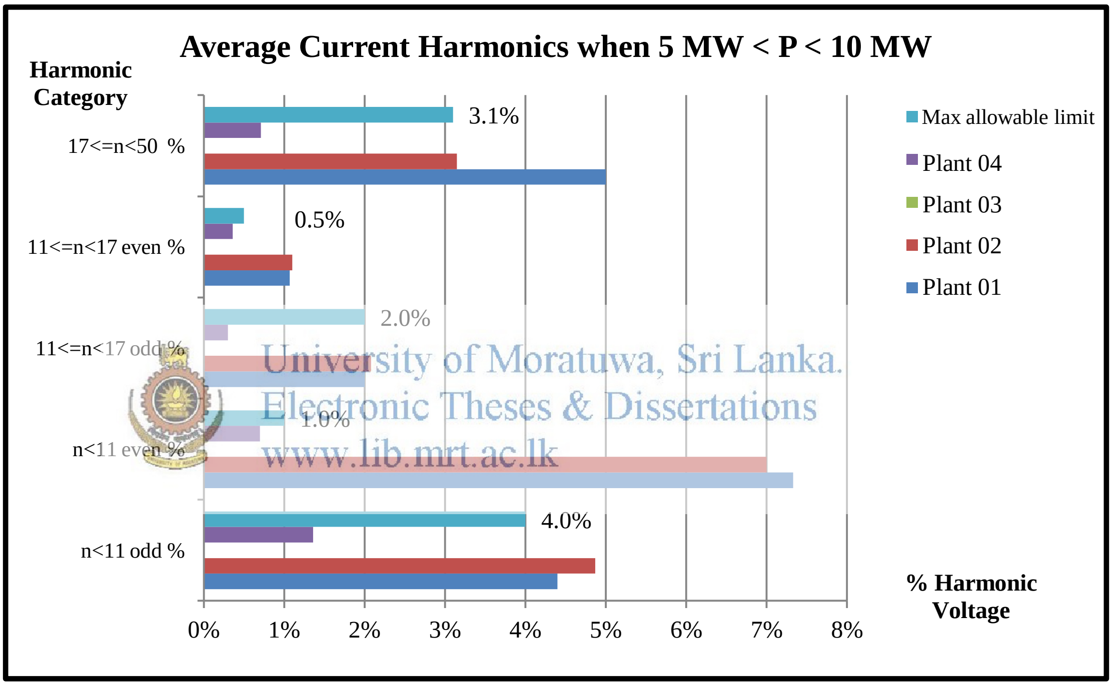


Figure 5.14 – Comparison of Average Harmonic Content in Current Waveform when 5 MW < P < 10 MW (Original in Colour)

Minimum, maximum and average current harmonic percentages along with the percentage durations that exceed the allowable maximum limits are given in Appendix E(v).

5.3.4.6 Total Harmonic Distortion (THD) of Current

Average, Minimum and maximum THD values of current observed as a percentage of the fundamental and the durations that I_{THD} exceeds its maximum allowable limit of 5% are given in Table 5.11.

Table 5.11 : Behavior of I_{THD}

Power Category	**I_{THD}**	**Plant 01**	**Plant 02**	**Plant 03**	**Plant 04**
P < 0	Minimum	10.49	9.36	12.30	7.07
	Average	44.56	31.90	93.90	12.45
	Maximum	327.67	327.67	327.67	25.28
	% Duration – V_{THD} exceeding 5%	100.0	100.0	100.0	100.0
P = 0	Minimum	NA	57.31	20.74	7.32
	Average	NA	64.81	173.15	11.35
	Maximum	NA	142.45	315.73	21.03
	% Duration – V_{THD} exceeding 5%	NA	100.0	100.0	100.0
0 < P < 850 kW	Minimum	19.31	40.06	3.02	4.46
	Average	83.91	79.10	4.33	12.80
	Maximum	327.67	327.67	324.75	26.35
	% Duration – V_{THD} exceeding 5%	100.0	100.0	6.97	99.86
850 kW < P < 5 MW	Minimum	7.45	5.48	NA	1.09
	Average	21.62	12.35	NA	4.71
	Maximum	199.32	66.53	NA	13.87
	% Duration – V_{THD} exceeding 5%	100.0	100.0	NA	37.28
5 MW < P < 10 MW	Minimum	5.00	3.67	NA	0.71
	Average	6.58	5.61	NA	1.26
	Maximum	121.89	50.56	NA	3.10
	% Duration – V_{THD} exceeding 5%	100.0	67.21	NA	**0%**

Following observations are made on the behavior of I_{THD}.

i. Plant 01 – Average I_{THD} levels are completely out of the acceptable range during the period of measurement. It has gone very high when there is no active power generation (P). It has reduced by 75% when P is in kW range. The minimum I_{THD} of 5% is shown when P is at its maximum in MW range.

ii. Plant 02 – As same in Plant 01, average I_{THD} levels have gone has gone very high when there is no active power generation. It has reduced by 85% when P is in kW range. Further reduction is observed when P rises to MW range.

iii. Plant 03 – This plant shows the highest I_{THD} levels during $P \leq 0$. When $P>0$, distortion level has reduced and have reached permissible levels.

iv. Plant 04 – Plant 04 shows the lowest I_{THD} levels during $P \leq 0$ but still greater than 10%. The same level continues when P is in kW range which is much lower than Plants 01 and 02 but higher than Plant 03. Average I_{THD} level have fallen below 5% when active power generation rises to MW range and further reduces with increase of P. out of all four Plants, only I_{THD} levels in Plant 04 during P>5 MW fully satisfies the grid code requirement.

5.3.5 Voltage unbalance during steady state

Voltage unbalance factor was calculated for each Plant according to the NEMA definition where,

$$\text{Voltage Unbalance} = \frac{\text{Maximum deviation from the mean of } \{V_{ab}, V_{bc}, V_{ca}\}}{\text{Mean of } \{V_{ab}, V_{bc}, V_{ca}\}} \quad \text{------------------------------------(6)}$$

Voltage unbalance measured at WPPs lie within following range.

Plant 01	-	0.01 % - 0.61 %
Plant 02	-	0.08 % - 0.60 %
Plant 03	-	0.01 % - 0.75 %
Plant 04	-	0.18 % - 0.28 %

Permissible limit of unbalance factor for LV and MV systems as per IEC is <2%. As all four Plants lies within the allowable range, there are no power quality issues to be further considered regarding voltage unbalance.

5.3.6 Variation of Power Factor during Steady State

Only the variation of power factor when P>0 is considered in this section. According to the grid code of CEB, fluctuation of Power Factor of a wind farm should be at least between 0.80 lagging to 0.95 leading. Unless a specific reactive power support is requested in the grid interconnection proposal; the wind farm shall operate in the range of 0.98 leading to unity power factor. Failure to operate below 0.98 leading power factor shall result in imposition of a penalty.

Average and Maximum power factors when P>0 are given in Table 5.12 below.

Table 5.12 – Behavior of Power Factor

Power Category	Power Factor	Plant 01	Plant 02	Plant 03	Plant 04
0 < P < 850 kW	Average	0.66	0.07	0.02	0.54
	Maximum	0.96	0.76	0.03	0.90
850 kW < P < 5 MW	Average	0.96	0.97	NA	0.95
	Maximum	0.99	0.99	NA	0.99
5 MW < P < 10 MW	Average	1.00	0.99	NA	1.00
	Maximum	1.00	1.00	NA	1.00

Behavior of Power Factor (PF) when 0 < P < 850 kW is very poor at all four plants; especially at Plant 03. For Plants 01, 02 and 04, PF lies in acceptable range when active power generation rises to MW range.

Reactive power (Q) of each plant with respect to active power generation (P) averaged over suitable intervals are shown in figures 5.15 (a), (b) and (c). Positive Q values represent kVArs generated at WPPs and negative Q values represent kVArs drawn from the system. Extremely unacceptable reactive power consumption is shown at Plant 01. In this Plant, average reactive power flow is negative for all intervals of active power. But the consumption of Q at wind plant reduces with the increase of active power from P>850 kW.

Reactive power flow at Plant 02 has the same behavior except when P>5 MW, consumption of reactive power at wind plant further reduces and Q becomes positive when P>8 MW.

In Plant 03, measurements are available only for P<250 kW and has an unacceptable reactive power consumption. Only Plant 04 shows an acceptable reactive power flow which is positive except when P is between 9-10 MW.

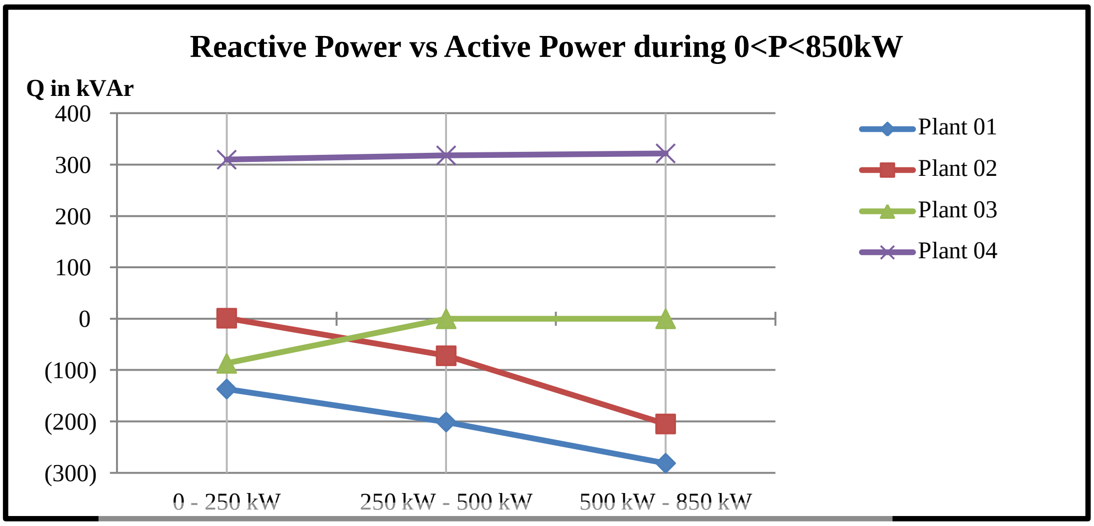


Figure 5.15 (a): Average Reactive Power vs Active Power during 0<P<850kW (Original in Colour)

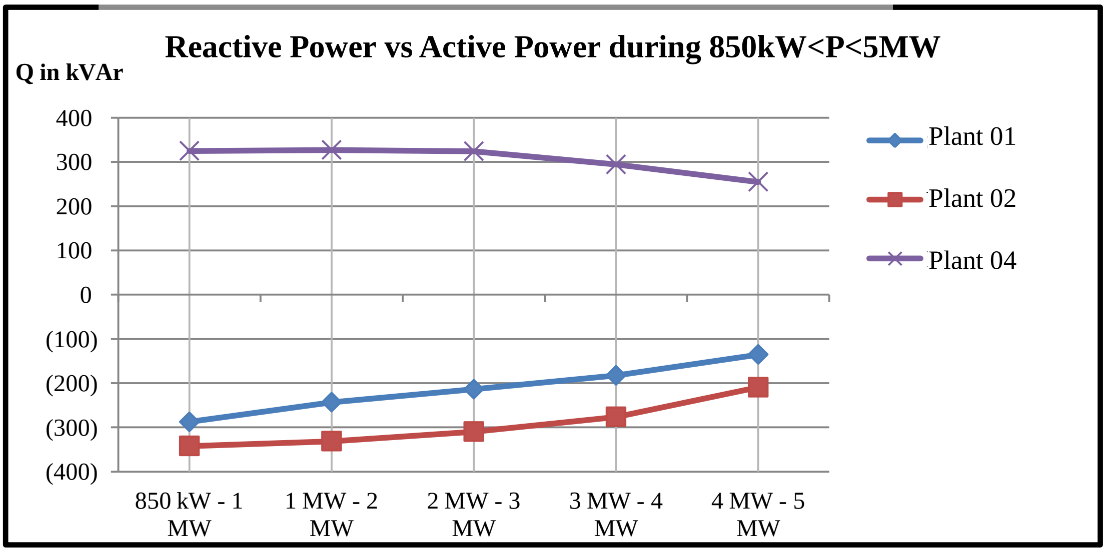


Figure 5.15 (b): Average Reactive Power vs Active Power during 850kW <P<5MW (Original in Colour)

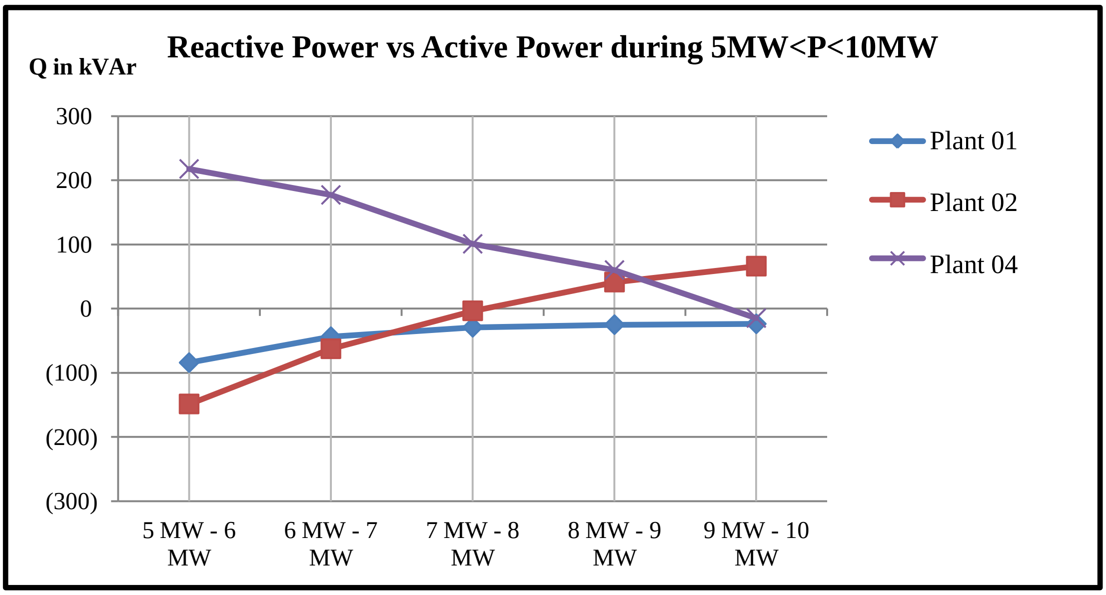


Figure 5.15 (c): Average Reactive Power vs Active Power during 5MW <P<10MW (Original in Colour)

5.3.7 Variation of Short Term Flicker Index (P_{ST}) during steady state

The usual threshold level for connecting wind turbines to grid is $P_{ST} \leq 1$. According to the Grid Code, P_{ST} should be ≤ 0.9.

As per the observations, when a wind plant comes to steady state after an immediate voltage disturbance or a few minutes after a voltage disturbance, the Short Term Flicker Index (P_{ST}) suddenly rises higher about 20-30. This scenario occurs due to high voltage fluctuations resulting from Voltage sag, Swell, Transient or an Interruption. This situation persists only for 1 minute at a time in Plant 01 and for about 10 minutes at a time in Plants 02 and 03. However, there are some random occurrences that $P_{ST} > 0.9$ when the plant's operation is in the middle of a steady state window. A brief analysis on these events is given below.

i. Plant 01 – P_{ST} has risen above 0.9 for 25 times with duration of 1 minute at a time during the measurement interval.

ii. Plant 02 – P_{ST} has risen above 0.9 for 7 times with duration of 10 minute at a time during the measurement interval. But, P_{ST} has not exceeded the allowable limit when active power generated by the WPP is in MW range.

iii. Plant 03 – P_{ST} has risen above 0.9 for 24 times with duration of 10 minute at a time during the measurement interval.

iv. Plant 04 – P_{ST} has risen above 0.9 for 28 times with duration of 1 minute at a time during the measurement interval.

Long Term Flicker Index (P_{LT}) is calculated as a rolling average of P_{ST} values over a two hour period. Compatibility level of P_{LT} for medium voltage networks is 0.8. Table 5.13 gives the range of Long Term Flicker Index at each Plant.

Table 5.13 :Variation of P_{LT} at each Plant

Plant	$\mathbf{P_{LT}}$
Plant 01	0.01 – 0.78
Plant 02	0.14 – 11.77
Plant 03	0.13 – 4.40
Plant 04	0.02 – 0.17

P_{LT} is within limits for Plant 01 and Plant 04 because violations of P_{ST} in these 02 Plants persist only for one minute at a time. As per above observations, all four wind plants have some power quality issues related to flicker.

Chapter 06

EVALUATION OF POWER QUALITY DURING VOLTAGE EVENTS AND IMPROVING TECHNIQUES

The objective of this research is to study about major power quality issues associated with four wind plants in Puttalam. The detailed data analysis was presented in chapter 05. From the results and observations of the data analysis, the behavior of power quality of each wind plant during voltage events is evaluated in this chapter. Basically, power quality of each plant is evaluated against the CEB Grid Code and a comparison among four Plant studies is carried out in order to identify the best wind technology for Sri Lankan power system. Improvements are suggested where necessary.

6.1 Power Quality during Voltage Events in Plant 01

Plant 01 is a type "D" WPP which employs synchronous generators. It has experienced two long interruptions that accounts for 8% of the duration of measurement. These interruptions have occurred due to network faults. Voltage sags have occurred immediately before or after an interruption. Since voltage sags have occurred in line with the interruptions, these sags can be considered as a part of the associated interruption.

6.2 Power Quality during Voltage Events in Plant 02

Plant 02 is also a type "D" WPP with synchronous generators. Most of the interruptions experienced at Plant 02 seem to have occurred due to internal faults of the WPP. There's one long interruption and a few short interruptions. Voltage sags have occurred when plant restores voltage after an interruption. Further, steady state operation of the plant has disturbed by two under voltage events resulted by a three phase fault.

Improve the internal installation and protection settings at Plants 01 and 02 are recommended to control interruptions. These two plants are located in a polluted environment with high salinity. Further, individual wind turbines of these plants are connected to the national grid via a 33 kV over head bare conductor line. A bare conductor line in a salty atmosphere causes frequent flashovers and breakdowns causing high number of interruptions at these two WPPs. Therefore, it is recommended to replace the bare conductor line with 33 kV Covered Conductor or Arial Bundle Conductor.

6.3 Power Quality during Voltage Events in Plant 03

Plant 03 is also a type “D” WPP but employs permanent magnet generators. Three short interruptions with durations of one minute have occurred at Plant 03. They have taken place in between two consecutive sags. In addition, the plant has experienced two under voltage events resulted by a three phase fault while the plant is operating in steady state.

6.4 Power Quality during Voltage Events in Plant 04

Plant 04; which is a type “C” WPP employing a Doubly-fed Induction Generator with a partial scale power converter have not experienced any voltage violations during the period of measurement. Recorded voltage waveform of Plant 04 is depicted in Figure 6.1.

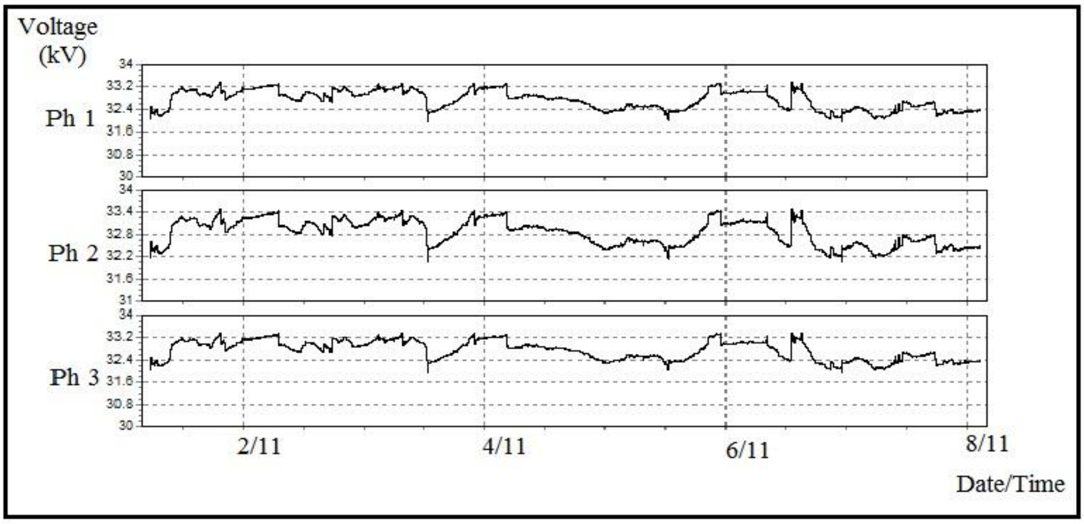


Figure 6.1: Voltage waveform measured at Plant 04

6.5 Performance Comparison of Voltage Events

A comparison on performance of wind plants against voltage events is illustrated in Figure 6.2. On the view of voltage variations, Plant 04 shows the best power quality as the operation of the plant is not disturbed by any voltage event. Plant 01 turns out to be the next finest plant. From the remaining two Plants, power quality at Plant 02 is better than power quality at Plant 03. The issue of voltage sag events at Plant 02 and Plant 03 needs to be addressed.

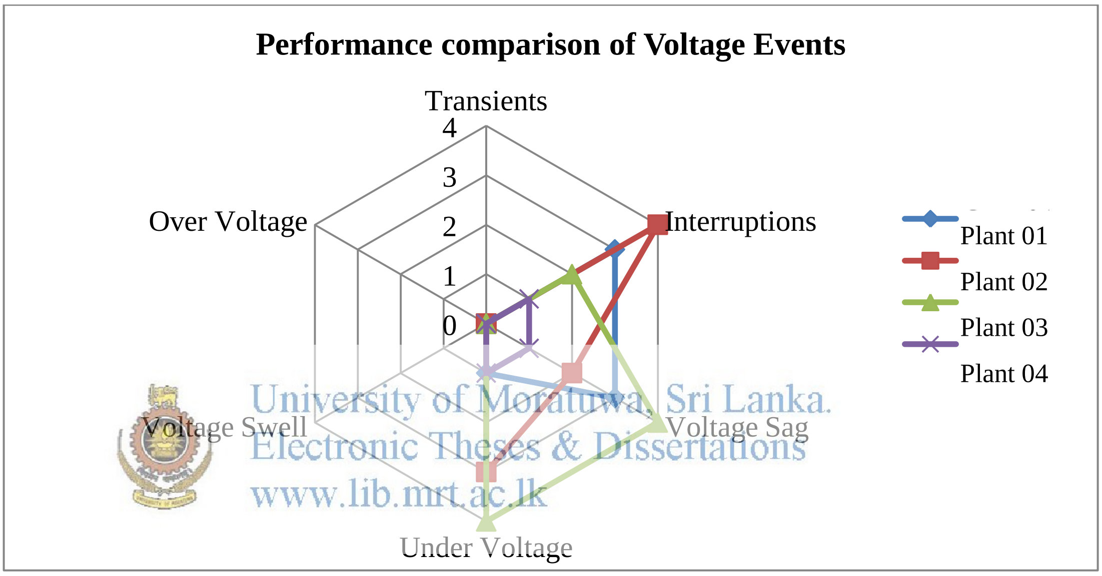


Figure 6.2: Comparison on performance of four Plants against voltage events (Original in Colour)

6.6 Simulation Results

These four wind plants are connected to CEB Network through two feeders as follows.

i. Plants 01 and 02 are connected to Puttalam GSS through a 14.7 km 33kV dedicated feeder (hereafter called as Palavi_F4).

ii. Plants 03 and 04 are connected to the 220/33 kV GIS Substation at Norochcholai through a dedicated 33kV feeder connecting all wind plants located in Kalpitiya peninsula. (hereafter called as Nor_WindF)

Simulation studies were done using Power System Simulation for Engineering (PSS/E) software and voltage profiles of the above two feeders were observed during following network faults.

i. A fault at the 33 kV line
ii. A fault at the 33 kV bus at the GSS
iii. A tripping of a generator unit at WPP

Figure 6.3 – 6.5 depicts the voltage profiles of each distribution feeders at fault events.

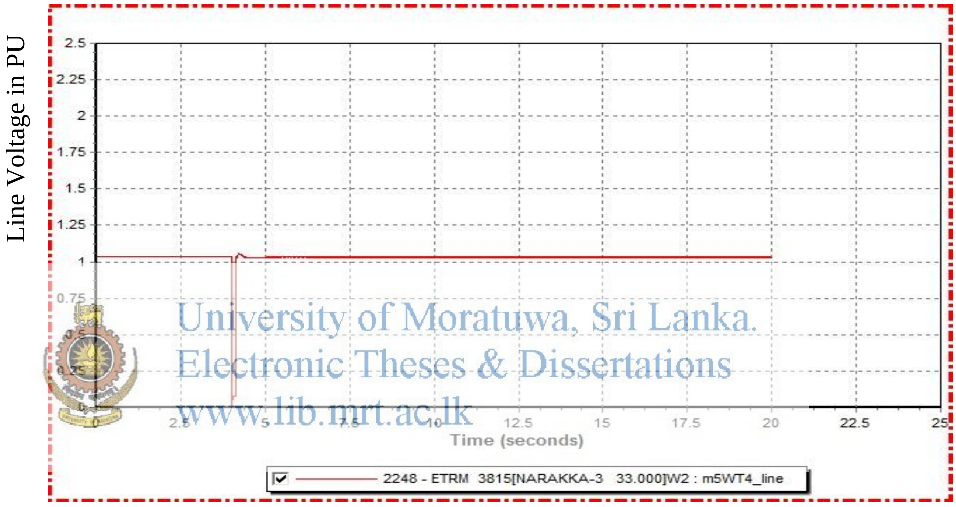


Figure 6.3(a) : Voltage during a line fault at Palavi_F4

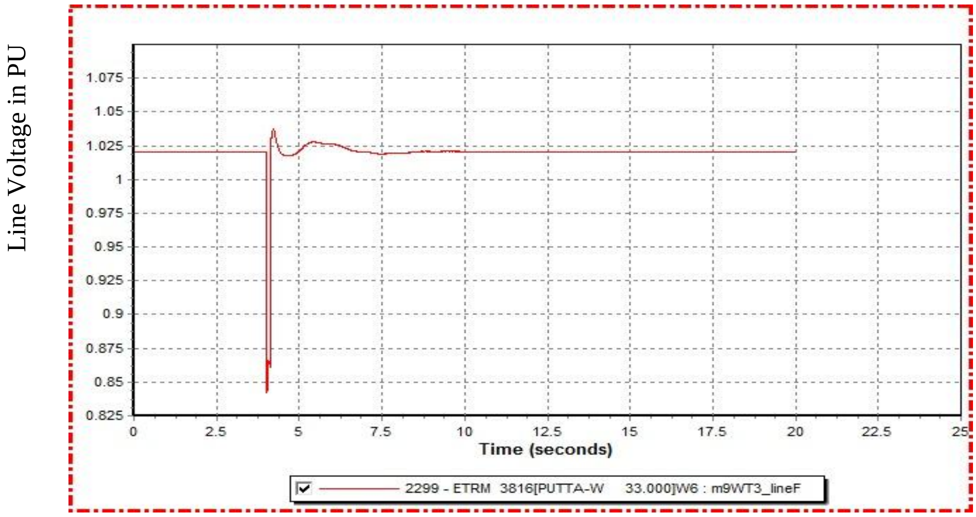


Figure 6.3(b) : Voltage during a line fault at Nor_WindF

Line fault at Palavi_F4 has resulted with a short interruption where the line fault at Nor_WindF causes a voltage sag of depth 0.84 pu. Both events last for a duration less than 0.5 seconds. A line fault at Palavi_F4 adversely affects the network than a line fault at Nor_WindF.

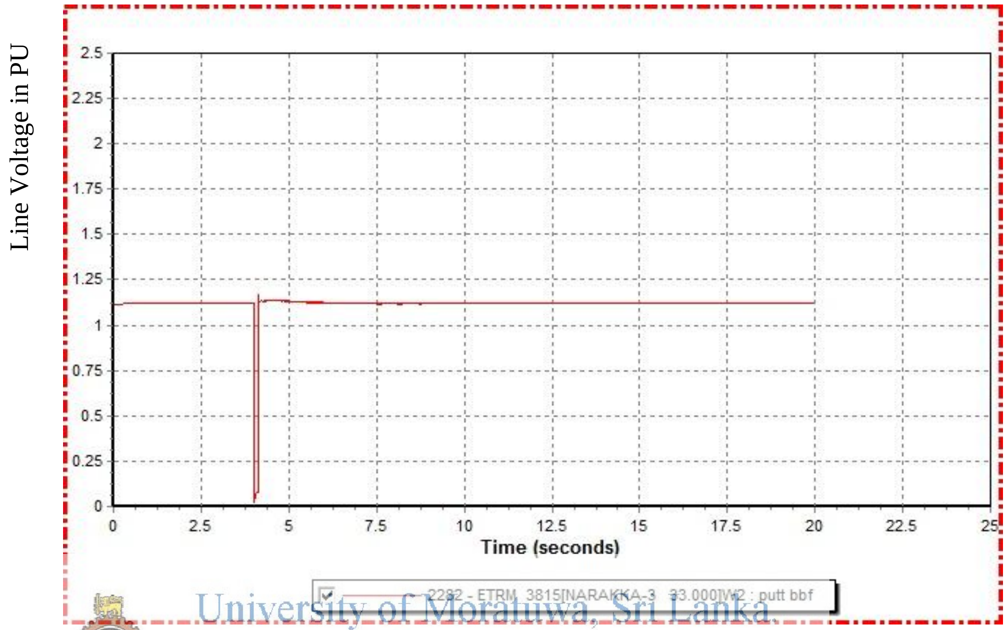


Figure 6.4(a) : Voltage during a bus fault at Palavi_F4

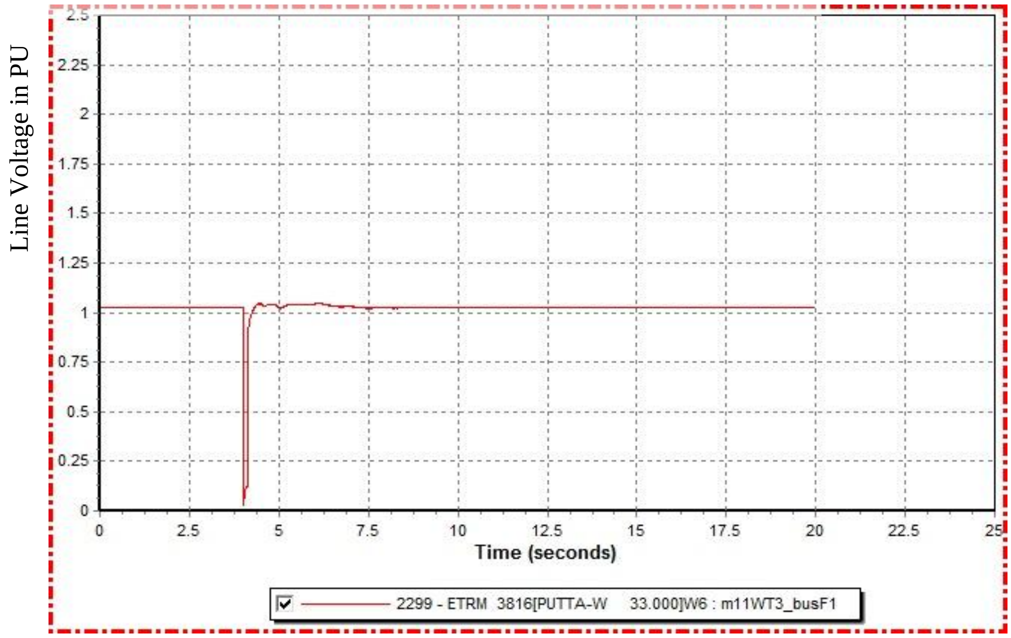


Figure 6.4(b) : Voltage during a bus fault at Nor_WindF

Bus fault at both feeders have resulted with short interruptions of duration less than 0.5 seconds.

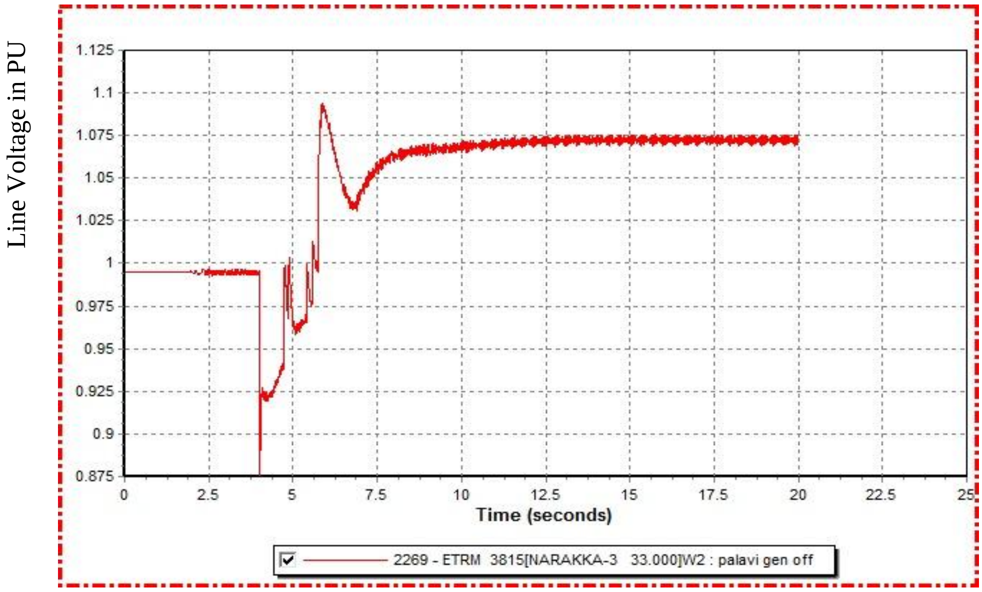


Figure 6.5(a) : Voltage during a tripping of a wind plant at Palavi_F4

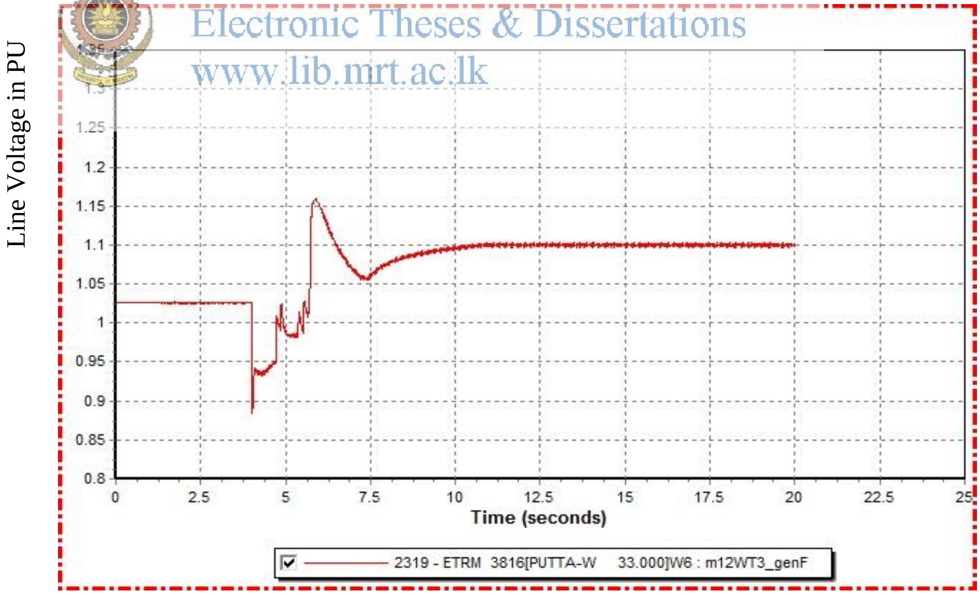


Figure 6.5(b) : Voltage during a tripping of a wind plant at Nor_WindF

The tripping of a wind plant has caused only a voltage fluctuation at both feeders.

6.7 Improving Voltage Sags in Wind Plants

If the wind turbines are properly equipped with soft starters, wind plants do not cause any voltage sags. But, voltage sags resulting from faults of the network have adverse impacts on the WPP. Voltage sags increase the current in the stator windings of the generator which in turn may lead to the destruction of the power converter. In addition, sags cause PMGs to increase its speed unlimitedly. Therefore, fast removal of the voltage sags is of high importance. Several researches have been carried out on mitigating voltage sags and swells at wind power plants and in transmission and distribution systems in general. The majority of the researches have proposed mainly two mitigation methods as follows. [54], [59]

1. Static Synchronous Compensator (STATCOM)
2. Dynamic Voltage Restorer (DVR)

6.7.1 Static Synchronous Compensator (STATCOM)

A static synchronous compensator (STATCOM) is a voltage source converter (VSC) based device. It helps a wind turbine to withstand voltage dips by controlling the active and reactive power injected to the grid. STATCOM basically consists of a VSC, a DC energy source (created from a DC capacitor in most of the Plants), a passive filter and a coupling transformer connecting the VSC to the distribution network and associated control system. In a wind plant, the STATCOM can be connected at the low voltage side of wind turbines allowing a huge cost reduction. A basic block diagram showing the installation of a STATCOM at a wind plant is given in Figure 6.6.

The control scheme of a STATCOM is designed to maintain a constant voltage at the PCC where the wind plant is connected under system faults and disturbances. When the terminal voltage of the converter is higher than the AC voltage at PCC, the STATCOM generates reactive current. On the other hand, when the amplitude of the voltage source is lower than the AC voltage, it absorbs reactive power. Passive filters are employed to suppress harmonics. In addition to mitigate voltage sags depending on the control strategy, STATCOM devices can be used to reduce flicker emission and harmonics. [58]

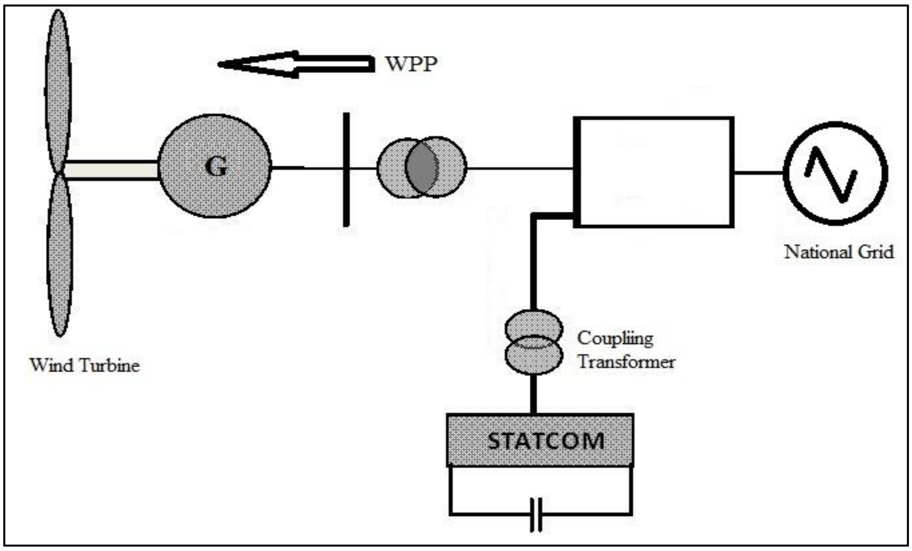


Figure 6.6 : WPP including a STATCOM connected at the PCC

6.7.2 Dynamic Voltage Restorer (DVR)

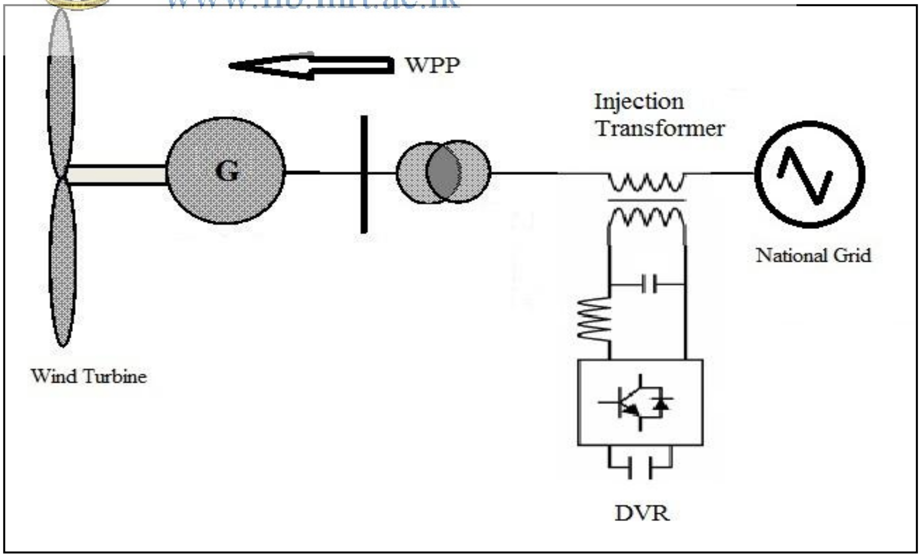


Figure 6.7 : WPP including a DVR connected at the PCC

A DVR mainly consists of following components.

i. Voltage Source Inverter circuit (VSI) – to supply required amount of voltage
ii. Low-Pass Passive Filter unit – to filter higher order harmonic components produced at the output of inverter due to semiconductor devices.
iii. Series Injection/ booster Transformer – to inject saged voltage into the grid while isolating the DVR circuit from the distribution network
iv. Energy storage Unit – Auxiliary supply for VSI
v. DC charging circuit
vi. Control and Protection System

The DVR has three basic operating modes as Protection mode, standby mode and injection mode. As soon as a voltage sag or a swell is detected, the DVR transfers into the injection mode and injects voltage equal to the difference between the voltage prior to fault and the fault voltage into the network thus; restoring pre-fault voltage during voltage sag/swell. A voltage sag/swell is associated with changes in both magnitude and phase angle. Therefore, the control technique should be designed to compensate voltage magnitude and phase shift as well. In addition to mitigating voltage sags/swells, a DVR is capable of performing other functions like compensation of harmonic, reduce voltage transients and fault currents. [59]

There are other different ways to mitigate voltage dips, swell and interruptions associated with wind connected distribution systems as; Distribution Static Compensator, Static Voltage Regulator (SVR), Static VAR Compensator, Soft Switching Line Conditioner and PWM-switched autotransformer. But, Static Synchronous Compensator (STATCOM) and the Dynamic Voltage Restorer (DVR) are the most effective devices, both of which are based on the Voltage Source Converter (VSC) principle and provide simultaneous power control and power quality functions. Either device can be connected at any distribution voltage level. However, the amount of harmonics injected from a system employing a STATCOM is higher than the harmonic emission of a system employing a DVR. [59]

Therefore, in the view of power quality; incorporating a suitable DVR is preferable.

Chapter 07

EVALUATION OF POWER QUALITY DURING STEADY STATE AND IMPROVING TECHNIQUES

From the results and observations of the data analysis presented in chapter 05, the power quality of each wind plant during its steady state operation is evaluated in this chapter. A special attention is given on harmonic distortion and each plant is evaluated against the CEB Grid Code and compared with each other to identify the most suitable wind technology for Sri Lankan power system. Improvements are suggested where necessary.

7.1 Behavior of Harmonics

Mainly, voltage and current harmonics emitted by each wind plant when the plants generate active power are evaluated under this section.

7.1.1 Harmonics in Voltage Waveform

7.1.1.1 Harmonic behavior at Plant 01

When active power generation (P) of the WPP varies from kW range to 5 MW, odd harmonic orders up to 17th harmonic order are within acceptable margin but even harmonics has violated the limits. From harmonic order 17-50, average percentages of voltage harmonics is high as 10% and the maximum percentage has risen to 30% which is extremely unacceptable. When 5 MW < P < 10 MW, all harmonic categories except “(n<11) odd harmonics” have exceeded allowable limits during entire measurement interval. Harmonic orders that a high harmonic content is detected are mentioned in Table 7.1.

During P < 0, average Total Harmonic Distortion levels of voltage (V_{THD}) are < 5%. During P > 0, average V_{THD} levels have gone above 7.5% and highest when (850 kW < P < 5 MW). When P is in MW range, V_{THD} has exceeded the maximum allowable limit of 5% for the entire period of measurement. Since the operation of the wind plant when it generates power closer to its maximum capacity is of main interest, the issue of harmonic distortion needs to be addressed.

7.1.1.2 Harmonic behavior at Plant 02

In Plant 02 when P is in kW range, only harmonic contents of harmonic orders 23-50 considerably exceeds the limit and maximum percentage has risen to 52.68%. When P rises from kW range to 5 MW, allowable limits of even harmonics for (n<23) have exceeded during the entire measurement interval. For 70% of the time, (17<=n<23) odd harmonics has risen due to high 17th harmonic. When n> 23, harmonic voltages have exceeded maximum limits during entire measurement interval. Averages are as high as 8.7% and the maximum has risen to 14%. When 5 MW < P < 10 MW, all harmonic categories except (n<11) odd harmonics have completely violated the limits. For harmonic order 23-50, average percentages of voltage harmonics are very high as 7.56%. Harmonic orders that a high harmonic content is detected are mentioned in Table 7.1.

Generally, Total Harmonic Distortion levels of voltage (V_{THD}) at Plant 02 are (6-10) % violating the allowable limit for the entire period of measurement. There are sudden V_{THD} hikes when the active power flow switches direction. During P > 850 kW, average V_{THD} levels have gone above 8%. Since the operation of the wind plant when it generates power closer to its maximum capacity is of main interest, the issue of harmonic distortion needs to be addressed.

7.1.1.3 Harmonic behavior at Plant 03

In this plant when P is in kW range, harmonic voltages of all harmonic orders are well below the maximum limits. Generally, V_{THD} is less than 5% but, there are sudden V_{THD} hikes when the active power flow switches direction and when the voltage difference between 02 consecutive records is larger than 1kV. For a few times, V_{THD} has risen to very high values above 100%. The duration showing this abnormal behavior is negligible therefore, V_{THD} in this plant can be considered as satisfactory. Since the maximum generation at the plant is 157.5 kW during the measurement period, it is not viable to comment on its harmonic behavior at higher generations.

7.1.1.4 Harmonic behavior at Plant 04

In Plant 04, average harmonic voltages are well below the maximum allowable limits for all power and harmonic categories. Average voltage THD level is below 1%. Even maximum voltage THD levels are within the limit during entire period of measurement. Therefore, voltage harmonic distortion in this plant is negligible.

A summarized comparison of the behavior of voltage harmonics for all four Plants is mentioned in Table 7.1 and Table 7.2.

Table 7.1 : Harmonic orders with a high voltage harmonic content

Harmonic category		**Plant 01**	**Plant 02**	**Plant 03**	**Plant 04**
0 < P < 850 kW	Odd Harmonics	NA	23-49	Nil	Nil
	Even Harmonics	02, 04, 14,16	24-50	Nil	Nil
850 kW < P < 5 MW	Odd Harmonics	17	17	NA	Nil
	Even Harmonics	02, 04, 08, 14, 16, 22	02, 04, 08, 14, 16, 22	NA	Nil
5 MW < P < 10 MW	Odd Harmonics	13, 17 & 23-49	13, 17 & 23-49	NA	Nil
	Even Harmonics	02, 14, 24-50	02, 14, 24-50	NA	Nil

Table 7.2 : Status of Voltage Harmonic levels at different harmonic categories

Harmonic Group	**Status of Voltage Harmonic level**			
	Plant 01	**Plant 02**	**Plant 03**	**Plant 04**
n<11 odd	**OK**	**OK**	**OK**	**OK**
n<11 even	OUT OF RANGE	OUT OF RANGE	**OK**	**OK**
11<=n<17 odd	**OK**	**OK**	**OK**	**OK**
11<=n<17 even	OUT OF RANGE	OUT OF RANGE	**OK**	**OK**
17<=n<23 odd	OUT OF RANGE	OUT OF RANGE	**OK**	**OK**
17<=n<23 even	OUT OF RANGE	**OK**	**OK**	**OK**
23<=n< 50	OUT OF RANGE	OUT OF RANGE	OUT OF RANGE	NA

All four wind plants use Power electronics converters that cause injection of harmonics into the power system. Harmonic emission during lower generations (kW range) is higher than in higher generations (MW range).

Plant 01 and Plant 02, which are identical wind plants in design and technical configuration, shows a similar behavior with regard to voltage harmonics. These two plants emit the highest amount of harmonics of four Plants with an average V_{THD} exceeding allowable limit for the entire period of measurements. Primarily these plants show a high 13th and 17th harmonics. In addition to that, high harmonic contents are shown in lower order of even harmonics and all higher order harmonics until n=50.

Voltage harmonic emission and distortion level at Plant 03 is acceptable. Since the maximum generation at Plant 03 is in kW range during the measurement period, it is not possible to comment on its harmonic behavior at higher generations. Plant 04 shows excellent voltage harmonic behavior with distortion levels well below the allowable maximum distortion.

7.1.2 Harmonics in Current Waveform

7.1.2.1 Harmonic behavior at Plant 01

Average harmonic currents have exceeded limits for all harmonic groups. Until P > 5 MW, harmonic currents have violated limits for the entire time interval. Largest harmonic currents are recorded when active power generation (P) of the WPP is in kW range. Least harmonic contents are when P is closer to plant's maximum generation. There are high 2nd, 4th, 5th, 13th and 17th Harmonics. Harmonic orders that a high harmonic current is detected under each power category are mentioned in Table 7.3 below. Total Harmonic Distortion levels of current (I_{THD}) completely violates the maximum allowable limit and generally > 10%. The minimum I_{THD} of 5% is shown when P is at its maximum. Sudden I_{THD} hikes are observed when the active power flow switches direction and when P jumps to MW range from kW range.

7.1.2.2 Harmonic behavior at Plant 02

As same as Plant 01, average harmonic currents have exceeded limits for all harmonic groups. Until P > 5 MW, harmonic currents have violated limits for 100% of the time interval. Largest harmonic currents are recorded when active power generation (P) of the WPP is in kW range and least harmonic contents are when P is closer to plant's maximum generation. All harmonic currents are comparatively high and gradually decreases from n=2 to n=50. Average I_{THD} levels have gone very high when there is no active power generation. It has reduced by 85% when P is in kW range. Further reduction is observed when P rises to MW range. However, Average I_{THD} completely violates the allowable limit and generally (6-10) %. The minimum I_{THD} of 3.7% is shown when P is at its maximum. Sudden I_{THD} hikes are observed when the active power flow switches direction.

7.1.2.3 Harmonic behavior at Plant 03

This plant shows the highest I_{THD} levels during $P \leq 0$. When P rises to few kilowatts, only (n<17 even) harmonic currents has violated the limits. When P>0, harmonic distortion level has reduced and reached permissible levels. I_{THD} hikes are observed when the active power flow switches direction and when the voltage difference between two consecutive records is larger than 1kV.

7.1.2.4 Harmonic behavior at Plant 04

Unlike other 03 plants, Plant 04 gives off a low even harmonic content than odd harmonics. Average harmonic currents have exceeded limits completely for all harmonic groups when $P \leq 850$ kW. Largest harmonic content is shown by $n < 11$ Odd harmonic group. When (850 kW $< P <$ 5 MW), only harmonic currents less than n= 11 has gone above acceptable margins. When P rises above 5 MW, harmonic currents are well below the maximum permissible limits.

I_{THD} levels at Plant 04 when P is in kW range are around 10% which is much lower than Plants 01 and 02 but higher than Plant 03. Average I_{THD} level have fallen below 5% when active power generation rises to MW range and further reduces with increase of P. Out of all four Plants, only I_{THD} levels in Plant 04 during P>5 MW fully satisfies the grid code requirement.

Harmonic orders that a high harmonic current is detected under each power category are mentioned in Table 7.3.

Table 7.3 - Harmonic orders with a high current harmonic content

Harmonic category		**Plant 01**	**Plant 2**	**Plant 03**	**Plant 04**
0 < P < 850 kW	Odd Harmonics	3, 5, 7, 13, 17, (27 – 49)	All current harmonics are comparatively high	05, 07	05, 07
	Even Harmonics	2, (26 – 50)		Nil	Nil
850 kW < P < 5 MW	Odd Harmonics	5, 7, 13, 17, (27 – 49)	5, 13, 17, (21 – 49)	NA	Nil
	Even Harmonics	2, 4, (26 – 50)	2, 4, (22 – 50)	NA	Nil
5 MW < P < 10 MW	Odd Harmonics	5, 13	05	NA	Nil
	Even Harmonics	2	02	NA	Nil

Similar to voltage harmonics, current harmonic content also reduces with the increase of power generation in all four Plants. Unlike voltage harmonics, current harmonic contents at Plant 01 and Plant 02 are different from each other. Still these two plants emit the highest amount of harmonics of four Plants. Plant 01 shows the highest distortion with $I_{THD} > 10\%$. I_{THD} is (6-10) % in Plant 02. Current harmonic distortion level has reached permissible levels in Plant 03. I_{THD} levels at Plant 04 have fallen below 5% only when P is in MW range.

As per above discussion, Plant 04 is the best performing wind plant which shows the lowest harmonic emission and distortion. It’s the only type “C” wind plant under investigation which employs DFIG technology. Harmonic distortion at this plant is minimized by the technology applied and due to the power electronics converter only rated at 30% of nominal generator power. Harmonic emission and distortion levels at Plant 03 are also acceptable with available generations. Plants 01 and 02 show highly unacceptable harmonic distortion levels in both voltage and current waveforms. A suitable harmonic mitigation technique should be immediately employed at these two wind plants to control harmonic injection to the power system.

7.2 Harmonics Mitigation Techniques

The harmonics voltages and currents should be limited to the acceptable level at the point of connecting wind plant to the power system. Techniques used to mitigate harmonic voltages and currents in power systems mainly fall into three categories. They are, [48]

i. Filtering Harmonic Components
ii. Cancellation of Harmonic currents
iii. Design considerations of equipment

Each of these approaches has their own advantages and disadvantages. Therefore, for a given configuration, the most appropriate mitigation technique should be determined after a detailed study on harmonics present at the particular installation.

7.2.1 Harmonic Filtering

An effective means of avoiding interference of harmonics generated by a WPP with the power system is to filter out Harmonic components. Harmonic filters connected to a power system has two main objectives as,

i. Reduce voltage and current harmonic components below permitted levels.
ii. Provide some of the reactive power absorbed by converter systems and hence improving power factor.

The selection of a harmonic filter must be based on System Configuration, Harmonic profiles and the kVA requirement of the installation. Basically there are four types of filter responses. [38] They are illustrated in Figure 7.1.

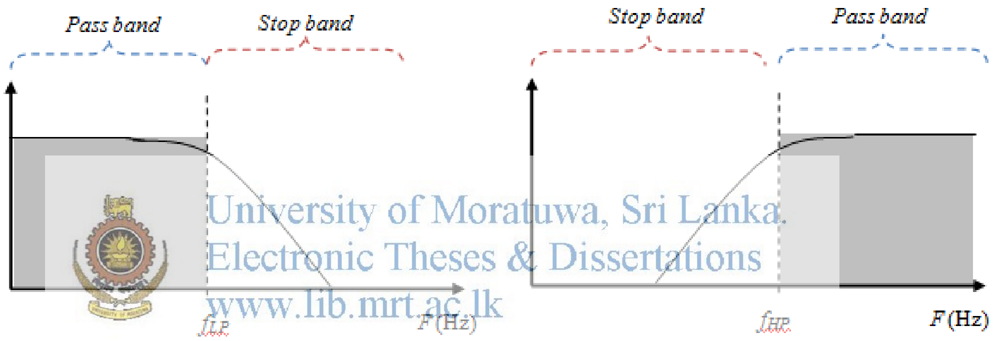


Figure 7.1 (a) – Low-Pass Filter Response

Figure 7.1 (b) – High-Pass Filter Response

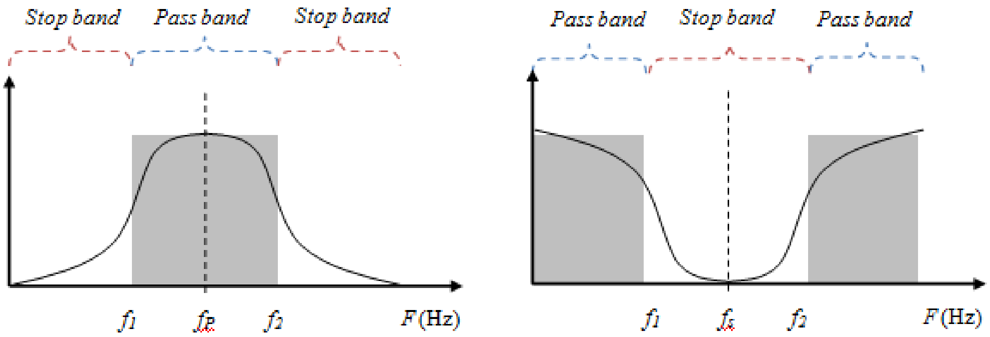


Figure 7.1 (c) – Band-Pass Filter Response

Figure 7.1 (d) – Band-Stop Filter Response

Figure 7.1 : Basic types of Filter Responses

Basic Harmonic Filter (HF) classification is as follows.

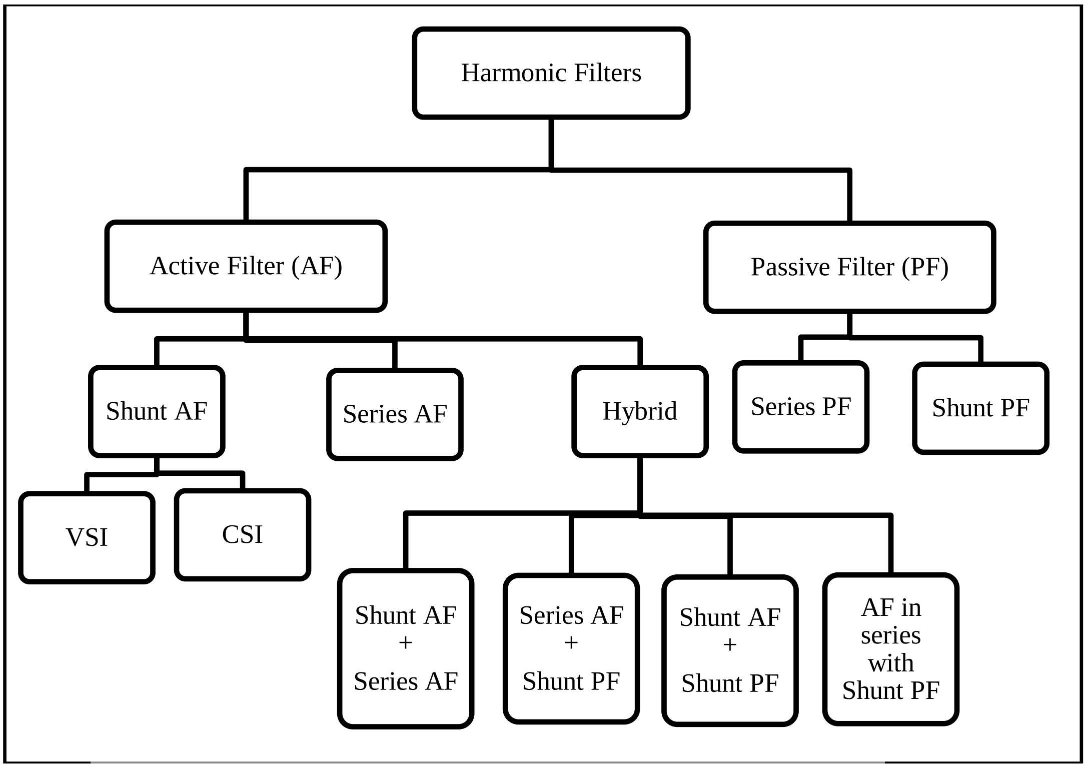


Figure 7.2 : Classification of Harmonic Filters

More details on each of these configurations are described in following sections. Basically, a Series connected HF compensates both harmonic currents generated by the harmonic source and the voltage distortion in the supply system. A series conditioner has to be sized for the total power rating. On the other hand, a Shunt conditioner needs to be sized only for the harmonic power.

7.2.1.1Passive harmonic filters

Passive filtering is the simplest conventional solution to mitigate the harmonic distortion in a power system. Passive harmonic filters, as the name specifies; are constructed from passive elements such as resistors, inductors and capacitors therefore, do not depend upon an external power supply. But, use of passive elements at high power levels makes the filter heavy and bulky. Passive filters provide a low impedance path for specific harmonic frequencies to flow out of the system. They offer a value-added function of achieving power-factor correction of inductive loads. But, sometimes passive filters do not respond properly to the dynamics of the power system. A passive filter should be installed as close as possible to the harmonic source to provide maximum protection for the upstream. Harmonics can be substantially reduced to 30% by using passive filters.

Passive filters can be classified into tuned filters and high-pass filters. The actual value of the low-impedance path for each single-tuned filter is affected by the quality factor of the filter inductor which determines the sharpness of tuning. Passive filters are much suitable for 3 phase 4 wire distribution systems. The combination of four single tuned filters for 5th, 7th, 11th and 13th harmonics and a second order high-pass filter tuned around 17th harmonic is a widely used filter configuration for a system with three-phase thyristor rectifiers. [48]

7.2.1.1.1 Series passive harmonic filter

The Filter is connected in series with the harmonic producing device. Harmonic current produced flows towards upstream of the power system. The Series Passive harmonic filter behaves as a current acceptor at its tuned frequency. It divides harmonic current in inverse proportion to the impedances according to Kirchhoff’s law. The purpose of series filter is to reduce the magnitude of harmonic current that flows back to the supply network. Consequently, harmonic voltage distortion would result. This configuration is popular for minimizing 3rd harmonic. Advantages and disadvantages of the Series Passive Filter are given in Table 7.4.

Table 7.4 : Advantages and Disadvantages of Series Passive Filter

Advantages	Disadvantages
Provides high impedance at tumed frequency	minimally effective for harmonics other than tuned frequency
Does not cause system resonance	Should be rated at fulll load current
Does not import harmonics from other sources	No limits in harmonic current therefore the risk of overloading
Improves Power factor	

7.2.1.1.2 Shunt passive harmonic filter

The Filter is connected in parallel with the source of harmonic distortion and provides a low impedance at its tunes frequency hence keeps harmonic currents out of the power system. It also provides some smoothing on voltage waveform. Shunt passive filters are the most common type of passive filter as they are cheaper compared to the series passive filters and carry only a part of the total load current. Advantages and disadvantages of the Shunt Passive Filter are given in Table 7.5.

Table 7.5 : Advantages and disadvantages of Shunt Passive Filter

Advantages	Disadvantages
Provides high impedance at tumed frequency	minimally effective for harmonics other than tuned frequency
only required to carry harmonic current and not the full load current	Can cause system resonance
Improves Power factor	No limits in harmonic current therefore the risk of overloading

A passive filter deals only with harmonic frequencies it was designed for. Therefore, Multiple filters are required to satisfy typical desired harmonic limits. More than one shunt or series passive filters can be used with or without each other in a power system. To overcome fixed compensation, large size, and resonance which are general drawbacks of passive filters, active filters appear as a dynamic solution.

7.2.1.2 Active harmonic filters

Active filters are made of both active and passive elements thus require an external power source. Active filters employ power electronic switching to filter harmonic components. They are self adapting and capable of filtering a wide frequency band. A great interest on active filters has come out due to wide availability of semiconductor devices such as IGBTs and Power MOSFETs with fast switching capability and analog-to-digital converters at reasonable prices.

An active harmonic filter involves a controller that detects the instantaneous feeder current. It extracts the harmonic current from the detected current by means of digital signal processing. Then the filter produces a waveform equal in amplitude and opposite in phase that cancels out the harmonics caused by nonlinear components. By this way, active filters can reduce harmonics by approximately 90%. Active filter is a flexible solution for any type of non linear load. They are widely used for compensation of variable frequency drives to reduce the effects of renewable energy sources on a grid. Unlike traditional passive filters, modern active filters are capable of performing multiple functions in addition to harmonic filtering as, [48]

i. Reactive-Power Control for Power Factor Correction and Voltage Regulation
ii. Load Balancing
iii. Flicker reduction
iv. Damping
v. Isolating

Active harmonic filters have following advantages over passive filters.

i. Reducing Total Harmonic Distortion by 90% where its only 30% in Plant of passive filters
ii. Improving overall power factor
iii. Not affected by frequency variations
iv. No risk of resonance
v. Don’t get overloaded
vi. High filtering performance
vii. Flexible in application - Adopts with variations in load and harmonic spectrum and can be programmed to filter specific harmonic frequencies.

Disadvantages of Active harmonic filters over passive filters are,

i. Higher cost
ii. Active filters are not preferred in filtering harmonics from small loads
iii. Switching frequency noise generated from fast switching devices and appear in compensated source current; requires additional filtering.

There are two types of power circuits applicable to active filters as Voltage-Source PWM Converter (VSC) and Current-Source PWM Converter (CSC). A VSC is equipped with a dc capacitor and a CSC is equipped with a dc inductor. In practical applications, voltage source converter is preferred over Current Source Converter as VSC shows high efficiency, smaller physical size and low cost.

A number of different configurations for the active harmonic filter have been proposed and some of them are in commercial stage at the moment. The main two configurations are briefly described in following sub sections.

7.2.1.2.1 Shunt active harmonic filter

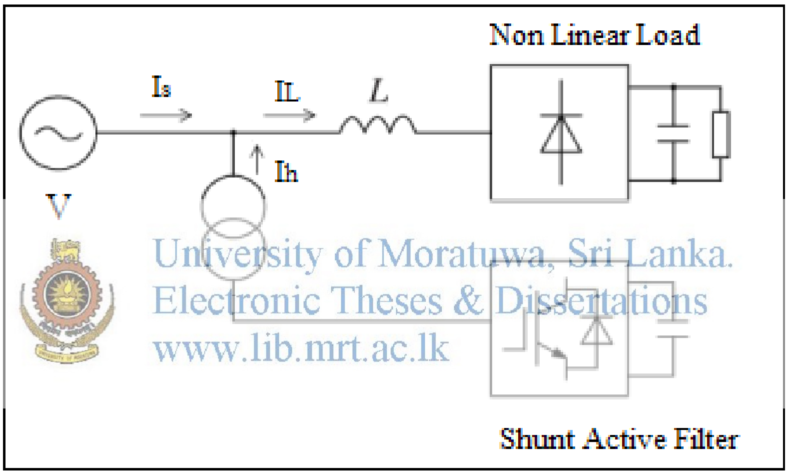


Figure 7.3 : Shunt Active Harmonic Filter

Shunt Active Filter is one of the most fundamental configurations of active filters. As illustrated in Figure 7.3, it is connected in parallel with the system therefore need to be sized only for harmonic power to be compensated. The Shunt Active Filter operates as a current source injecting equal and opposite (phase shifted by 180^0) harmonic compensating current thereby keep supply current sinusoidal. It generally supports harmonic orders from H5 to H25. With an appropriate control scheme, the Shunt Active Filter can compensate the load power factor. The main advantage of Shunt Active Filter is that it is of self limiting type in terms of harmonic cancellation provided. If the harmonic currents drawn by the non linear loads are greater than the filter rating, the filter automatically limits its compensating current to its maximum rating and will continue to correct up to the maximum current rating. The active filter will not get overloaded and will function continuously without damage. Shunt Active Filter technology has proven to be commercially successful.

7.2.1.2.2 Series active harmonic filter

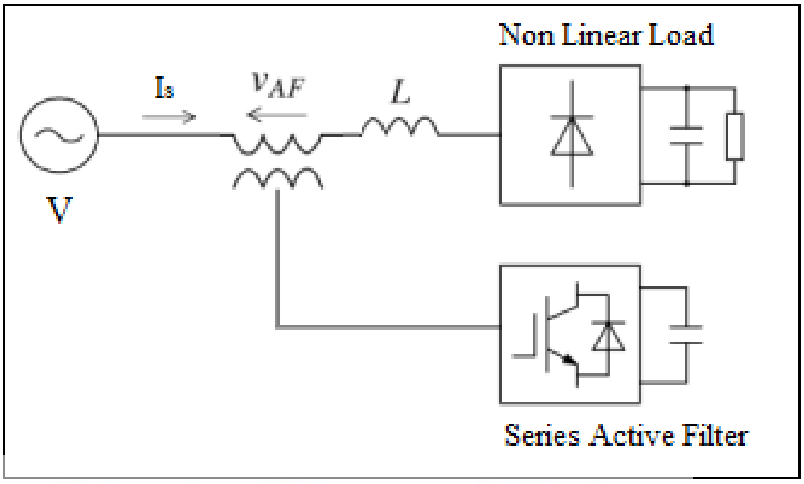


Figure 7.4: Series Active Harmonic Filter

The Series filter, as illustrated in Figure 7.4 is connected in series with the system through a transformer and acts as a voltage source. It compensates both harmonic current generated by the non-linear loads and voltage distortion present on the supply system. The Series filter must be sized for total load rating. The Series Active Filter technology is still in laboratory stage and not yet established in the market.

7.2.1.2.3 Hybrid active/ passive harmonic filters

The hybrid conditioner is a combination of an active filter and passive filters which may be either series or parallel type. It’s a good technical-economic solution for harmonic filtering combining advantages of both active and passive filtering. A hybrid filter offers cost effective high filtering performance covering a wide range of frequency band and power rating. Combination with the passive filter significantly reduces the rating of the active filter. Hybrid filtering is ideal for the conditions where both voltage and current harmonic distortion is present than conventional pure filtering.

In Hybrid Filters, harmonic filtering task is divided between two types of filters. The passive filter carries out basic filtering with tuned filters (5th, 7th order etc.), a high-pass filter for the higher order harmonics and the active filter; through its precise and dynamic technique, covers the other harmonic orders mainly lower order harmonics.

7.2.2 Harmonic Current Cancellation

Cancellation of harmonic currents is another effective harmonic suppression method that can be used in power systems. Transformers with phase shift can be employed to cancel out certain harmonic currents. Supplying harmonic producing loads with a Δ-Δ and a Y-Y transformer in parallel makes 5th and 7th harmonics cancel out at the PCC. This is due to the 30^0 phase shift between two transformer connections.

When information technology (IT) equipment is heavily in use, there will be a high content of triple-N (odd multiples of three) harmonics that can cause overloading of the neutral. Zig-zag transformers and delta wound isolation transformers are effective against triple-N harmonics but have no effect on other harmonics. [48]

7.2.3 Design Considerations of Equipment

Since the demand for power electronic devices is increasing day by day, it is essential to design those devices to minimize harmonic production thus ease the burden on the grid. With the issues of power quality, industries are tempted to utilize for devices with lower distortion. Significant technical improvements have been done on Adjustable Speed Drives, Uninterruptable Power Sources, Battery Charges and Fluorescent Lamp Ballasts recently. [48]

7.2.4 Recommended Harmonic Mitigation Method

In above Plants 01 and 02, both plants use a Six Pulse Bridge as the Full Power Converter. A Six Pulse Bridge theoritically produces harmonics with orders of $6n \pm 1$. [48] As the most appropriate harmonic mitigation method for above two Plants, my recommendation is to install a Hybrid Harmonic Filter consisting of a Shunt Active Filter with separately tuned filters for 5th, 7th, 13th and 17th harmonics.

Figure 7.5 illustrates the basic diagram of a hybrid filter consists of an active filter and a passive filter. The total filtering unit is connected in parallel with the network.

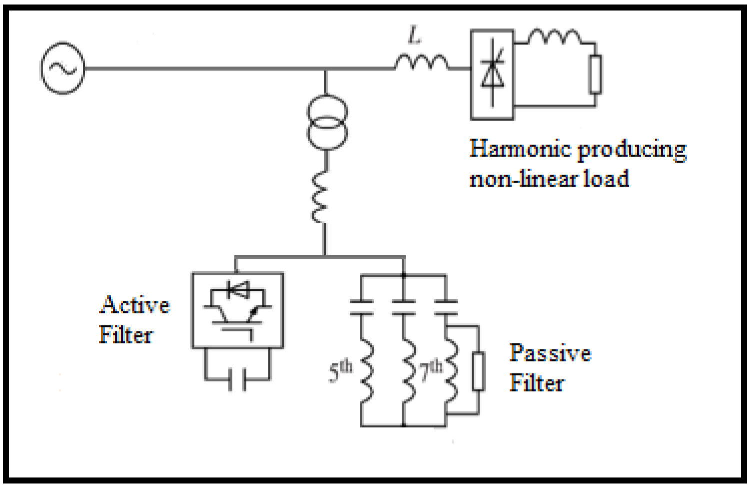


Figure 7.5: Hybrid Filter with an Active Filter and a Passive Filter

Chapter 08 describes the computer modeling and control of a shunt hybrid harmonic filter together with the results of the simulation carried out under the MATLAB/Simulink environment.

7.3 Flicker Emission and Mitigation

According to the data analysis, all four wind plants under investigation had issues related to flicker. The most preferable technique to mitigate the flicker is reactive power compensation. Hybrid filters proposed above for Plants 01 and 02 are capable of controlling reactive power and reducing flicker in addition to filtering of harmonics. As described under section 6.6, a suitable STATCOM device can be incorporated to reduce flicker emission at Plant 03 in addition to mitigating voltage variations. In Plant 04, the Short Term Flicker Index has risen above the specified maximum only for 0.3% of the measurement interval which is negligible. Further, the maximum recorded Long Term Flicker Index in Plant 04 is well below the limit therefore, incorporating mechanisms to mitigate flicker is not recommended at the moment.

7.4 Behavior of Power Factor and Power Factor Improvement

Methods used to improve power factor in power systems are briefly described under this section and suitable power factor improving methods are suggested for each Plant.

7.4.1 Power factor improving methods

Conventional devices and equipments used to improve the power factor in power systems are, [37]

i. Static Capacitor
ii. Synchronous Condenser
iii. Phase Advancer

7.4.1.1 Static capacitor

Installation of Static capacitor banks is the most widely used power factor correction technique, mainly by the industries. Capacitors are connected in parallel with the inductive loads which decreases system power factor. These capacitors provide leading capacitive current which decreases the lagging inductive component of load current partially or totally thus improving the power factor of the load circuit.

Capacitor banks offer several advantages like low loss, less or no maintenance, operating in normal atmospheric conditions and ease of installation. The major drawback of capacitor banks is the surges resulting when switching the capacitors. The capacitors have a short life time (8-10 years) and when capacitors are damaged, repairing them is highly uneconomical.

7.4.1.2 Synchronous condenser

An over-excited synchronous motor running on no-load is called a Synchronous Condenser. When connected in parallel with the power system, it behaves as a capacitor and draws a leading current and partially eliminates the lagging reactive current, thus improving the power factor of the circuit. [37]

7.4.1.3 Phase Advancer

Phase Advancer is an AC exciter used to improve the power factor of induction motors. The power factor of an induction motor is low as the stator winding draws exciting current that is lagging behind the supply voltage by 90°. When exciting ampere-turns are provided by means of a Phase Advancer, the induction motor operates on leading power factor as an over-excited synchronous motor. To achieve this, the Phase Advancer should be mounted on the main shaft of the motor and connected to the rotor circuit of the motor.

7.4.2 Improving Power Factor at Wind Plants

In Plants 01 and 02, power factor is closer to unity when active power generation is in MW range. But in average, a high reactive power consumption is shown at both Plants. Therefore, power factor improvement at these two plants is essential. Since Active Filter units are capable of Power Factor Correction and Voltage Regulation in addition to harmonic filtering, the hybrid filters proposed under 7.1.4 for harmonic mitigation can be employed for power factor improvement in these two Plants.

Plant 03 shows the poorest power factor of the four Plants. To improve the power factor, a suitable STATCOM device as described under section 6.6 can be utilized. Plant 04 has the best power factor variation but still needs to be improved. Since there is no other suggested power quality improvements for Plant 04 to combine, an appropriate power factor improvement technique as the “Phase Advancer” can be employed.

7.5 Comparison of Wind Plants during Normal Operation

An overall comparison on performance of four wind plants under study during their normal operation is illustrated as a radar chart in Figure 7.6.

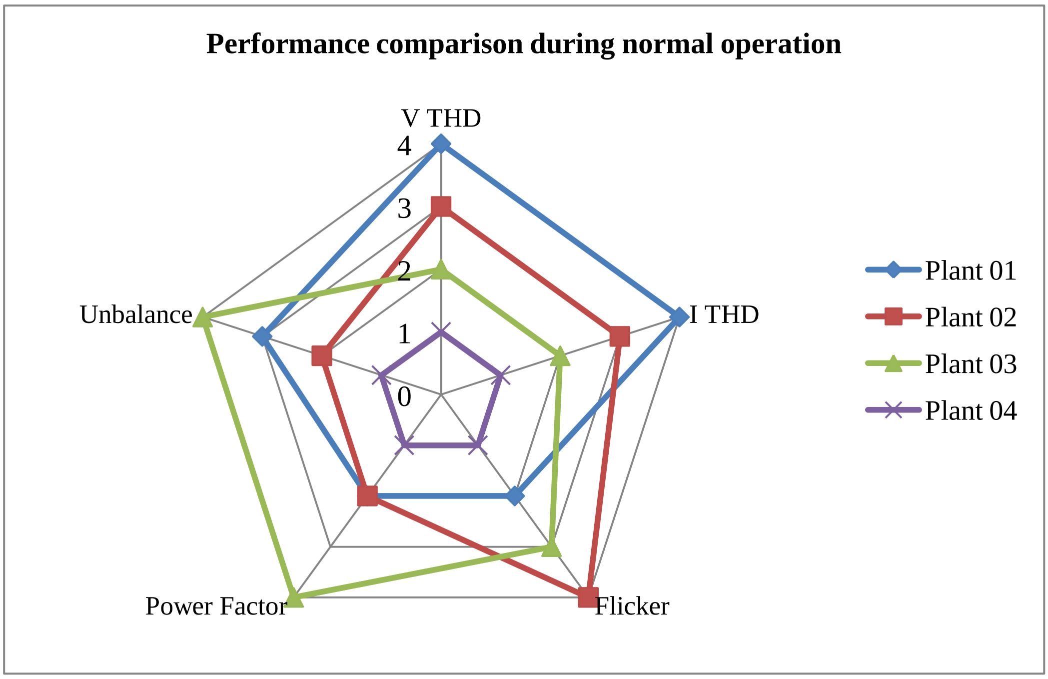


Figure 7.6: Performance comparison of four wind plants during their normal operation (Original in Colour)

As per above illustration, Plant 04 shows the overall best power quality characteristics during normal operation as well.

Chapter 08

COMPUTER MODELING AND SIMULATION OF A HARMONIC FILTER

After discussing Harmonic Distortion Levels of the four wind plants under investigation in Chapter 05 and various mitigation techniques in Chapter 07, this chapter describes computer modeling and simulation of a Shunt Harmonic Filter. Modeling and simulation is done in MATLAB/ SIMULINK V 7.7 environment. The Name MATLAB stands for MATrix LABoratory. Simulation studies were very useful at this stage of the research to evaluate distortion levels and to propose and analyze possible improvements.

As mentioned under clause 7.2.4 in Chapter 07, a shunt hybrid filter is proposed as the most effective harmonic mitigation method among various techniques available. The filter described in this chapter consists of a Shunt Active Filter and a Passive Filter. Development of the model and simulation results is explained below.

8.1 Development of the Computer Model

The Active Filter uses power electronic switching to generate harmonic currents that cancel out the harmonic currents in the power system. Shunt Active Filter operates as a current source that injects equal and opposite harmonic compensating current into the system. It consists of two sub units as the “Controller” and the “Converter”. The Controller detects the instantaneous output current of the wind plant and extracts its harmonic component to be eliminated. Then, an inverter is used to generate the compensating current.

The complete computer model was developed in number of steps corresponding to the development of main components of the filter unit and the power system. The output of the Wind Plant was modeled using actual plant parameters and measured data. Equivalent circuit of the Power System was developed using fault levels at the Grid Substation at Palavi. The system feeds a 1 MW inductive bulk load at 33 kV level.

8.1.1 Development of the controller for harmonic detection and Generation of gate signals

In order to determine the harmonic content of the current waveform, method of "Filtering the Fundamental" was used among various techniques available. In this method, the feeder current is filtered by a band-stop filter, which removes the fundamental. A single Butterworth filter unit available in "Analog Filter Design" block set with a bandwidth of 5Hz was utilized for each phase to create the band-stop filter.

After extracting harmonic content from the feeder current, a Voltage-fed PWM inverter (VSI) is used to generate the compensating current. A bipolar triangular waveform with a high frequency is used as the carrier signal to generate gate pulses for the PWM inverter. The reference signal generated by the controller is compared with the carrier signal and normalized between 0 and 1. The basic block diagram of the Controller and Gate Signal Generator is shown in Figure 8.1.

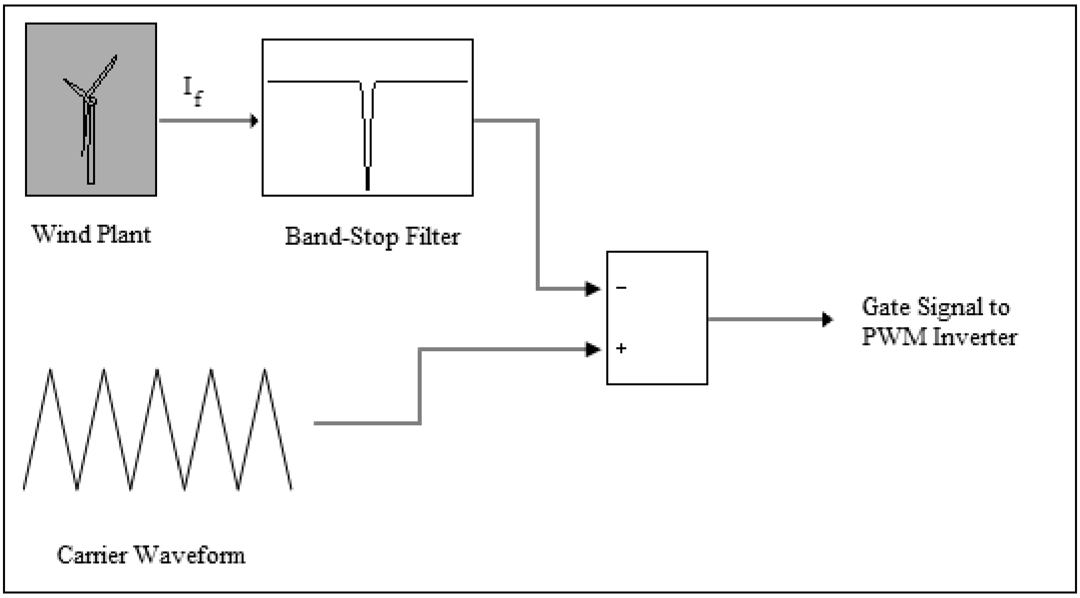


Figure 8.1 : Basic Block Diagram of the Controller and Gate Signal Generator

When the Reference Waveform is larger than the Carrier Signal, the gate pulse is negative DC and when the Reference Waveform is smaller than the Carrier Signal, the gate pulse is positive DC. This is illustrated in Figure 8.2.

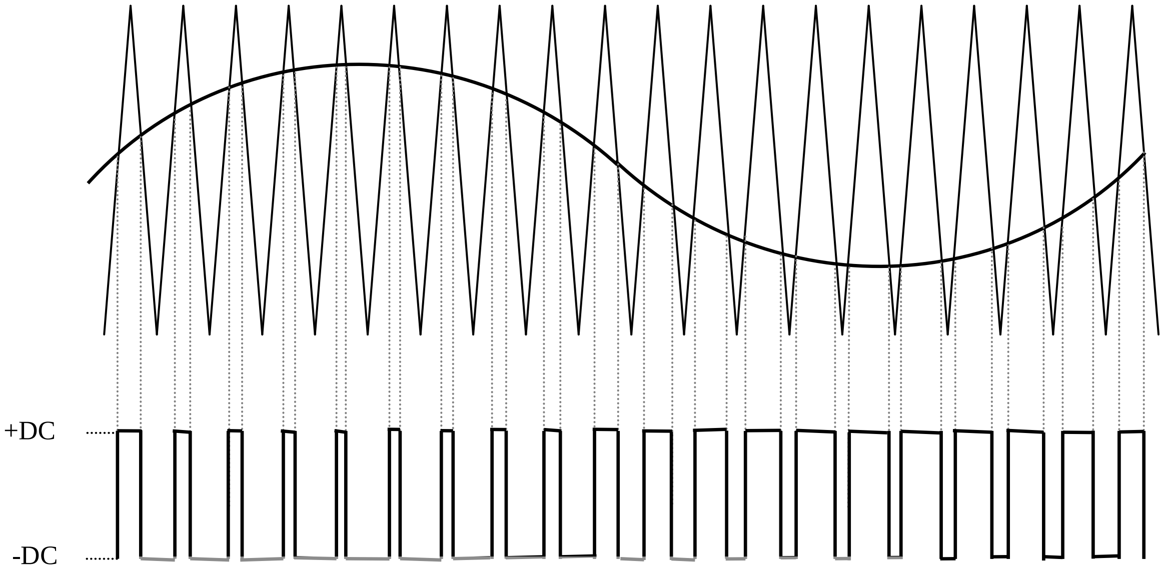


Figure 8.2 : Generation of the Gate Signal by Pulse Width Modulation

8.1.2 Development of the Voltage Fed PWM Inverter (VSI)

The Voltage Fed PWM Inverter was developed using the "Universal Bridge" block available in the "Power Electronics" library and it implements a three phase inverter consisting of six power switches. Insulated Gate Bipolar Transistor (IGBT) Switches were used as the switching device. Six gate pulses generated by PWM (Pulse Width Modulation) are given to the inverter as switching signals for the IGBT Switches. The inverter input DC voltage was modeled using the "DC Voltage Source" block available in "Electrical Sources" library. The compensating current waveform produced by the inverter was fed to the system through a current injecting transformer to cancel out the harmonics in the feeder.

8.1.3 Development of the Passive Filter

According to Chapter 07, a Passive Filter with tuned filters for 5th, 7th, 13th and 17th harmonics is proposed for both Plant 01 and Plant 02. The Passive Filtering unit was developed using the "Three Phase Harmonic Filter" block available in Power System Elements library.

The complete block diagram of the model is shown in Figure 8.3.

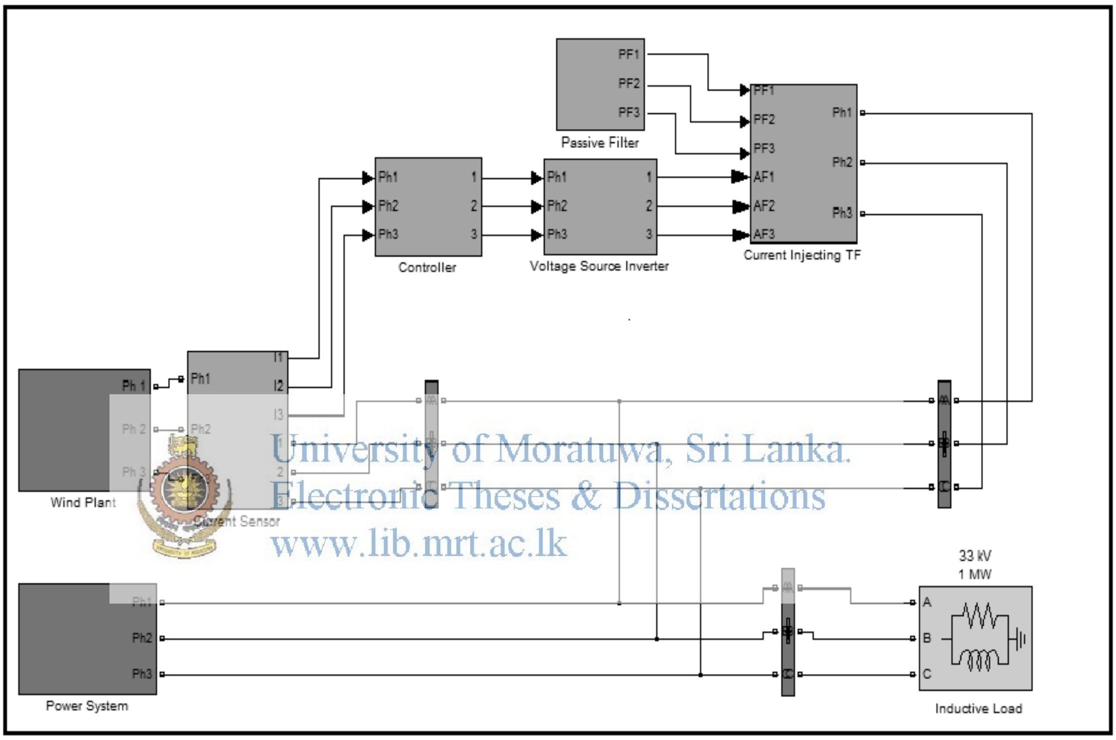


Figure 8.3: Block Diagram of the Complete System Model

8.2 Simulation Results

The current waveform of the wind plant is shown in Figure 8.4. The distortion level is selected as 14% to represent the average Current Harmonic Distortion (THDI) recorded at Plants 01 and 02. Fundamental component of the current is 46 A.

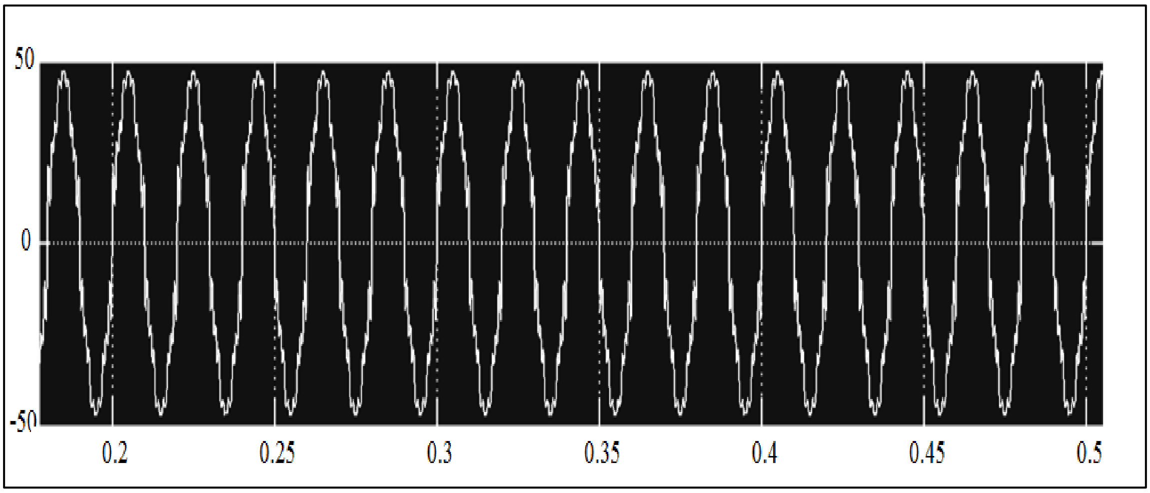


Figure 8.4 : Current waveform from the Wind Power Plant (Phase 01)

Figure 8.5 shows waveforms of the detected feeder current by the controller, subtracted fundamental component of 50 Hz and the harmonic content respectively.

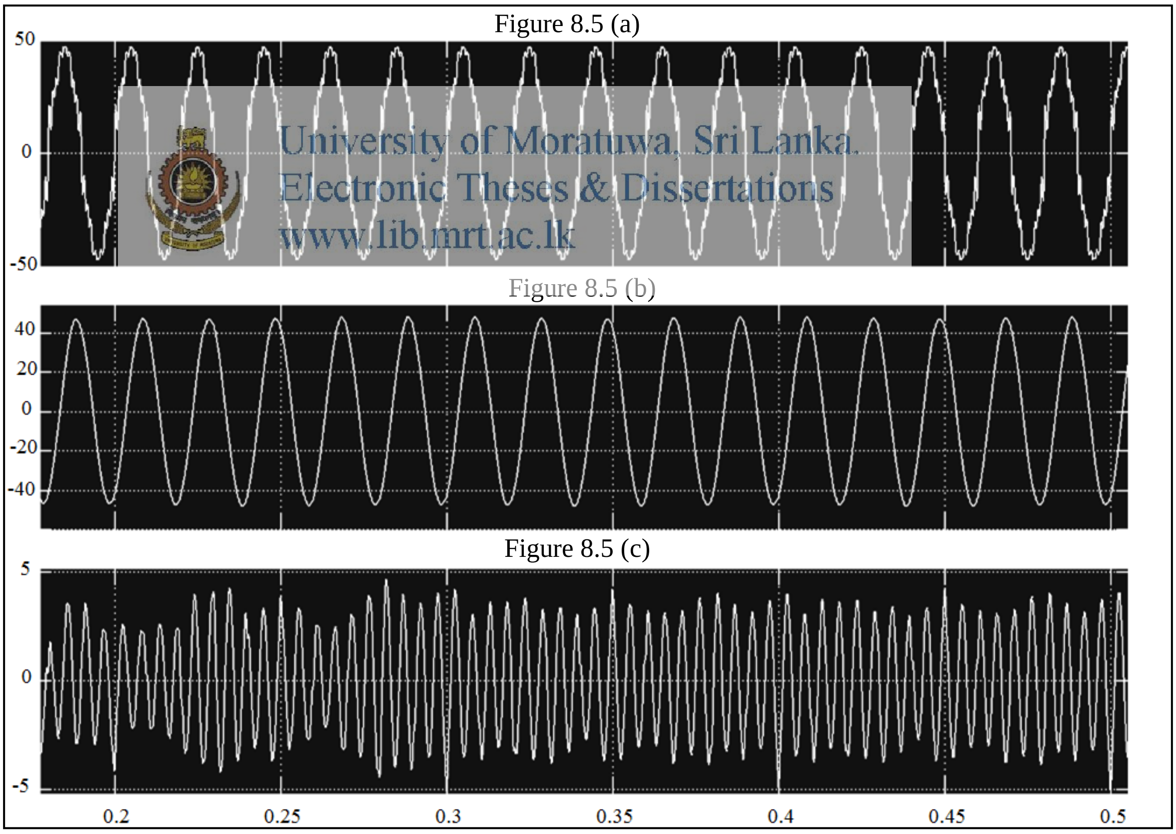


Figure 8.5 (a)

Figure 8.5 (b)

Figure 8.5 (c)

Figure 8.5: (a) Feeder Current (b) Fundamental component of the Feeder Current (c) Harmonic component of the Feeder Current

After extracting the harmonic componenets of the feeder current by the controller, the Voltage-fed PWM inverter generates the harmonic compensating current. The compensating current is equal in magnitude to the extracted harmonic signal and phase is shifted by 180^0. These two waveforms obtained at the simulation is shown in Figure 8.6.

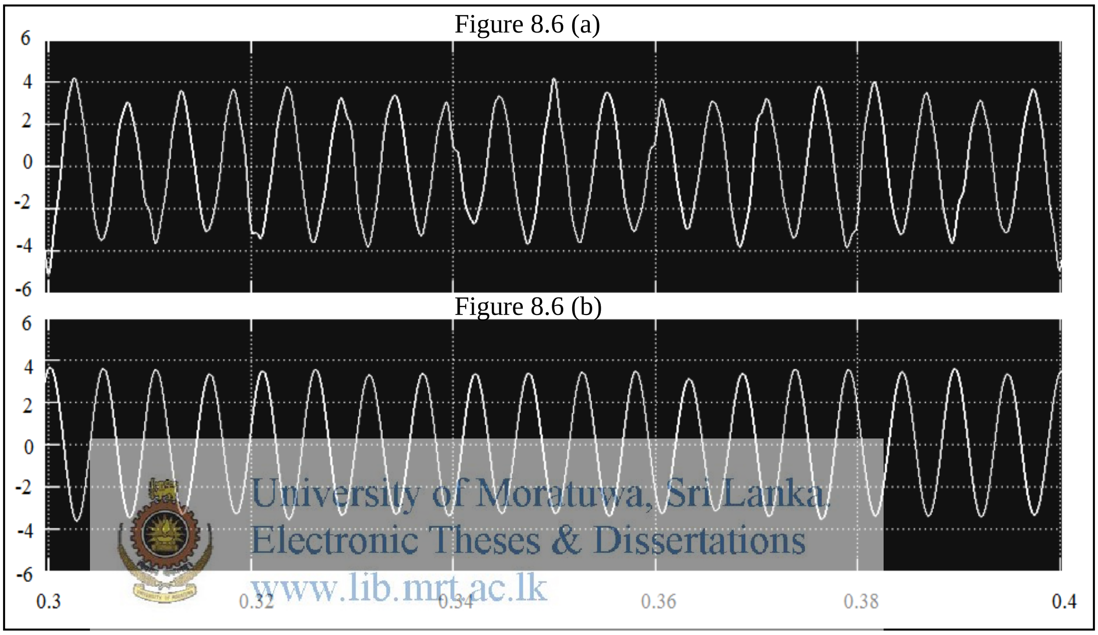
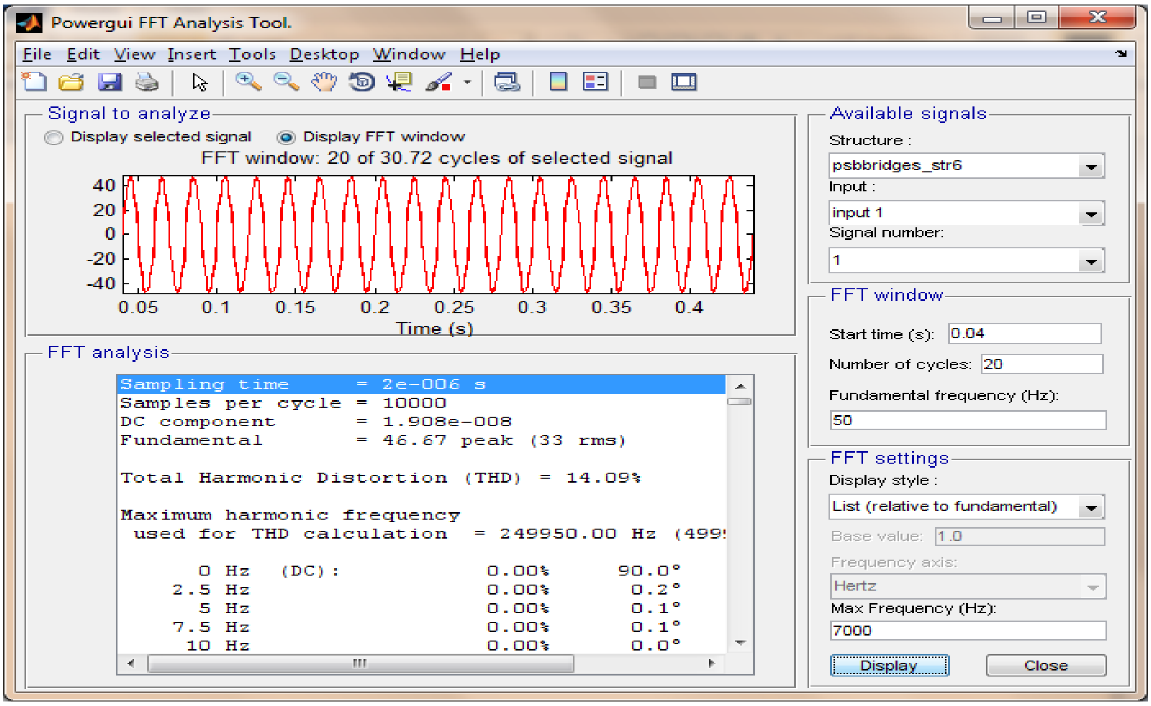


Figure 8.6: (a) Harmonic component of the Feeder Current
(b) Compensating Current generated by the VSI

The frequency spectrums and distortion levels of the waveforms were analysed using the "FFT analysis tool" available in the Power Gui Block. The fundamental component and total harmonic distortion (THD) of the selected waveform are displayed in the spectrum window. Harmonic contents are displayed as a percentage of the fundamental component. Figures below shows these properties of the feeder current before and after harmonic filteration. It is observed that the filter unit has reduced the Source THDI of 14% to 2% which is well below the allowed maximum THD of the Grid Code of 5%.



○ Display selected signal ● Display FFT window

```
Sampling time          = 2e-006 s
Samples per cycle = 10000
DC component           = 1.908e-008
Fundamental            = 46.67 peak (33 rms)

Total Harmonic Distortion (THD) = 14.09%

Maximum harmonic frequency
 used for THD calculation   = 249950.00 Hz (499!

     0 Hz   (DC):               0.00%      90.0°
   2.5 Hz                       0.00%       0.2°
     5 Hz                       0.00%       0.1°
   7.5 Hz                       0.00%       0.1°
    10 Hz                       0.00%       0.0°
```

Structure : psbbridges_str6

Input : input 1

Signal number: 1

Start time (s): 0.04

Number of cycles: 20

Fundamental frequency (Hz): 50

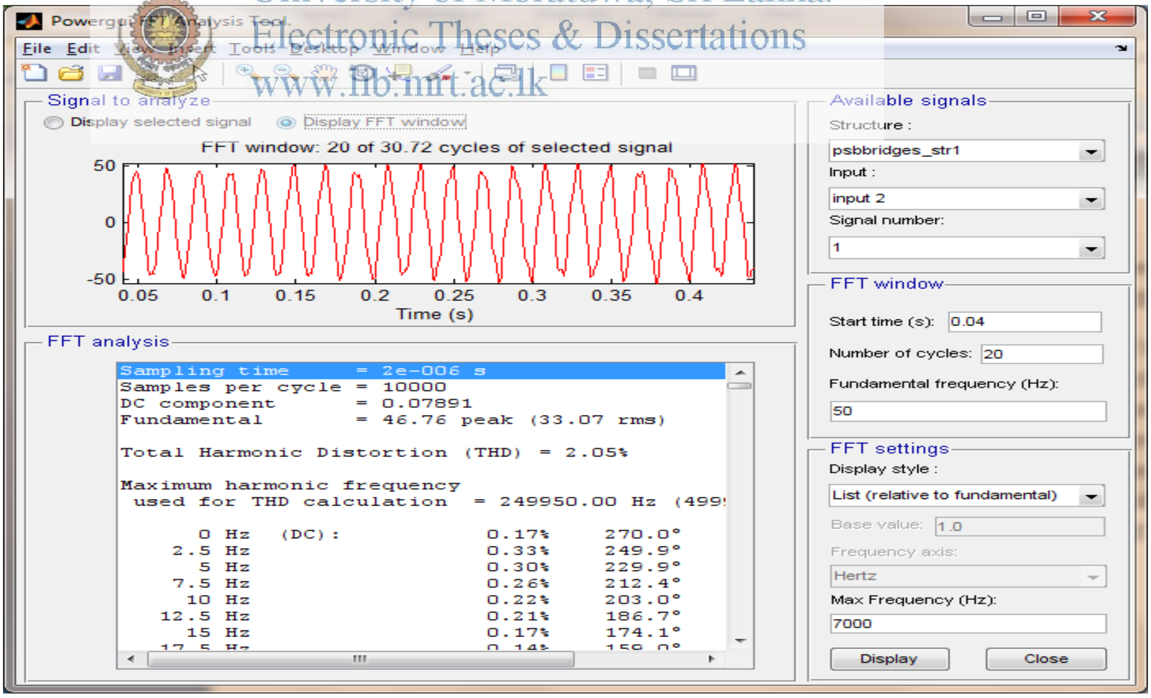
Display style : List (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 7000

Figure 8.7 : FFT Analysis of the Current from the Wind Power Plant (Original in Colour)



○ Display selected signal ● Display FFT window

```
Sampling time          = 2e-006 s
Samples per cycle = 10000
DC component           = 0.07891
Fundamental            = 46.76 peak (33.07 rms)

Total Harmonic Distortion (THD) = 2.05%

Maximum harmonic frequency
 used for THD calculation   = 249950.00 Hz (499!

     0 Hz   (DC):               0.17%     270.0°
   2.5 Hz                       0.33%     249.9°
     5 Hz                       0.30%     229.9°
   7.5 Hz                       0.26%     212.4°
    10 Hz                       0.22%     203.0°
  12.5 Hz                       0.21%     186.7°
    15 Hz                       0.17%     174.1°
```

Structure : psbbridges_str1

Input : input 2

Signal number: 1

Start time (s): 0.04

Number of cycles: 20

Fundamental frequency (Hz): 50

Display style : List (relative to fundamental)

Base value: 1.0

Frequency axis: Hertz

Max Frequency (Hz): 7000

Figure 8.8 : FFT Analysis of the Filtered Feeder Current (Original in Colour)

Two Harmonic Spectrums of the feeder current before and after harmonic filteration is shown in Figure 8.9 and Figure 8.10 respectively. Harmonic currents are presented as a percentage of the fundamental to simplyfy the comparison.

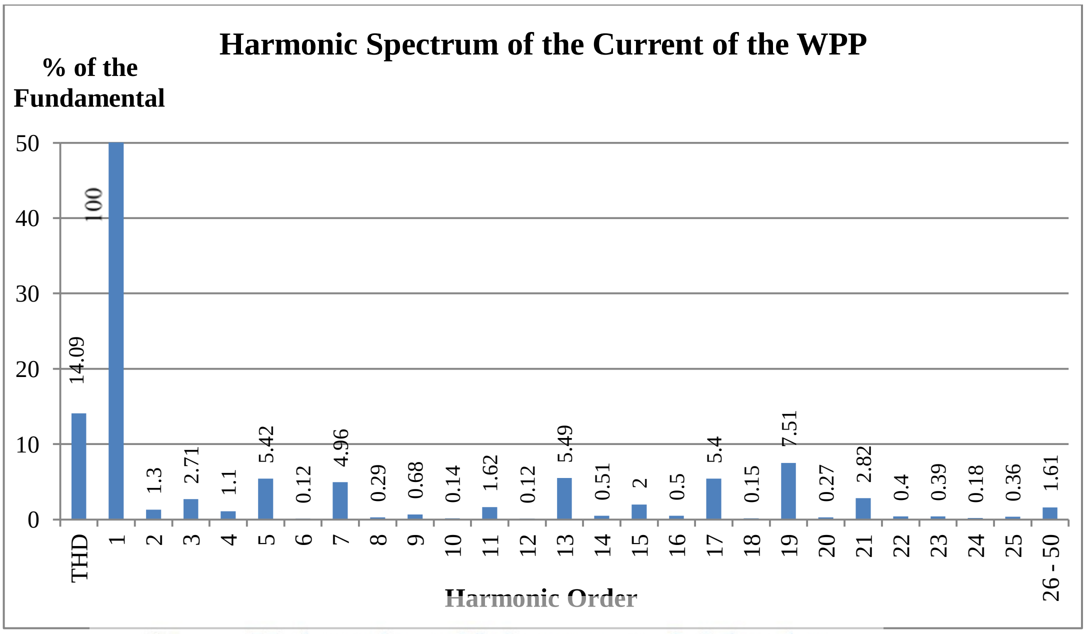


Figure 8.9 : Harmonic Spectrum of the Current Output of the Wind Plant

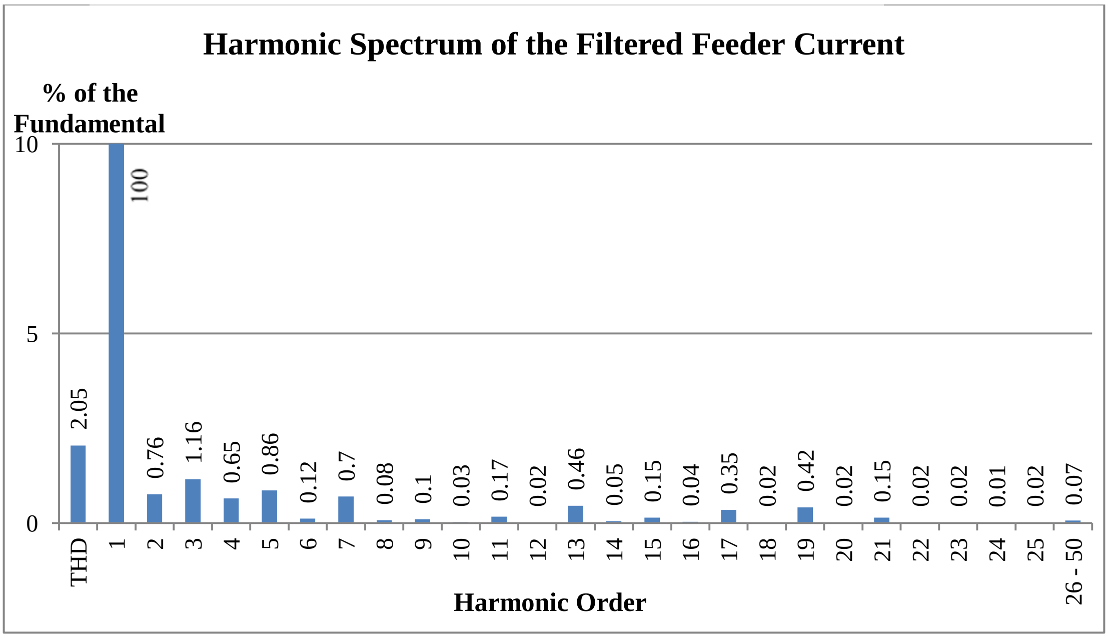


Figure 8.10 : Harmonic Spectrum of the Filtered Feeder Current

Harmonic levels of all harmonic orders have been reduced after the installation of the filter unit. Percentage reductions of the major harmonic currents are shown in Table 8.1.

Table 8.1 : Comparison of the Harmonic contents of the Feeder Current before and after Harmonic Filter.

Harmonic Order	**Before Harmonic Filter**	**After Harmonic Filter**
THDI	14.09 %	2.05 %
03	2.71 %	1.16 %
05	5.42 %	0.86 %
07	4.96 %	0.70 %
11	1.62 %	0.17 %
13	5.49 %	0.46 %
15	2.00 %	0.15 %
17	5.40 %	0.35 %
19	7.51 %	0.42 %
21	2.82 %	0.15 %

Resulting feeder current after the harmonic filter; which is almost sinusoidal is shown in Figure 8.11.

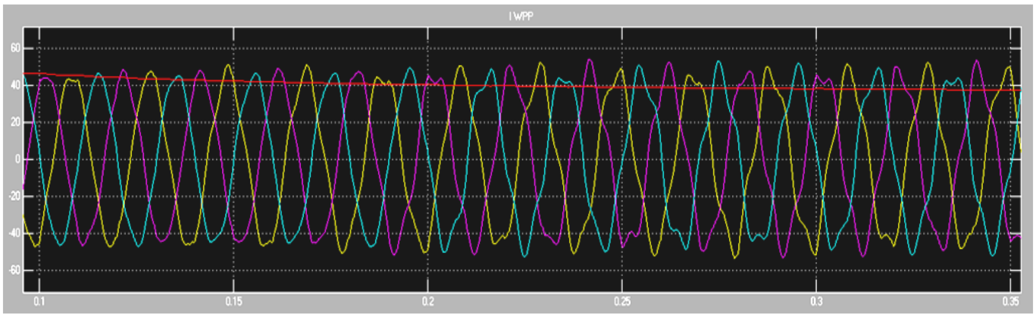


Figure 8.11 : Filtered Feeder Current (Original in Colour)

Chapter 09

CONCLUSIONS AND RECOMMENDATIONS

Today, Electricity has become an essential commodity with extensive use of power electronic equipment and non-linear loads in industrial, commercial and domestic applications. With the improved life standards, electricity consumers are concerned not only on the availability of power at their user end but also of its quality. Usually, wind energy is considered as a risky source in terms of power quality. Major concerns associated with wind plants are; Voltage changes and Fluctuations, Voltage and Current Harmonics, Flicker, Frequency variations and Reactive power compensation. These disturbances ultimately lead to huge economic losses and safety concerns.

Basically, there are four types of distinct technologies of wind plants and three of them are available in Sri Lanka. This research is focused on major power quality issues associated with four wind plants in Puttalam. A special consideration is given on the effect of harmonics during steady state operation. The scope of the project includes,

i. Measurement of electrical parameters of the wind plants from the utility side.
ii. Detailed data analysis.
iii. Study on mitigation techniques.
iv. Computer Modeling and Simulation using MATLAB/SIMULINK environment to investigate harmonic mitigation.

9.1 Conclusions

Conclusions made based on Measurements and Data Analysis are as follows.

1. CEB has published an Interconnection Standard (referred as the Grid Code in this dissertation) for Wind Power Plants; clearly specifying Power Quality

limitations and requirements. But, it was observed that none of the investigated plants adhere to power quality requirements of this grid code.

2. Each individual plant violates at least one PQ parameter for more than 70% of the data measuring time. But, neither the utility (CEB) or the Wind Power Producers pay adequate attention on these violations.
3. At present, there is no appropriate system to continuously monitor the parameters related to power quality.
4. High harmonic distortion is the most severe power quality issue identified in Wind Plants under study.
5. Wind power plants with full power converters have not implemented adequate harmonic mitigation methods. Even though, the use of Active/ Hybrid harmonic filters is becoming a widely popular solution, WPPs in Sri Lanka have not installed any Active harmonic filters yet.
6. Most of the power quality improving and mitigating methods discussed in this dissertation are not yet implemented in Sri Lanka.
7. Wind Turbine type "C" which employs a Doubly-Fed Induction Generator (DFIG) concept with a partial scale power converter shows the best power quality characteristics.

9.2 Recommendations

9.2.1 General Recommendations for grid connected wind power plants

1. Both the Utility and Wind Power Producers must pay more attention on power quality disturbances imposed by the wind plants. A system must be developed to continuously monitor Power quality parameters and take necessary actions to keep them within the specified levels.
2. For the upcoming Wind Plants, wind turbine type "C" employing a Doubly-Fed Induction Generator is identified as the most suitable wind technology to be integrated with the Sri Lankan Power System in the view of Power Quality.

9.2.2 Specific Recommendations for wind plants under study

9.2.2.1 Recommendations for Plant 01 and Plant 02

1. Plants 01 and 02 show highly unacceptable harmonic distortion levels. Therefore, employing a suitable harmonic mitigation technique at these two wind plants is recommended to control harmonic injection to the network.

2. Installation of a Shunt Hybrid harmonic Filter is identified as the most suitable harmonic mitigation technique. A filter unit similar to the harmonic filter described in Chapter 08 can be employed.

3. The same hybrid filter unit can be utilized to mitigate flicker and improve power factor at these two WPPs.

4. To reduce the frequency of interruptions, it is recommended to replace the bare conductor line which connects individual wind turbines to the distribution network with 33 kV Covered Conductor or Arial Bundle Conductor.

5. Installation of a suitable Dynamic Voltage Restorer (DVR) which injects voltage into the system thus; restore pre-fault voltage during a voltage sag/swell is recommended for Plant 02.

9.2.2.2 Recommendations for Plant 03

Installation of a suitable Static Synchronous Compensator (STATCOM) device is recommended for Plant 03 to achieve following improvements.

1. Mitigate Voltage Sags/ Swells
2. Reduce Flicker Emission
3. Power Factor Improvement

9.2.2.3 Recommendations for Plant 04

Plant 04 shows the best power quality of four wind plants under study. There were no considerable violations of the requirements mentioned in CEB Grid Code. Therefore, no improvements are suggested.

9.3 Provision for Future Research

1. Behavior of wind power quality at distinct turbine/generator capacities was not included in this research. It was not possible to study on such area as all four wind plants taken for study had installed equipment of similar capacities. This topic could be studied to identify the optimum generator ratings for the future wind developments.
2. Further study on Active Harmonic filters to design more efficient filters and design and simulation of a DVR is recommended for future research.
3. A Financial evaluation /cost benefit analysis was not done for the suggested power quality improvements. Further future study on these economic factors will be beneficial to both Utility and Wind Power Producers.

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Appendix A

DETAILS OF VOLTAGE INTERRUPTION EVENTS

Event/ Ref No.	Interval	Description
Plant 01		
01 (889-1133)	13th July 2012; 0917 hrs to 1321 hrs	(i) Plant has tripped after the immediate voltage sag. (ii) V_{THD} is mostly 327.67. High 2nd harmonic voltage content at start. Harmonic orders from 2-25 shows a harmonic voltage around 100V and V fundamental = 0, which causes the abnormal V_{THD} = 327.67. (iii) I_{THD} is > 200%. High 2nd harmonic content closer to 50A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iv) STFI does not exceed the allowable limit.
02 (2088-2089)	14th July 2012; 0516 hrs to 0517 hrs	(i) The interruption must have caused due to an L-G fault in Phase 01. Units 01 & 03 are tripped. (ii) V_{THD} > 12%. Very High harmonic voltage content in Phase 2. I_{THD} is > 200%. High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. $I_f = 0$. (iii) P_{ST} has increased over 16 due to heavy fall in voltage but has recovered within 01 min.

Event/ Ref No.	**Interval**	**Description**
03 (2181-2545)	14th July 2012; 0649 hrs to 1253 hrs	(i) Plant has tripped after the immediate voltage sag. (ii) $V_f = 0$ V_{THD} >>> 5% and = 327.67-abnormal in phase 02. Harmonic orders from 2-25 shows a harmonic voltage around 80V, which causes the abnormal $V_{THD} = 327.67$ in phase 02. Harmonic orders 2-25 in Phases 01 & 03 are around 20V. (iii) $I_f = 0$. I_{THD} is > 200%. High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iv) STFI does not exceed the allowable limit.
Plant 02		
01 (3326-3330)	25th July 2012; 2136 hrs to 2140 hrs	(i) Units 01, 02, 07, 08, 10, 11 & 13 are out of operation. (ii) V_{THD} has risen to >15%. I_{THD} also jumps > 50% and same in 03 phases. High 2nd harmonic content closer to 45A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. $I_f = 0$. (iii) STFI does not exceed the allowable limit.

Event/ Ref No.	**Interval**	**Description**
02 (3689-3693)	26th July 2012; 0339 hrs to 0343 hrs	(i) Units 03, 04, 07, 08, 11, 12 & 13 are out of operation. (ii) V_{THD} has risen to around 17% in phase 03; twice of P03 in phase 02 and twice of P02 in phase 01. I_{THD} also jumps > 80%. $I_f = 0$ for last 04 mins. High 2nd harmonic content closer to 45A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iii) P_{ST} has jumped to 6.6 from 0.17 and continues.
03 (3707-3709)	26th July 2012; 0357 hrs to 0359 hrs	(i) Units 03, 04, 07, 08, 11, 12 & 13 are out of operation. (ii) V_{THD} has risen to around 12% in phase 03; twice of P03 in phase 02 and twice of P02 in phase 01. I_{THD} also jumps > 80%. $I_f = 0$. High 2nd harmonic content closer to 45A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iii) P_{ST} = 30.36 due to rapid voltage variations prevailing from previous interruption.

Event/ Ref No.	Interval	Description
04 (3725-3727)	26th July 2012; 0415 hrs to 0417 hrs	(i) Units 03, 04, 07, 08, 11, 12 & 13 are out of operation. (ii) V_{THD} has risen to around 12% in phase 03; twice of P03 in phase 02 and twice of P02 in phase 01. $I_f = 0$. I_{THD} also jumps > 80%. High 2nd harmonic content closer to 45A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iii) P_{ST} is within allowable limits.
05 (3747-3932)	26th July 2012; 0437 hrs to 0742 hrs	(i) Units 03, 04, 07, 08, 11, 12 & 13 are out of operation. (ii) $V_f = 0$. V_{THD} variation is around 20% in phase 03; twice of P03 in phase 02 and twice of P02 in phase 01 until 3750. At 3751, V_{THD} of phase 03 shows 327.67 until 3757 where V_{THD} is around 55% other 2 phases. From 3758 to 3929, V_{THD} in Phases 01 & 02 are 70-90% and in Phase 03 is 250-327%. From 3930 to 3932, V_{THD} in Phases 01 & 02 are 160-200% and 327.67% in Phase 03. (iii) Pattern of V_{THD} variation followed in previous interruptions has been changed and a very high distortion is shown in ph03. After the turning point mentioned above, Phase 01 & 02 shows high harmonic voltages as 24V in 03rd harmonic, 80V in 5th harmonic & 11V in 11th

Event/ Ref No.	**Interval**	**Description**
		harmonic. Ph 03 shows a heavy harmonic content of 50V in all harmonic orders. (iv) $I_f = 0$. I_{THD} also jumps > 80% and sometimes shows 327.67% abnormal value. High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (v) P_{ST} is within allowable limits.
06 (6070-6073)	27th July 2012; 1920 hrs to 1923 hrs	(i) Units 01, 02, 05 & 10 are out of operation. (ii) $V_f = 0$. V_{THD} is 327.67 in phase 02 and 20-50% in other 2 phases. Harmonic voltages in phases 01 & 03 are generally <8V and around 15V in n=3. All harmonic orders have risen to 90V in phase 02. (iii) $I_f = 0$. I_{THD} is > 80%. High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iv) P_{ST} rises to 5.64 from 0.24.

Event/ Ref No.	Interval	Description
Plant 03		
01 (1319)	17th August 2012; 1457 hrs	(i) Short Interruption. V_{THD} has risen to 130% in phase 01 and >25% in phases 02 &03 from <5%. High 5^{th} harmonic order of 10V. (ii) I_{THD} jumps > 215% from <5%. High 2^{nd} harmonic content closer to 40A. 3^{rd} harmonic content closer to 25A. 4^{th} harmonic content closer to 20A and gradually decreasing until n=20. $I_f = 0$ (iii) P_{ST} is within allowable limits.
02 (1321)	17th August 2012; 1459 hrs	(i) Short Interruption in the middle of two voltage sags. (ii) V_{THD} is >12%. V_f = 300 V. All harmonic order voltages are in the range of (3-8) V (iii) I_{THD} > 160% & 327.61% in Phase 01. High 2^{nd} harmonic content closer to 40A. 3^{rd} harmonic content closer to 25A. 4^{th} harmonic content closer to 20A and gradually decreasing until n=20. $I_f = 0$ (iv) P_{ST} has risen to 21 after the sag.
03 (3771)	19th August 2012; 0749 hrs	(i) Short Interruption in the middle of two voltage sags. $V < 0.1V_{rms.}$ PH01 - V_{THD} = 39%. All harmonic order voltages have risen to (8-12) V; except 15V in 5^{th} Harmonic. V_f = 30 V.

Event/ Ref No.	**Interval**	**Description**
		PH02 - V_{THD} = 28%. All harmonic order voltages have risen to (4-6) V; except 16V in 5th Harmonic & 11 in 2nd Harmonic. V_f = 30 V. PH03 - V_{THD} = 50%. All harmonic order voltages have risen to (10-15) V; except 21V in 5th Harmonic. V_f = 30 V. (ii) I_{THD} jumps > 215% from <5%. High 2nd harmonic content closer to 43A. 3rd harmonic content closer to 28A. 4th harmonic content closer to 20A and gradually decreasing until n=20. I_f = 0 (iii) P_{ST} has risen to 6 following the sag.
Plant 04 – No Events		

Appendix B

DETAILS OF VOLTAGE SAGS

Event/ Ref No.	Interval	Description
Plant 01		
01 (888)	13th July 2012; 0916 hrs	(i) Sag before interruption. V = 0.788 $V_{rms.}$ Considered to have LVRT capability. The plant has tripped after 1 min (ii) V_{THD} has suddenly increased to 74.34% from 1.3%. V_f has reduced to 30V and then to zero. All harmonic orders have risen. (iii) I_{THD} also shows a sudden increase. In general, all harmonic orders have risen; prominently, High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iv) With the sag, Pst has increased to 16.4. (v) P=2kW. Q=6kVar.
02 (1134)	13th July 2012; 1322 hrs	(i) Sag followed by the interruption**.** V = 0.48 $V_{rms.}$ Considered to have LVRT capability. The plant has recovered above 90% of voltage after 1 min (ii) V_{THD} = 327.67-abnormal. Very High harmonic voltages. Harmonic orders from 2-25 shows a harmonic voltage around 5-10V. (iii) I_{THD} > 200%. In general, all harmonic orders have risen; prominently, High 2nd

Event/ Ref No.	**Interval**	**Description**
		harmonic content closer to 40A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iv) P=0, Q=2 kVAR. (v) With the sag, Pst has increased over 32.
03 (2180)	14th July 2012; 0648 hrs	(i) Sag before interruption. V = 0.298 $V_{rms.}$ Doesn't have LVRT capability. The plant has fallen below 40% of voltage. (ii) V_{THD} > 24% and 4-5 times of it in ph 2. Very High harmonic voltages in phase 02 when compared with others. (iii) I_{THD} > 200%. $I_f \approx 0$. In general, all harmonic orders have risen; prominently, High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 30A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iv) P>0, Q<0. (v) With the sag, Pst has increased to 14.83.
Plant 02		
01 (3543)	26th July 2012; 0113 hrs	(i) V = 0.41 $V_{rms.}$ Units 05, 07, 08, 10 & 11 seems to be tripped. Doesn't have LVRT capability. The plant hasn't either recovered 90% voltage or tripped within 1 min. (ii) V_{THD} has suddenly increased to 24.4%.

Event/ Ref No.	**Interval**	**Description**
		(iii) I_{THD} also shows a sudden increase >50% and 327.67 in phase 03. Prominently, High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 25A. 4th harmonic content closer to 20A and gradually decreasing until n=25. (iv) P_{ST} & Voltage unbalance is within allowable limits. (v) With the sag, PF has become closer to zero. P=0, Q>0
02 (3653)	26th July 2012; 0303 hrs	(i) V = 0.761 $V_{rms.}$ Units 03, 04, 05, 10, 11 & 12 seems to be tripped. (ii) Considered to have LVRT capability. The plant has recovered above 90% of voltage after 1 min. (iii) V_{THD} has suddenly increased to above 35%. (iv) I_{THD} also shows a sudden increase >60% and 327.67 in phase 03. High 2nd harmonic content closer to 30A. 3rd harmonic content closer to 20A. 4th harmonic content closer to 15A and gradually decreasing until n=25. (v) P_{ST} & Voltage unbalance is within allowable limits. (vi) P, Q < 0; PF < 0.
03 (6524)	28th July 2012; 0254 hrs	(i) V = 0.83 $V_{rms.}$ At this point, all 13 units show a consumption of 23.6kW. Considered to

Event/ Ref No.	**Interval**	**Description**
		have LVRT capability. The plant has recovered above 90% of voltage after 1 min (ii) V_{THD} increased to 24%. (iii) I_{THD} increased to > 60%. High 2nd harmonic content closer to 35A. 3rd harmonic content closer to 20A. 4th harmonic content closer to 15A and gradually decreasing until n=25. (iv) P=6kW,Q=6 kVAR. With the sag, PF has reduced to 0.02. (v) P_{ST} & Voltage unbalance is within allowable limits.
Plant 03		
01 (1320)	17th August 2012; 1458 hrs	(i) V = 0.6 $V_{rms.}$ Followed by an interruption event. Considered to have LVRT capability. The plant has tripped after 1 min (ii) V_{THD} is >100% and almost twice in PH02. High 5th harmonic order of 10V &. All other harmonic order voltages of (2-6) V prevailing from interruption. V_f = 19 kV. (iii) I_{THD} >200% & highest in PH02. High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 25A. 4th harmonic content closer to 20A and gradually decreasing until n=20. I_f = 0 (iv) PF <0 & closer to zero. P=0,Q=2 kVAR. (v) STFI has suddenly risen to 21.05 following the interruption.

Event/ Ref No.	**Interval**	**Description**
02 (1322)	17th August 2012; 1500 hrs	(i) V = 0.31 $V_{rms.}$ Followed by an interruption event. Doesn’t have LVRT capability. The plant has fallen below 40% of voltage. (ii) V_{THD} is >13%. V_f = 8 kV. All harmonic voltages have risen to (2-8)V. (iii) I_{THD} >235%. High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 25A. 4th harmonic content closer to 20A and gradually decreasing until n=20. I_f = 0 (iv) PF = 0. P=0,Q=0. (v) STFI = 21 prevailing from above interruption & sag.
03 (1526)	17th August 2012; 1824 hrs	(i) V = 0.8 $V_{rms.}$ Voltage drop in all 03 phases. Considered to have LVRT capability. The plant has recovered above 90% of voltage after 1 min (ii) V_{THD} is >35%. All harmonic voltages have risen to (1-4)V. (iii) I_{THD} >210% and 327.67 in PH03. High 2nd harmonic content closer to 20A. 3rd harmonic content closer to 12A. 4th harmonic content closer to 9A and gradually decreasing until n=20. I_f = 0 (iv) PF close to zero. P=32.5kW, Q= - 40kVar. (v) STFI is within allowable limits.

Event/ Ref No.	Interval	Description
04 (1620)	17th August 2012; 1958 hrs	(i) V = 0.85 $V_{rms.}$ Voltage drop in all 03 phases. Considered to have LVRT capability. The plant has recovered above 90% of voltage after 1 min (ii) V_{THD} is =25% in phase 02 & almost twice in Phases 01 & 03. All harmonic voltages have risen to (1-4)V. (iii) I_{THD} is 150%, 320% & 210% in 03 phases respectively. High 2nd harmonic content closer to 40A. 3rd harmonic content closer to 25A. 4th harmonic content closer to 20A and gradually decreasing until n=20. (iv) PF = 0. P=0, Q= 7.5kVar. (v) STFI has suddenly risen to 13.1.
05 (2851)	18th August 2012; 1629 hrs	(i) V = 0.8 $V_{rms.}$ Voltage drop in all 03 phases. Considered to have LVRT capability. The plant has recovered above 90% of voltage after 1 min (ii) V_{THD} is >36%. All harmonic voltages have risen to (0.5-2.0)V in all 3 phases. (iii) I_{THD} is >145%. High 2nd harmonic content closer to 14A. 3rd harmonic content closer to 08A and gradually decreasing until n=20. (iv) PF close to zero. P=65 kW, Q= - 65kVar. (v) STFI has is within allowable limits.

Event/ Ref No.	Interval	Description
06 (3770)	19th August 2012; 0748 hrs	(i) V = 0.75 $V_{rms.}$ Voltage drop in all 03 phases. Considered to have LVRT capability. The plant tripped after 1 min (ii) V_{THD} is >60%. All harmonic voltages have risen to (1-4)V in all 3 phases. (iii) I_{THD} is >165%. High 2nd harmonic content closer to 15A. 3rd harmonic content closer to 08A and gradually decreasing until n=20. (iv) PF close to zero. P=35kW Q= (-27.5kVar) (v) STFI has risen to 6.04.
07 (3772)	19th August 2012; 0750 hrs	(i) V = 0.45 $V_{rms.}$ Followed by an interruption event. Considered to have LVRT capability. The plant has recovered above 90% of voltage after 1 min PH01 - V_{THD} = 36%. All harmonic order voltages have risen to (6-8) V; except 10V in 3rd Harmonic & 11V in 5th Harmonic. V_f = 13.6kV. PH02 - V_{THD} = 26%. All harmonic order voltages have risen to (3-6) V; except 8V in 3rd Harmonic & 12V in 5th Harmonic. V_f = 13.6kV. PH03 - V_{THD} = 60%. All harmonic order voltages have risen to (9-13) V; except 19V in 5th Harmonic. V_f = 13.6kV. (ii) I_{THD} is >210% & highest in PH01. High 2nd harmonic content closer to 40A. 3rd harmonic

Event/ Ref No.	Interval	Description
		content closer to 26A. 4th harmonic content closer to 20A and gradually decreasing until n=20. (iii) P=0 Q= 2.5kVar. PF=0 (iv) STFI = 6.04 prevails following the interruption.
08 (4290)	19th August 2012; 1628 hrs	(i) V = 0.37 $V_{rms.}$ Doesn't have LVRT capability. The plant has fallen below 40% of voltage. (ii) V_{THD} is >24%. All harmonic voltages have risen to (3-6)V in all 3 phases. (iii) I_{THD} is >165% and twice in PH02. High 2nd harmonic content closer to 42A. 3rd harmonic content closer to 27A. 4th harmonic content closer to 20A and gradually decreasing until n=20. Harmonic current of PH02 are about 1A low than other phases. (iv) PF close to zero. P=0, Q= 2.5kVar (v) STFI has suddenly risen to 18.12.
09 (5639)	20th August 2012; 1457 hrs	(i) V = 0.71 $V_{rms.}$ Considered to have LVRT capability. The plant has recovered above 90% of voltage after 1 min (ii) V_{THD} is >45%. All harmonic voltages have risen to (0.5-3.0)V in all 3 phases. (iii) I_{THD} is >180% and highest in PH02. High 2nd harmonic content closer to 20A. 3rd

Event/ Ref No.	**Interval**	**Description**
		harmonic content closer to 11A and gradually decreasing until n=20. (iv) PF close to zero. P=0, Q= 2.5kVar (v) STFI is within allowable limits.
Plant 04 – No Events		

Appendix C

DETAILS OF UNDER VOLTAGE EVENTS

Event/ Ref No.	Interval	Description
Plant 01 : No Events		
Plant 02		
01 (2302-2303)	25th July 2012; 0432 hrs to 0433 hrs	(i) V = 0.782 $V_{rms.}$ Doesn't have LVRT capability. The plant hasn't either tripped or recovered above 90% of voltage within 1 min. V_{THD} has suddenly increased to 24. 4% from 5.65%. (ii) I_{THD} also shows a sudden increase from 5.75 to 31.25. (iii) P suddenly drops to zero. PF remains at 0.99 and fall to 0.02.
02 (5245-5246)	27th July 2012; 0535 hrs to 0536 hrs	(i) V = 0.87 $V_{rms.}$ Doesn't have LVRT capability. The plant hasn't either tripped or recovered above 90% of voltage within 1 min. V_{THD} has suddenly increased to 23% from 9.5%. (ii) I_{THD} in phase 01 is 327.67 and 36 in Phase 02 & 03. (iii) PF remains at 0.96 and fall to 0.02.
Plant 03		
01 (4395-4396)	19th August 2012; 1813 hrs to 1814 hrs	(i) V = 0.68 $V_{rms.}$ Doesn't have LVRT capability. The plant hasn't either tripped or recovered above 90% of voltage within 1 min.

Event/ Ref No.	**Interval**	**Description**
		(ii) P<0, Q>0 in **k** range. PF close to zero. (iii) I_{THD} is 160-300%. Random variation between phases. High 2nd harmonic content closer to 35A. 3rd harmonic content closer to 20A and gradually decreasing until n=20. (iv) STFI & Voltage unbalance are within allowable limits.
02 (5668-5669)	20th August 2012; 1526 hrs to 1527 hrs	(i) V = 0.57 $V_{rms.}$ Doesn't have LVRT capability. The plant hasn't either tripped or recovered above 90% of voltage within 1 min. (ii) P,Q fluctuate directions in **k** range. PF close to zero. (iii) V_{THD} is 20-57%. Random variation between phases. All harmonic voltages have risen to (1-5)V in all 3 phases except 9V of 5th Harmonic. (iv) I_{THD} is 160-265%. Random variation between phases. High 2nd harmonic content closer to 35A. 3rd harmonic content closer to 20A and gradually decreasing until n=20. (v) STFI & Voltage unbalance are within allowable limits.
Plant 04 : No Events		

Appendix D

MINIMUM, MAXIMUM AND AVERAGE VOLTAGE HARMONIC PERCENTAGES WITH PERCENTAGE DURATIONS THAT EXCEED THE ALLOWABLE MAXIMUM LIMITS

Appendix D (i): Minimum, maximum and average voltage harmonic percentages with percentage durations that exceed the allowable maximum limits when P < 0.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	1.10	0.99	1.33	0.48
		Average	1.95	1.43	2.17	1.04
		Maximum	2.48	2.03	4.00	1.54
	% Duration –harmonic content exceeding allowable limit		0.0	0.0	0.0	0.0
n<11 Even %	(<1%)	Minimum	0.13	0.14	0.22	0.17
		Average	0.48	0.75	0.45	0.48
		Maximum	1.68	2.16	1.00	1.11
	% Duration –harmonic content exceeding allowable limit		20.51	18.00	0.0	0.21
11<=n<17 Odd %	(< 2%)	Minimum	0.12	0.28	0.21	0.17
		Average	0.51	0.99	0.44	0.70
		Maximum	2.38	2.68	0.74	1.61
	% Duration –harmonic content exceeding allowable limit		4.27	4.75	0.0	0.0
11<=n<17 Even %	(< 0.5%)	Minimum	0.03	0.04	0.04	0.04
		Average	0.24	0.45	0.10	0.18
		Maximum	1.49	1.72	0.19	1.28
	% Duration –harmonic content exceeding allowable limit		20.51	43.50	0.0	5.61

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
17<=n<23 Odd %	(< 1.5%)	Minimum	0.09	0.08	0.03	0.02
		Average	0.42	0.71	0.07	0.12
		Maximum	2.97	3.41	0.18	0.22
	% Duration –harmonic content exceeding allowable limit		9.40	9.25	0.0	0.0
17<=n<23 Even %	(< 0.4%)	Minimum	0.03	0.02	0.01	0.02
		Average	0.26	0.23	0.03	0.05
		Maximum	1.11	0.66	0.07	0.12
	% Duration –harmonic content exceeding allowable limit		21.37	11.50	0.0	0.0
23<=n< 50 Odd + Even %	(< 1.2%)	Minimum	0.09	0.20	0.20	-
		Average	1.72	2.64	2.70	-
		Maximum	10.91	10.60	11.93	-
	% Duration –harmonic content exceeding allowable limit		34.19	65.25	27.69	-

Appendix D (ii): Minimum, maximum and average voltage harmonic percentages with percentage durations that exceed the allowable maximum limits when P = 0.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	NA	1.07	0.22	0.44
		Average	NA	1.65	2.44	1.04
		Maximum	NA	2.05	3.30	1.54
	% Duration –harmonic content exceeding allowable limit		NA	0.0	0.0	0.0
n<11 Even %	(<1%)	Minimum	NA	0.17	0.05	0.18
		Average	NA	1.14	0.49	0.48
		Maximum	NA	1.85	1.04	1.13

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
	% Duration –harmonic content exceeding allowable limit		NA	59.84	7.14	0.35
11<=n<17 Odd %	(< 2%)	Minimum	NA	0.38	0.04	0.17
		Average	NA	1.13	0.62	0.53
		Maximum	NA	2.97	0.87	1.61
	% Duration –harmonic content exceeding allowable limit		NA	12.60	0.0	0.0
11<=n<17 Even %	(< 0.5%)	Minimum	NA	0.06	0.02	0.05
		Average	NA	0.56	0.14	0.17
		Maximum	NA	1.67	0.30	1.28
	% Duration –harmonic content exceeding allowable limit		NA	51.18	0.0	3.13
17<=n<23 Odd %	(< 1.5%)	Minimum	NA	0.10	0.04	0.03
		Average	NA	0.97	0.09	0.11
		Maximum	NA	3.28	0.14	0.22
	% Duration –harmonic content exceeding allowable limit		NA	27.56	0.0	0.0
17<=n<23 Even %	(< 0.4%)	Minimum	NA	0.03	0.02	0.02
		Average	NA	0.29	0.04	0.05
		Maximum	NA	0.54	0.07	0.12
	% Duration –harmonic content exceeding allowable limit		NA	11.81	0.0	0.0
23<=n< 50 Odd + Even %	(< 1.2%)	Minimum	NA	0.11	0.33	-
		Average	NA	2.58	3.07	-
		Maximum	NA	28.63	10.10	-
	% Duration –harmonic content exceeding allowable limit		NA	60.63	35.71	-

Appendix D (iii): Minimum, maximum and average voltage harmonic percentages with percentage durations that exceed the allowable maximum limits when 0 <P< 850 kW.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	1.04	1.02	0.07	0.44
		Average	1.60	1.70	1.64	0.92
		Maximum	2.89	10.28	23.03	1.46
	% Duration –harmonic content exceeding allowable limit		0.0	1.37	0.04	0.0
n<11 Even %	(<1%)	Minimum	0.24	0.12	0.03	0.22
		Average	1.98	1.12	0.67	0.46
		Maximum	2.86	10.25	22.46	1.55
	% Duration –harmonic content exceeding allowable limit		79.18	51.37	3.92	0.65
11<=n<17 Odd %	(< 2%)	Minimum	0.19	0.33	0.03	0.12
		Average	1.45	1.17	0.29	0.46
		Maximum	3.96	6.51	1.00	1.11
	% Duration –harmonic content exceeding allowable limit		20.45	14.38	0.0	0.0
11<=n<17 Even %	(< 0.5%)	Minimum	0.12	0.04	0.02	0.06
		Average	0.93	0.60	0.14	0.13
		Maximum	2.85	6.00	0.39	0.62
	% Duration –harmonic content exceeding allowable limit		84.01	47.95	0.0	0.23
17<=n<23 Odd %	(< 1.5%)	Minimum	0.12	0.06	0.19	0.05
		Average	1.78	0.99	0.11	0.12
		Maximum	4.70	4.14	0.52	0.27
	% Duration –harmonic content exceeding allowable limit		58.36	26.03	0.0	0.0

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
17<=n<23 Even %	(< 0.4%)	Minimum	0.04	0.02	0.02	0.02
		Average	0.90	0.30	0.07	0.05
		Maximum	1.63	3.80	0.18	0.12
	% Duration –harmonic content exceeding allowable limit		85.50	19.86	0.0	0.0
23<=n< 50 Odd + Even %	(< 1.2%)	Minimum	0.26	0.16	0.18	-
		Average	8.13	4.04	0.70	-
		Maximum	64.28	52.68	327.66	-
	% Duration –harmonic content exceeding allowable limit		94.05	57.53	2.13	-

Appendix D (iv): Minimum, maximum and average voltage harmonic percentages with percentage durations that exceed the allowable maximum limits when 850 kW <P< 5 MW.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	1.09	1.18	NA	0.44
		Average	1.60	1.60	NA	0.91
		Maximum	2.60	2.21	NA	2.00
	% Duration –harmonic content exceeding allowable limit		0.0	0.0	NA	0.0
n<11 Even %	(<1%)	Minimum	0.90	1.44	NA	0.22
		Average	2.56	2.61	NA	0.46
		Maximum	3.81	3.21	NA	2.70
	% Duration –harmonic content exceeding allowable limit		98.76	100.0	NA	0.83
11<=n<17 Odd %	(< 2%)	Minimum	0.52	0.57	NA	0.12
		Average	1.78	1.77	NA	0.44
		Maximum	4.45	4.92	NA	0.96

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
	% Duration –harmonic content exceeding allowable limit		32.09	32.87	NA	0.0
11<=n<17 Even %	(< 0.5%)	Minimum	0.39	0.36	NA	0.06
		Average	1.15	1.13	NA	0.14
		Maximum	2.87	3.10	NA	0.56
	% Duration –harmonic content exceeding allowable limit		98.17	98.54	NA	0.08
17<=n<23 Odd %	(< 1.5%)	Minimum	0.68	0.55	NA	0.05
		Average	2.29	1.98	NA	0.12
		Maximum	5.65	5.60	NA	0.30
	% Duration –harmonic content exceeding allowable limit		83.73	68.87	NA	0.0
17<=n<23 Even %	(< 0.4%)	Minimum	0.47	0.37	NA	0.02
		Average	1.05	0.50	NA	0.06
		Maximum	1.55	0.95	NA	0.18
	% Duration –harmonic content exceeding allowable limit		100.0	95.8	NA	0.0
23<=n< 50 Odd + Even %	(< 1.2%)	Minimum	3.20	3.42	NA	-
		Average	9.87	8.70	NA	-
		Maximum	29.11	14.43	NA	-
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	-

Appendix D (v): Minimum, maximum and average voltage harmonic percentages with percentage durations that exceed the allowable maximum limits when 5 MW <P< 10 MW.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	1.26	1.34	NA	0.44
		Average	1.70	1.70	NA	0.91
		Maximum	2.22	2.35	NA	2.00
	% Duration –harmonic content exceeding allowable limit		0.0	0.0	NA	0.0
n<11 Even %	(<1%)	Minimum	1.53	1.75	NA	0.22
		Average	2.27	2.37	NA	0.46
		Maximum	2.97	3.35	NA	0.74
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	0.0
11<=n<17 Odd %	(< 2%)	Minimum	0.67	0.62	NA	0.12
		Average	2.10	2.02	NA	0.44
		Maximum	5.43	6.40	NA	0.96
	% Duration –harmonic content exceeding allowable limit		47.60	44.71	NA	0.0
11<=n<17 Even %	(< 0.5%)	Minimum	0.40	0.37	NA	0.06
		Average	1.22	1.20	NA	0.14
		Maximum	3.67	3.71	NA	0.63
	% Duration –harmonic content exceeding allowable limit		99.30	99.05	NA	3.45
17<=n<23 Odd %	(< 1.5%)	Minimum	0.76	0.41	NA	0.05
		Average	2.60	2.12	NA	0.12
		Maximum	6.58	7.87	NA	0.30
	% Duration –harmonic content exceeding allowable limit		91.63	74.49	NA	0.0

Harmonic Category	**Grid Code Requirement**		**Plant 01**	**Plant 02**	**Plant 03**	**Plant 04**
17<=n<23 Even %	(< 0.4%)	Minimum	0.53	0.38	NA	0.02
		Average	0.78	0.50	NA	0.06
		Maximum	1.32	1.01	NA	0.18
	% Duration –harmonic content exceeding allowable limit		100.0	97.23	NA	0.0
23<=n< 50 Odd + Even %	(< 1.2%)	Minimum	0.93	2.03	NA	-
		Average	8.10	7.56	NA	-
		Maximum	15.30	18.70	NA	-
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	-

Appendix E

MINIMUM, MAXIMUM AND AVERAGE CURRENT HARMONIC PERCENTAGES WITH PERCENTAGE DURATIONS THAT EXCEED THE ALLOWABLE MAXIMUM LIMITS

Appendix E(i): Minimum, maximum and average current harmonic percentages with percentage durations that exceed the allowable maximum limits when P < 0.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	13.00	13.00	11.33	6.81
		Average	29.47	24.76	23.00	13.02
		Maximum	225.54	197.30	55.78	23.70
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	100.0	100.0
n<11 Even %	(<1%)	Minimum	6.22	6.20	3.95	2.80
		Average	21.93	22.16	12.88	5.04
		Maximum	363.54	285.76	81.84	8.27
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	100.0	100.0
11<=n<17 Odd %	(< 2%)	Minimum	1.91	2.30	0.91	1.73
		Average	8.11	8.88	7.54	9.96
		Maximum	112.38	129.55	14.71	24.56
	% Duration –harmonic content exceeding allowable limit		99.43	100.0	98.46	99.68
11<=n<17 Even %	(< 0.5%)	Minimum	1.10	1.10	0.91	0.81
		Average	4.80	5.10	2.91	2.85
		Maximum	63.23	62.57	13.22	20.74
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	100.0	100.0

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
17<=n<50 Odd + Even %	(< 3.1%)	Minimum	8.11	0.68	4.70	2.24
		Average	42.60	7.03	88.40	11.06
		Maximum	333.24	116.69	325.87	19.08
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	100.0	99.36

Appendix E(ii): Minimum, maximum and average current harmonic percentages with percentage durations that exceed the allowable maximum limits when P = 0.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	NA	55.00	19.60	7.02
		Average	NA	55.97	51.56	13.53
		Maximum	NA	56.87	56.77	25.32
	% Duration –harmonic content exceeding allowable limit		NA	100.0	100.0	100.0
n<11 Even %	(<1%)	Minimum	NA	84.20	5.00	3.13
		Average	NA	85.44	75.96	5.68
		Maximum	NA	87.10	86.57	8.36
	% Duration –harmonic content exceeding allowable limit		NA	100.0	100.0	100.0
11<=n<17 Odd %	(< 2%)	Minimum	NA	16.13	4.69	1.78
		Average	NA	16.48	15.05	4.49
		Maximum	NA	16.77	16.64	16.62
	% Duration –harmonic content exceeding allowable limit		NA	100.0	100.0	98.95
11<=n<17 Even %	(< 0.5%)	Minimum	NA	14.97	1.59	0.88
		Average	NA	15.25	13.49	1.92
		Maximum	NA	15.56	15.41	8.33

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
	% Duration –harmonic content exceeding allowable limit		NA	100.0	100.0	100.0
17<=n<50 Odd + Even %	(< 3.1%)	Minimum	NA	7.27	1.58	3.70
		Average	NA	7.40	7.04	12.27
		Maximum	NA	7.96	7.88	18.63
	% Duration –harmonic content exceeding allowable limit		NA	100.0	100.0	100.0

Appendix E(iii): Minimum, maximum and average current harmonic percentages with percentage durations that exceed the allowable maximum limits when 0 <P< 850 kW.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	14.51	30.13	0.60	4.81
		Average	43.53	63.42	2.34	15.28
		Maximum	205.66	419.77	55.00	31.87
	% Duration – harmonic content exceeding allowable limit		100.0	100.0	7.80	100.0
n<11 Even %	(<1%)	Minimum	19.49	36.80	3.05	2.53
		Average	87.51	100.27	4.04	5.45
		Maximum	516.30	803.34	79.00	9.71
	% Duration – harmonic content exceeding allowable limit		100.0	100.0	100.0	100.0
11<=n<17 Odd %	(< 2%)	Minimum	2.44	16.24	0.25	0.65
		Average	22.35	20.88	1.00	3.02
		Maximum	149.17	159.60	15.59	16.93
	% Duration – harmonic content exceeding allowable limit		100.0	100.0	2.52	73.35

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
11<=n<17 Even %	(< 0.5%)	Minimum	1.58	10.78	0.19	0.38
		Average	13.28	17.07	0.85	0.96
		Maximum	83.31	85.86	12.73	3.92
	% Duration – harmonic content exceeding allowable limit		100.0	100.0	76.58	92.4
17<=n<50 Odd + Even %	(< 3.1%)	Minimum	14.87	27.00	0.20	3.72
		Average	69.13	27.93	1.56	8.48
		Maximum	359.80	321.70	323.45	19.60
	% Duration – harmonic content exceeding allowable limit		100.0	100.0	1.90	100.0

Appendix E(iv): Minimum, maximum and average current harmonic percentages with percentage durations that exceed the allowable maximum limits when 850 kW <P< 5 MW.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	5.63	4.94	NA	1.18
		Average	13.76	10.47	NA	5.40
		Maximum	40.27	48.93	NA	13.47
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	67.32
n<11 Even %	(<1%)	Minimum	8.60	1.15	NA	0.64
		Average	26.88	16.73	NA	2.18
		Maximum	74.44	78.60	NA	4.62
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	92.08

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
11<=n<17 Odd %	(< 2%)	Minimum	1.35	1.25	NA	0.26
		Average	6.45	4.39	NA	1.09
		Maximum	23.05	18.79	NA	3.76
	% Duration –harmonic content exceeding allowable limit		95.09	91.37	NA	7.56
11<=n<17 Even %	(< 0.5%)	Minimum	0.80	0.66	NA	0.17
		Average	3.68	2.43	NA	0.35
		Maximum	14.15	11.84	NA	1.16
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	7.10
17<=n<50 Odd + Even %	(< 3.1%)	Minimum	4.55	2.16	NA	0.85
		Average	16.88	7.48	NA	3.15
		Maximum	210.20	302.13	NA	8.08
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	51.52

Appendix E(v): Minimum, maximum and average current harmonic percentages with percentage durations that exceed the allowable maximum limits when 5 MW <P< 10 MW.

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 Odd %	(< 4%)	Minimum	3.26	3.27	NA	0.64
		Average	4.40	4.87	NA	1.36
		Maximum	8.77	31.62	NA	2.23
	% Duration –harmonic content exceeding allowable limit		33.75	78.89	NA	0.0

Harmonic Category	Grid Code Requirement		Plant 01	Plant 02	Plant 03	Plant 04
n<11 **Even %**	(<1%)	Minimum	5.50	4.55	NA	0.44
		Average	7.33	7.00	NA	0.70
		Maximum	14.50	48.47	NA	1.08
	% Duration –harmonic content exceeding allowable limit		100.0	100.0	NA	2.29
11<=n<17 **Odd %**	(< 2%)	Minimum	0.40	0.62	NA	0.11
		Average	2.00	2.08	NA	0.30
		Maximum	3.85	16.31	NA	0.58
	% Duration –harmonic content exceeding allowable limit		39.00	42.28	NA	0.0
11<=n<17 **Even %**	(< 0.5%)	Minimum	0.40	0.40	NA	0.29
		Average	1.07	1.10	NA	0.36
		Maximum	3.85	6.23	NA	0.49
	% Duration –harmonic content exceeding allowable limit		89.47	98.91	NA	0.0
17<=n<50 **Odd +** **Even %**	(< 3.1%)	Minimum	2.55	1.36	NA	0.36
		Average	5.00	3.15	NA	0.71
		Maximum	92.57	295.86	NA	1.13
	% Duration –harmonic content exceeding allowable limit		97.23	41.08	NA	0.0