MITIGATION OF POWER QUALITY ISSUES IN DISTRIBUTION NETWORK DUE TO WIND ENERGY PENETRATION IN KILINOCHCHI AREA

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Degree of Master of Science

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Thesis submitted in partial fulfillment of the requirements for the degree of Science

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DECLARATION OF THE CANDIDATE AND SUPERVISORS

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(Dr. Asanka S. Rodrigo)

ABSTRACT

Due to the significant increase of energy demand in electricity sector, many countries are switching to Renewable sources. Wind energy plays major role in renewable energy throughout the world. Since Sri Lanka has good wind potential, it is great opportunity to develop wind energy and now the government policy also has changed to develop renewable energy generation.

The high level of wind energy penetration to the grid, cause to increase power quality disturbances in distribution network such as voltage variation ,flickering, distortion of voltage and current waveform. It creates huge losses in economy as well as inconvenience of day to day activities for affected peoples in different ways. With the increment of sensitive load utilization in distribution sector, power quality measurements became as major concern.

It is understood that, a proper monitoring is need to identify mitigating mechanism for power quality measurements in distribution network in order to provide quality power to customers in line with existing standards and codes.

This postgraduate research thesis describes the power quality issues due to wind integration to the distribution network with theoretical background.

Data collection and measurements on wind power generation has been carried out and identified the issues of power quality parameters of wind plant such as voltage sag, voltage swell, lamp flickering and harmonics. The recorded power quality measurements were analyzed with existing standards and codes.

Existing power quality mitigating techniques were discussed for identified power quality disturbances.

This study proposed to install SVC (Static Var compensator) and passive filter at the point of common coupling.

Simulation results of developed PSCAD model proved that proposed SVC and passive filter provides power quality improvement in line with standards.

ACKNOWLEDGEMENTS

Foremost, I would like to express my sincere gratitude to my supervisor Dr. Asanka Rodrigo for the continuous support given to this research. His patience, motivation, enthusiasm, and immense knowledge are helped me to carry this research in sincere manner. And also, his guidance is remarkable throughout the research.

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S.M. K. Parsad

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LIST OF ABBREVIATIONS

AC - Alternating current

CEB - Ceylon Electricity Board

DC - Direct current

DFIG - Doubly fed induction generator

GW - Giga Watts

IEC - International electromechanical commissions

IEEE - Institute of electrical and electronics Engineers

kV - Kilo Volt

LVRT - Low voltage ride through

MPPT - Maximum power point tracker

MW - Mega Watts

NCRE - Non Conventional renewable energy

NE - North East

NREL - National Renewable Energy Laboratory

NREL - National Renewable Energy Laboratory

PSCAD - Power System Computer Aided Design

PWM - Pulse width modulation

Rms - Root mean square

STATCOM - Static Synchronous Compensator

SW - South West

THD - Total harmonic distortion

Chapter 01: Introduction

1.1.Background

Electricity generation using wind energy source rapidly increased due to its advantage over conventional thermal energy. In end of 2016, the worldwide total cumulative installed electricity generation capacity from wind power is 486,790 MW, an increase of 12.5% compared to the previous year.

During 2016, china has added 23,370 MW by sharing 42.8% of the total installation. In 2015, China installed close to half of the world's added wind power capacity [1].

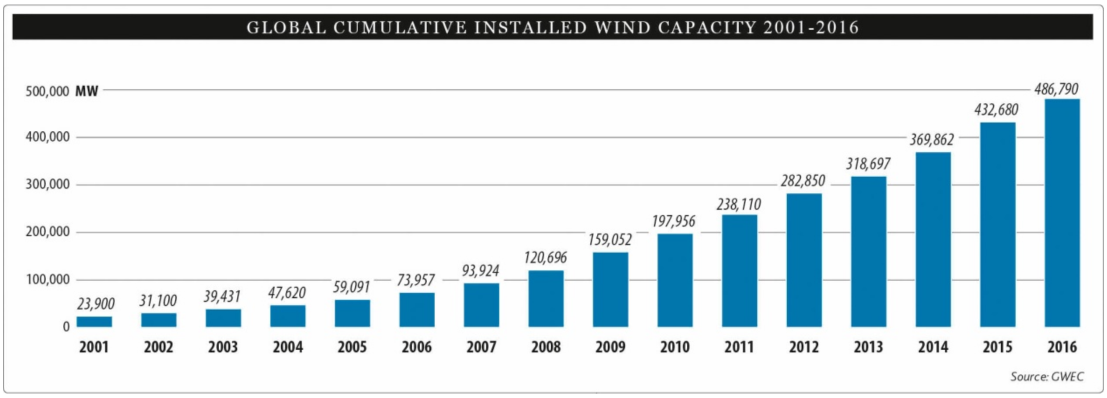


Figure 1.1: Increase of global cumulative installed wind capacity

(Source: Global wind energy council)

Sri Lanka has good wind potential due to its latitude position. Country's wind climate is primarily determined by the two Monsoons wind patterns; the Southwestern (SW) which is the stronger of two Monsoons lasts from May to October and Northeastern (NE) Monsoon lasts from December to February.

Hambanthota wind farm is the first grid connected wind farm in Sri Lanka, owned by Ceylon Electricity Board (CEB) and was commissioned in 1999.The project was funded by local and foreign parties. Foreign funds were raised by the Global Environmental Facility and the World Bank. This was a pilot project aimed to demonstrate the viability of electricity generation through wind energy and obtained clear knowledge on control and operation of wind turbines. The wind farm is located along south-eastern coast of Hambantota, and consists five numbers of 600 kW .the wind farm generates up to approximately 4,500 MWh of power annually.

According to the study of National Renewable Energy Laboratory (NREL) in year 2003, has identified three major regions as having good to excellent wind resources. They are:

- Northwestern coastal region from the Kalpitiya Peninsula north to the Mannar Islands and the Jaffna Peninsula.
- Central highlands in the interior of the country – largely in the Central Province
- Parts of the Sabaragamuwa and Uva Provinces.

This study has estimated that wind potential of Sri Lanka is nearly 20740 MW and that can be changed due to the factors consideration such as the existing transmission grid availability and accessibility, socio-economic etc.

1.2.Motivation

Sri Lankan government policy of electricity generation is focused to giving priority to non conventional renewable energy. According to that, they introduced *"Sri Lanka Energy Sector Development Plan for a Knowledge-Based Economy 2015 – 2025"* in 2015 states their strategies as follows.

- Develop the renewable energy portfolio in the generation mix to an optimum level.
- Establish a competitive bidding process for large scale wind and solar power generation projects
- Promote grid connected small renewable based power generation through net metering.

In order to achieve above target, independent power producers are encouraged to invest in renewable energy like wind, solar, small hydro, dendro, biogas etc. government provide special attention to wind and solar sector due to Sri Lanka having good wind potential and solar potential respectively.

According to that, Sri Lanka reached cumulative installed capacity of grid integrated wind plant is 128.8 MW and Sri Lankan government proposed to implement large scale wind farm at Mannar and Kilinochchi by each having 100 MW.

Figure 1.2 shows the NCRE development in Sri Lanka up to 2014 and Figure 1.3 shows the considerable contribution of wind energy for particular day. According to both figures, it is understood that the contribution of the wind energy to Sri Lankan energy sector getting increase rapidly.

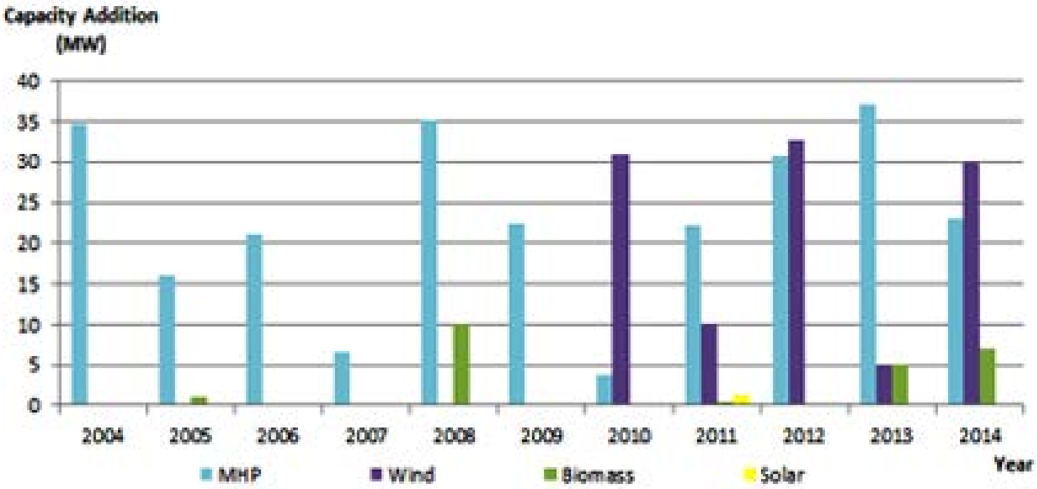


Figure 1.2: Non conventional renewable energy development

(Source: Sustainable Energy Authority)

Electricity Generated on : December 23, 2017

Peak Power Demand 2195.2 MW
Reservoir Storage 935.0 GWh

Energy		Percentage %
CEB Thermal (Coal)	10.13 GWh	29.24
CEB Thermal (Oil)	6.61 GWh	19.09
IPP Thermal (Oil)	3.86 GWh	11.15
Laxapana Complex Hydro	6.09 GWh	17.58
Mahaweli Complex Hydro	4.76 GWh	13.73
Samanala Wewa	1.05 GWh	3.03
Kukule Ganga	1.10 GWh	3.18
CEB (Small Hydro)	0.09 GWh	0.26
Wind	0.83 GWh	2.39

Figure 1.3: Generated electricity for particular day

(Source: CEB statistics)

Wind power plants are generally connected to the 33 kV distribution feeder and wind plant produce power quality disturbances due to intermittent nature of wind. Because of having lower fault level than transmission line, it is difficult to bear power quality disturbances and situation getting worst when customers are directly connect to same feeder. In that kind of situation, customers directly experienced with power quality disturbances generated by wind power plants.

With high level of wind integration to the distribution network, should pay more attention on power quality issues. This research is good opportunity to that and focused to analyzing power quality issues of distribution network due to penetration of wind plant in Kilinochchi area.

1.3.Problem statement

Due to high level of wind penetration to distribution network power quality issues arise frequently. Power electronic equipments such as information technology, power electronic converter, programmable logic controller and energy-efficient lighting are sensitive in nature and simultaneously it is a major cause and major victim of power quality problems by generating harmonics to the system. In order to provide quality supply to the customers, it is need to analyze power quality issues due to high level wind energy penetration and adopt proper mitigation technique to prevent distribution network from power quality disturbances.

1.4.Objectives

- Analyze the power quality issues of distribution network in Kilinochchi area due to high wind energy penetration.
- Propose appropriate mitigation methods to minimize power quality issues in line with existing standards.

1.5.Scope of the Research

- Study the power quality issues in distribution network due to high wind energy penetration to and relevant standards of power quality measures.
- Measurements of power quality parameters of the wind plant and Load side
- Data analysis and power quality mitigation techniques
- Computer based modeling, simulation using PSCAD and Propose appropriate mitigation techniques

Chapter 02: Wind Power Generation

2.1.Components of a wind turbine

In order to convert kinetic energy of wind into electrical energy, wind turbine has mechanical component as well as electrical component. Main components of a modern wind turbine are shown in Figure 2.1.

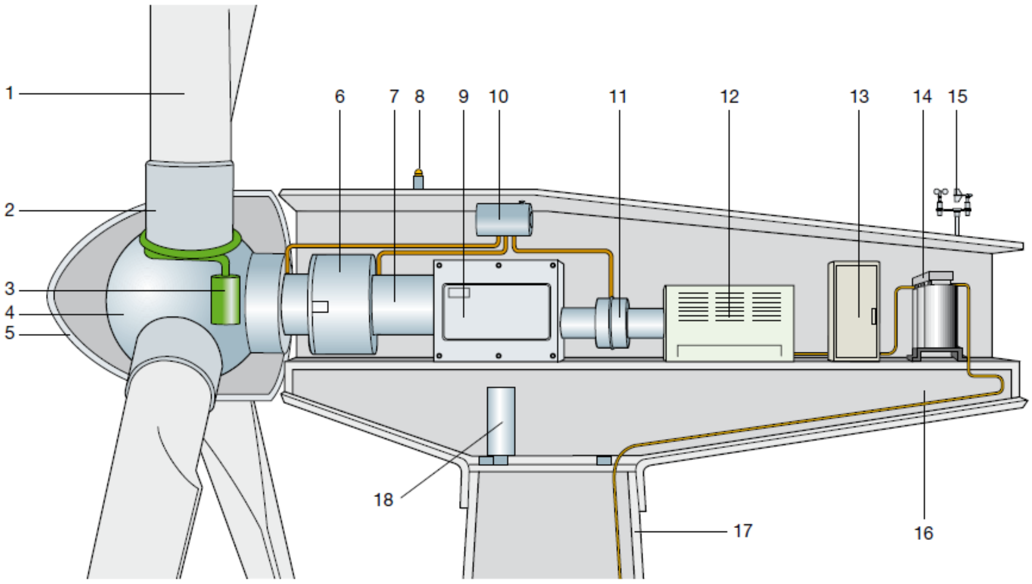


Figure 2.1: Main component of a modern wind turbine

1. Blade
2. Blade support
3. Pitch angle actuator
4. Hub
5. Spinner
6. Main support
7. Main shaft
8. Aircraft warning lights
9. Gearbox
10. Mechanical brakes
11. Hydraulic cooling devices
12. Generator
13. Power converter and electrical control, protection and disconnection devices
14. Anemometers
15. Transformer
16. Frame of the nacelle
17. Supporting tower
18. Yaw driving device

2.2.Types of wind plants/ turbines

Generally there are two types of wind turbine as fixed speed and variable speed. According to the distinct control mechanism of modern wind turbines, can be divided into four categories

- Type A: fixed speed wind turbine
- Type B: partial variable speed wind turbine with variable rotor resistance
- Type C: Variable speed wind turbine with partial scale power converter
- Type D: Variable speed wind turbine with full scale power converter

2.2.1. Type A : fixed speed wind turbine

In these types of turbines induction electrical machines (also known as asynchronous machines), are used for the conversion of the mechanical energy extracted from the wind into electrical energy. In the wind turbines, these electrical machines are used as generators, above all because of their constructional simplicity and toughness, their relative cost effectiveness and for the simplicity of connection and disconnection from the grid. Figure 2.2 shows the fixed speed wind turbine.

The stator of an induction machine consists of copper windings for each phase, as the stator of synchronous machines. But, the rotor in squirrel cage motors has no windings, but consists of a series of copper bars set into the grooves of the laminated magnetic core. Some induction machines can have windings also on the rotor and in this case they are called wound rotor machines. They are expensive and less sturdy than the previous type and are used in variable speed wind turbines. Induction machines require a given quantity of reactive power to function. This power shall be either drawn from the grid or delivered locally through a capacitor bank, which shall be properly sized so that self excitement of the synchronous generator can be avoided in case of grid disconnection due to failure. Additionally, these machines need an external source at constant frequency to generate the rotating magnetic field and consequently they are connected to grids with high short circuit power able to support frequency. When working as a generator, the asynchronous machine is speeded up by the wind rotor up to the synchronous speed and then connected to the grid, or it is at first connected to the grid and started as a motor up to the steady state speed. If the first starting method is used, the turbine clearly is self starting and therefore the Pitch control must be present, whereas the second method is used for passive stall regulated turbines.

In this case the control system stores the wind speed and defines the speed range within which the generator is to be started. Once the synchronous speed has been achieved, the wind power extracted makes the rotor run in hyper synchronous operation with negative slip, thus supplying active power to the grid.

As a matter of fact, since the slip has values in the order of 2%, the deviation from the rated speed is very limited and that’s why the use of these machines makes the wind turbine run at constant speed. To reduce the starting current, a soft starter is usually kept in between the asynchronous machine and the grid.

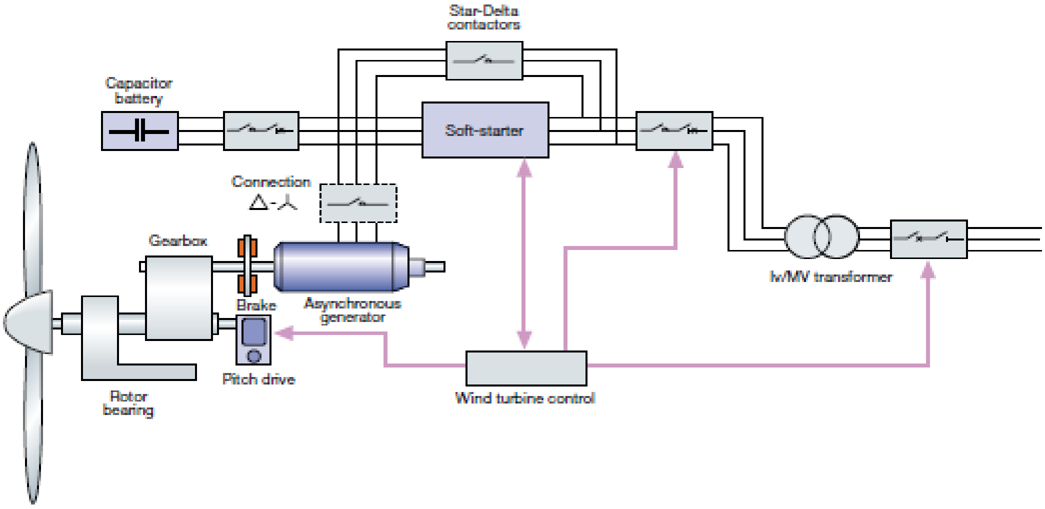


Figure 2.2 : Schematic diagram of fixed speed wind turbine

2.2.2. Type B:Partial variable speed wind turbine with variable rotor resistance

By adding an external variable resistor in series with the rotor windings of a wound rotor asynchronous generator, it is possible to get a variation of the electromagnetic torque of the generator and of the speed at which it is delivered. Thus, both the possibility of operating at the optimum TSR point as a function of wind as well as allowing the rotor to accelerate changing the speed due to wind gusts is guaranteed, even though the losses due to joule effect in the external resistor rise.

Additionally, at high wind speeds, the total resistance of the rotor can be increased to keep constant the current flowing in the rotor (and therefore also in the stator), and with it also the power put into the grid, around the nominal power. The excess of mechanical energy generated by the rotor is therefore dissipated as heat by the additional external resistor. Through this resistor it is possible to achieve a variation in the speed exceeding the synchronism speed in the range 0-10%. The equivalent electric diagram of an asynchronous generator with variable resistor R_x is shown in the Figure 2.3, in which the resistive component $R^{'}_{x}/s$ has been added to the common T circuit of the squirrel cage asynchronous motor.

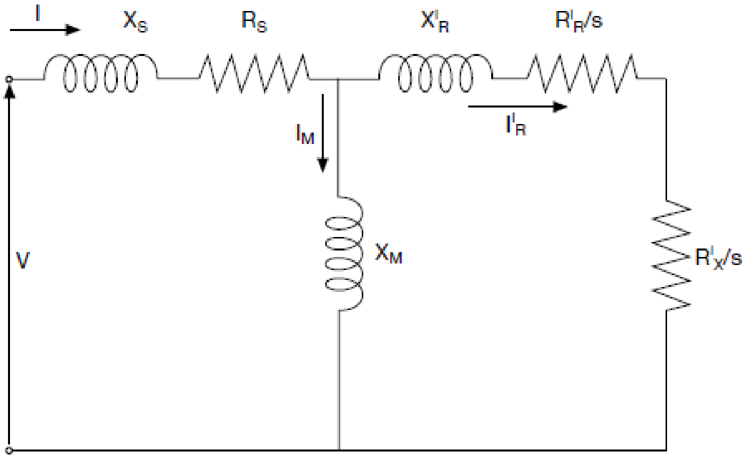


Figure 2.3: Equivalent circuit diagram of an asynchronous generator with variable resistor

2.2.3. Type C : Variable speed wind turbine with partial scale power converter

In order not to lose the power dissipated as heat in the additional resistor, this power can be put into the grid at the rated frequency by interposing an electronic power converter between the rotor of the asynchronous ring generator and the grid. This device converts the exceeding alternating power at the rotor first into direct power through a controlled rectifier and then reconverts it in alternating current at the rated frequency through an inverter. Thus it is possible to supply the rotor with voltages of the proper width and frequency supplied by the electronic converter with the purpose of compensating for the difference of frequency between the angular velocity of the stator rotating magnetic field and the effective angular velocity of the rotor. The term “doubly fed” reflects the fact that the stator voltage is applied by the grid, whereas the rotor voltage is applied by the electronic converter. The equivalent electrical diagram of the DFIG is shown in Figure 2.5, where, with the purpose of representing the converter influence, the varying voltage generator (V’r/s), which is a function of slip s, has been added to the common T circuit of the squirrel cage asynchronous motor. The active power shall always be going out from the stator and put into the net, independently of the operation state whereas the rotor shall absorb power when operating as motor and deliver it when operating as a generator.

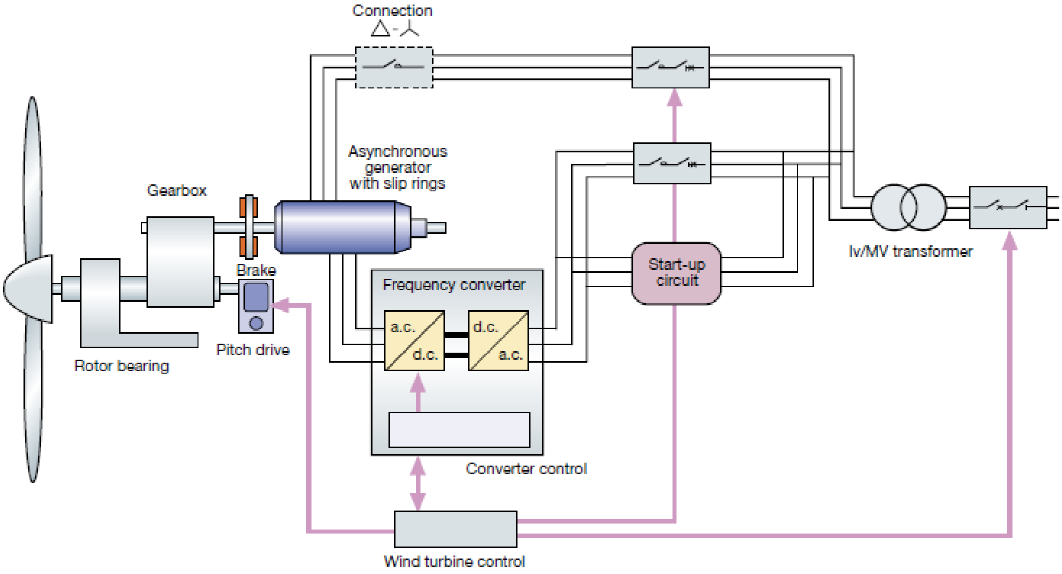


Figure 2.4: Schematic diagram of doubly fed induction wind generator

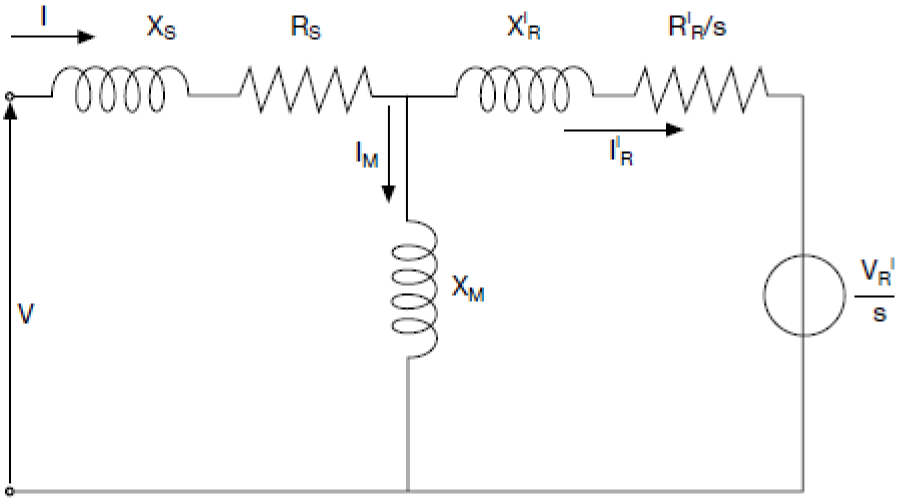


Figure 2.5: The equivalent electrical diagram of the DFIG

With this type of configuration, the electric generator supplies the network with 2/3 of the rated power through the stator directly connected and 1/3 through the rotor connected through the converter. Therefore also the converter can be sized for power equal to 1/3 of the rated power of the generator. Additionally, it is possible to control the reactive power production; this allows voltage regulation and magnetization of the machine by the rotor regardless of the grid voltage.

By means of the doubly fed configuration it is possible to obtain 30% speed variation above or below the synchronism speed. The wound rotor asynchronous generator usually has a synchronism speed up to 2000 rpm and it is connected to the rotor axis through a three stage gearbox. The connection of the rotor windings to the converter is carried out by means of the slip rings and relevant brushes.

2.2.4. Type D : Variable speed wind turbine with full scale power converter

The most common constructional shape of a synchronous generator (alternator) consists of a rotor, which creates the magnetic field, and of a stator comprising the induced windings. The rotor magnetic field ($\Phi=kr.Ir$) is generated by a continuous current (Ir) circulating in the field windings. Such continuous current is supplied by a dynamo coaxial to the alternator or it is drawn at the stator terminals and then rectified by a diode bridge. The movements of the rotor magnetic field with respect to the stator windings due to the rotation of the main shaft induces a triad of alternating voltages in the stator windings with an r.m.s. value proportional to the magnetic flow of the rotor and to the rotation speed (n):

When the generator is connected to a load (island or grid connection) and the current is delivered, this generates in the air gaps of the machine a rotating magnetic field synchronized with the induction field, without the relative slip. Besides, if the two magnetic fields are aligned (angle $\delta=0$), there is no resistive torque and consequently the active power provided to the grid is null. Otherwise, if there is a displacement due to an external motive torque, a resistive electrical torque is generated balancing the active power put into the grid ($\delta>0$).The higher the deviation, the higher the active power put into the grid. By keeping the angle δ fixed, the active power put into the grid increases linearly with the r.m.s. value of the induced voltage and therefore proportionally to the rotation speed and to the voltage frequency.

Synchronous generators are not intrinsically self starting. The alternator generally reaches the synchronous speed by means of the prime mover and then it is connected in parallel following a proper procedure. In applications, for which self starting is needed, the rotor is equipped with dampening copper bars, which start the alternator as an induction machine and during operation they dampen the dynamic oscillations of the machine. In wind applications, turbines with synchronous generators are normally started by the wind itself and a speed control system is used for the synchronization procedure.

Permanent magnet alternators are often used in wind turbines, in which the rotor is without the excitation winding and the induction magnetic field is generated directly by the permanent magnets built-in into the rotor. As a consequence, slip rings and brushes are not necessary for the supply of the excitation circuit. The operating principle is analogous to that of the alternators with the induction winding, but in the permanent magnet alternators the voltage induced into the stator windings cannot be adjusted through the excitation current; therefore the voltage at the generator terminals is only a function of the rotation speed of the rotor. Since the frequency generated by the alternator depends on the rotation speed of the rotor and on the number of pole couples, to be able to use the synchronous generator in a variable speed wind turbine keeping constant the frequency on the grid side, it is necessary to interpose a two stage power converter controlling the whole of the generated electric power.

- In the first stage, either a diode or a thyristor controlled bridge rectifier converts the electrical quantities generated by the alternator from variable frequency alternating quantities into direct quantities;
- In the second stage, through a DC link, supply is given to an inverter which converts the direct electrical quantities of voltage and current into alternating quantities at the grid frequency.

In case of a separated excitation alternator, the regulation of the r.m.s. value of the generated voltage is obtained by acting on the excitation current, while with a permanent magnet alternator the voltage can be adjusted either through a thyristor controlled bridge rectifier or through a PWM controlled inverter.

The PWM control of the inverter can be carried out through different modalities.

- Regulation of the value of the sinusoidal modulating amplitude by comparing the voltage value of the DC link with the optimum curve P-V_{dc}.
- MPPT (Maximum Power Point Tracker) by using an anemometer. The power on the dc side is compared with the reference power and from a comparison with the optimum curve, depending on the wind speed, the new voltage on the dc side is determined. The PWM (Pulse Wide Modulation) control signal varies instantaneously as the operating conditions vary.
- MPPT with wind forecast: the energy previously extracted is taken into consideration and, by statistical models; the wind speed in the following moments is forecast. This control system tracks the optimum points as function of the foreseen speeds.

The use of the configuration alternator power converter allows decoupling the generator from the grid, thus reducing the mechanical shocks on turbines during grid faults. Additionally, there is generation also of the desired reactive power and full control on the active power.

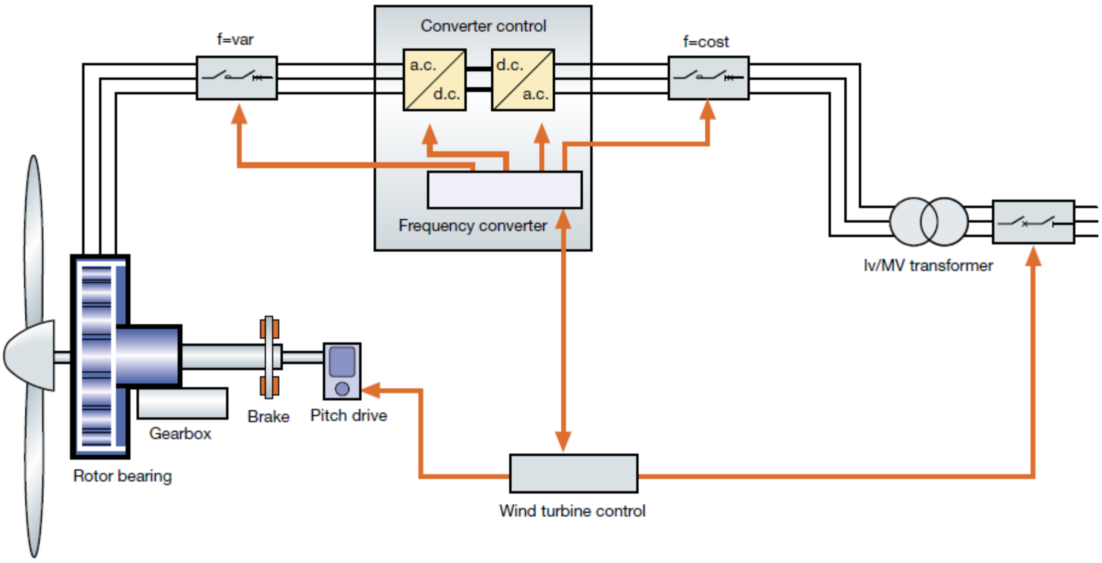


Figure 2.6: Illustration of permanent magnet synchronous generator

Chapter 03: Power quality issues and mitigating techniques

The power quality is used to describe how closely the electrical power delivered to customers corresponding to the appropriate standard and so operate their end use equipment correctly. It is an essential customer focused measure and is greatly affected by the operation of a distribution and transmission network. The growing importance of power quality is due to the widespread use of power electronic equipments such as information technology, power electronic converter, programmable logic controller and energy efficient lighting. These loads are sensitive in nature and simultaneously it is a major cause and major victim of power quality problems by generating harmonics to the system. Due to this non linear nature of such load, causes the disturbance in the waveform. This issue of power quality is of great importance to the wind turbine.

In case of fixed speed wind turbine operation, all the fluctuation in the wind speed are transmitted as fluctuations in the mechanical torque, electrical power on the grid and leads to large voltage fluctuations. Thus the network needs to manage, the excessive voltage transients which are to be avoided. Today in the variable speed wind turbine designs, the uses of power electronic converters are mostly used. Thus the issue of harmonic distortion of the network voltage should be considered. During the normal operation, wind turbine produces a continuous variable output power. These power variations are mainly caused by the effect of turbulence, wind shear, and tower shadow and of control system in the power system. These effect leads to periodic power variation at the frequency with which the blade passes through the tower, which are superimposed on slow variation caused by changes in the wind speed. There may be a high frequency power variation caused by the dynamics of the turbine. Today, the use of variable speed wind turbine operation has got the advantage; the fast power variations are not transmitted and can be made smooth. Thus the power quality issues can be viewed with respect to the wind generation and the transmission and distribution network can cause the variation in voltage to which the wind turbine is connected, such as voltage sag, swells, etc. However the wind generator introduces disturbances into the distribution network. The connection of power converter into the power system may inject the harmonic current into the grid and cause a reduction in power quality. Today the PWM inverter control technology has been developed and it can technically manage to control the power level associates with the commercial wind turbines. The wind turbine and their quality are assessed according to the national and international guidelines such as

- Grid connection requirement for wind power plants (Grid code) – Ceylon electricity board
- International electromechanical commissions (IEC) standard 61400-21:2008 ; Measurement and assessment of power quality characteristics of grid connected wind turbines,
- Institute of electrical and electronics Engineers (IEEE) standard 1159-2009: IEEE recommended practice for monitoring electric power quality.

Power quality issues of grid connected wind plant are occurred mainly due to following three factors

- Wind climate
- Design and technology of wind plant
- Dependency of relevant Grid

Power quality disturbances occur in three ways. They are;

- Voltage Events
    - Voltage fluctuation
    - Over voltage
    - Under voltage
    - Voltage sag/ Dip
    - Voltage swell
    - Voltage unbalance
    - Short term interruption
    - Long term interruption
- Frequency events
- Waveform events
    - Harmonics
    - Notching and noise
    - Transients

3.1. Voltage events

Classification of voltage events with relevant magnitude and time duration is shown in Figure 3.1.

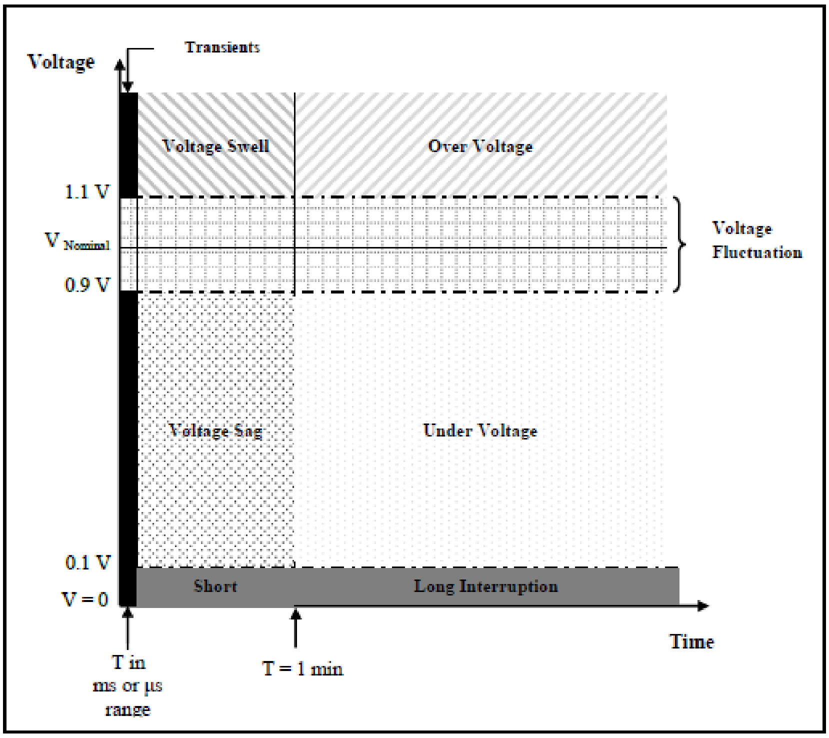


Figure 3.1: Classification of Voltage Events

3.1.1. Over voltage

When the voltage exceeds 10% of rms nominal voltage for the duration more than one minute is defined as over voltage. However, the grid code of CEB allows only 6%.

It is often the result of

- High distribution voltage due to incorrect tap settings on distribution transformers switching off a large load or excessive correction for voltage drop on the transmission and distribution systems such as energizing several capacitor banks.
- Over compensation of reactive power

These occur mainly because either the voltage controls are inadequate or the system is too weak for voltage regulation. Over voltage is caused to reduce life time of the electrical and in some cases it is caused to boost efficiency due the result of lower copper lose.

In order to provide electricity with complying with existing standards, have to mitigate over voltage events. Mitigation techniques of over voltage are as follows.

- Adjusting transformers to the correct tap setting (for manual tap changers) or installing voltage regulators or automatic on load tap changers to improve the voltage profile. Voltage regulators include the servo mechanical tap switching voltage regulators, electronic tap switching voltage regulators and the Ferro resonant transformers.
- Manually or automatically switching off excess capacitor banks during light load or off peak hours.

3.1.2. Under voltage

Under voltage is described by IEEE 1159 as the decrease in the AC voltage (RMS), typically to 80% - 90% of nominal voltage, at the power frequency for a period of time greater than 1 minute. Under voltage generally results from low distribution voltage because of heavily loaded circuits that lead to considerable voltage drop, switching on a large load or group of loads, or a capacitor bank switching off and islanding large grid connected wind plants.

Mitigation techniques are required in order to provide electricity within acceptable limit of Voltage. Mitigation techniques of under voltage are as follows.

- Reducing the system impedance - reduce the line length, add series capacitors or increase the size of line conductors.
- Improving the voltage profile - adjust transformers to the correct tap setting (for manual tap changers) or install voltage regulators or automatic on-load tap changers. Voltage regulators include the mechanical tap changing voltage regulators, electronic tap switching voltage regulators and the Ferro resonant transformers.
- Reducing the line current – de load the feeder or circuit by transferring some loads to other substations or load centers, add shunt capacitors or static VAR compensators, or upgrade the line to the next voltage level.

3.1.3. Voltage Sag/ Dip

Voltage sags occurs in distribution network mainly due to network fault and sudden integration of large load into the system. Sags can be characterized by their depth and duration. The maximum reduction of rms voltage is considered as Sag depth.

There are two definitions of voltage sag;

The IEC electro technical vocabulary, IEC 60050, defines voltage sag as any *"sudden reduction of the voltage at a point in the electrical system, followed by voltage recovery after a short period of time, from half a cycle to a few seconds"*.

IEEE Standard 1159 defines voltage sag as a variation in the rms voltage of duration greater than ½ a cycle and less than 1 minute with a retained voltage of between 10% and 90 % of nominal.

IEEE clearly mentioned the limitations of two characters of sag as depth of sag and duration.

Low voltage ride through (LVRT) capability is critical factor when voltage sag is taken in to account. The LVRT term is capturing the ability of a wind turbine to stay connected to the grid throughout a short system voltage drop or a system failure /blackout.

When the voltage of the grid is dropping it is essential that a wind plant stay online in order to prevent major blackouts. It is not only essential that the plant stays online, it is equally essential that the park is working actively to compensate for the faulty grid condition.

As per the grid code, wind farm which exceed installed capacity of 5MW should have LVRT capability. The conditions are as follows.

- The wind plant shall be connected to grid during voltage disturbances of the power system for a short period time.

- If the voltage at point of common coupling 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 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.

Mitigation techniques of voltage sags are as follows;

- STATCOM
- Static Var Compensator (SVC)
- Dynamic Voltage Restorer (DVR)
- Coil Hold In Devices
- Ferro resonant Transformer
- Uninterruptible power supply (UPS)
- Flywheel and Motor Generator (MG)
- Sag Proofing Transformers

3.1.4. Voltage swell

Voltage Swell is defined by IEEE 1159 as the increase in the RMS voltage level to 110% - 180% of nominal, at the power frequency for durations of ½ cycles to one minute

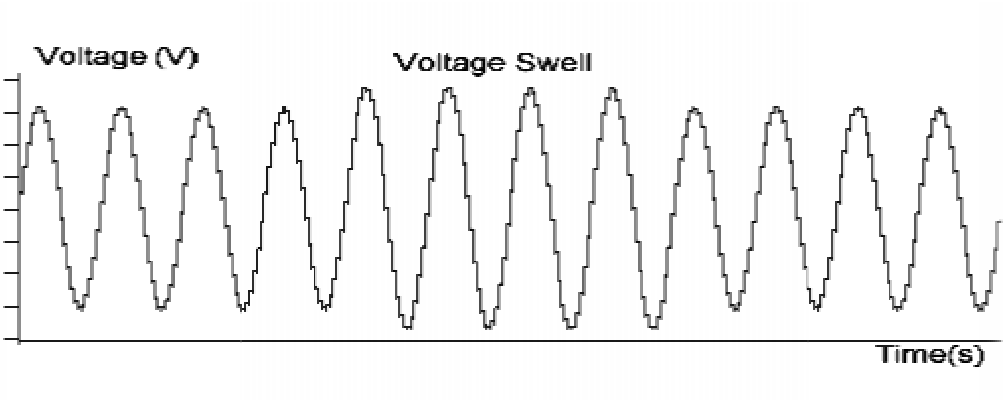


Figure 3.2: Voltage swells in a waveform.

3.1.5. Voltage unbalance

Voltage unbalance is a significant power quality issue in electricity distribution sector. Electrical system can become unbalanced due to the unequal system impedances and the unequal distribution of single phase loads.

There are two definitions for voltage unbalance

- Using symmetrical components

Widely used in European standards, the first definition is considering theory of Symmetrical Components which mathematically breaks down each (balanced or unbalanced) system, into three symmetrical components as positive sequence, negative and zero sequence systems. For a perfectly balanced system both negative and zero sequence are negligible. Figure 3.3 shows that the symmetrical representation of asymmetrical three phase voltage. First diagram shows asymmetrical voltage and then shows positive, negative and zero sequences respectively.

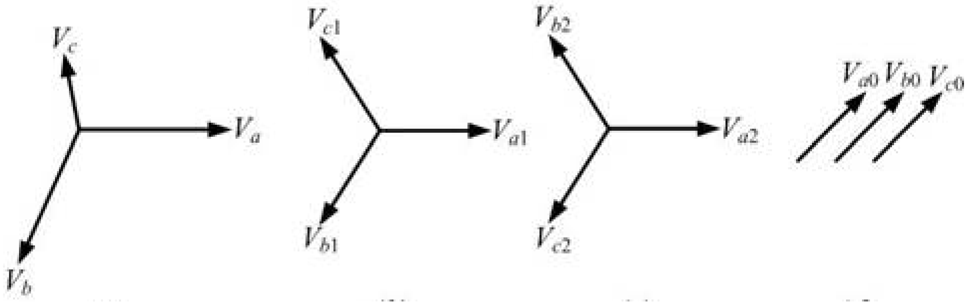


Figure 3.3: representation of symmetrical component

Negative sequence voltage unbalance (V_2/V_1);

$$\frac{V_2}{V_1} = \sqrt{\frac{1-\sqrt{3-6\beta}}{1+\sqrt{3-6\beta}}} \qquad ; \text{Where } \beta = \frac{V_{ab}^4 + V_{bc}^4 + V_{ca}^4}{(V_{ab}^2 + V_{bc}^2 + V_{ca}^2)^2}$$

- Definition of NEMA

NEMA (National Electrical Manufacturers Association of USA) standard definition is given as follows

$$Voltage\ Unbalance = \frac{Maximum\ \ deviation\ \ from\ mean\ \ of\ \{V_{ab}, V_{bc}, V_{ca}\}}{mean\ \ of\ \{V_{ab}, V_{bc}, V_{ca}\}}$$

Acceptable limit for voltage unbalance is 2%

Mitigation techniques of voltage unbalance can be adopted at utility level as well as at plant level

- Utility level techniques:
    - Distribution of single phase loads equally to all phases.
    - Reduction of the system unbalance that arise due to system impedances such as those due to transformers and lines.
    - Single phase regulators have been suggested as devices that can be used to correct the unbalance but care must be exercised to ensure that they are controlled carefully not to introduce further unbalance.
    - Passive network systems and active power electronic systems such as Static Var Compensators and line conditioners also have been suggested for unbalance correction. Compared to passive systems, active systems are able to dynamically correct the unbalance.

- Plant level techniques:
    - Load balancing.
    - Use of passive networks and static var compensators.
    - Equipment that is sensitive to voltage unbalance should not be connected to systems which supply single phase loads.
    - Effect of voltage unbalance on ac variable speed drives can be reduced by properly sizing ac side and dc link reactors.

3.1.6 Interruptions

There are two interruptions as short interruptions and long interruptions. When the rms value of nominal voltage falls less than 0.1 pu for less than 1 minute period it is called as short interruption and interruption duration is longer than 1 minute it is called as long interruption. Short interruption may occur due to network fault and most of the long interruptions are scheduled interruption for maintenance and system augmentation works.

3.1.7. Voltage fluctuation

Voltage fluctuations defined as repetitive or random variations of the voltage envelope due to sudden changes in the real and reactive power. The magnitudes of these variations do not exceed ± 6% of the nominal voltage. The characteristics of voltage fluctuations depend on the load/source type and size and the power system capacity. The voltage waveform shows variations in magnitude due to the fluctuating nature or intermittent operation of connected loads/source. In a wind plant, voltage fluctuates due to variation of energy production with the varied wind speed. The frequency of voltage envelope is referred as flicker frequency. Therefore, there are two important parameters as flicker frequency and magnitude of flicker. Figure 3.4 shows the fluctuation of voltage waveform

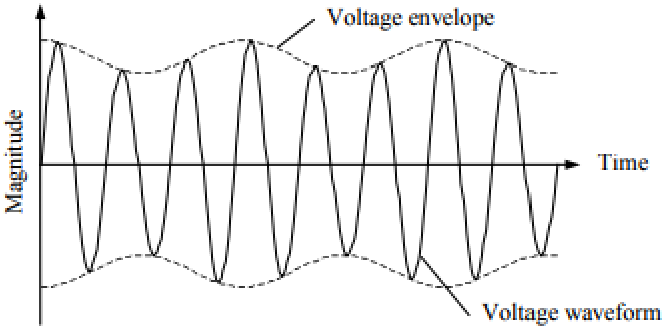


Figure 3.4: Fluctuation of a voltage waveform

Lamp flicker

Flicker is referred as a physiological effect and defined as "Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time"

Lamp flicker occurs when the intensity of the light from a lamp varies with the changes in the magnitude of supply voltage. The intensity change can create disturbance to human eye. Voltage variations as low as 0.3% could result in perceptible light flicker, if the frequencies are in the range of 6 to 8 Hz as shown in Figure 3.5.

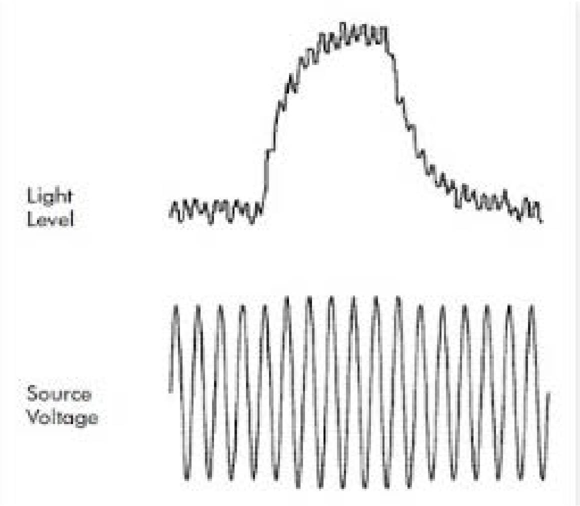


Figure 3.5: Voltage fluctuation and variation of light level

Two indexes are used to measure flicker level, short term flicker index (P_{st}) and long term flicker index (P_{lt}). The measure of the severity of short term flicker, P_{st} is then calculated every 10 minutes using weighted cumulative probability values of the flicker levels exceeding 0.1, 1, 3, 10 and 50% of the time using equation

$$P_{st} = \sqrt{0.0314P_{0.1} + 0.0525P_1 + 0.0657P_3 + 0.28P_{10} + 0.08P_{50}}$$

People's tolerance to flicker over longer periods is less than for the short term. Due to this, the second index is introduced by the standards, the long term flicker index; P_{lt}. P_{lt} is an average of P_{st} values evaluated over a period of two hours using a cubic law as defined in equation

$$P_{lt} = \sqrt[3]{\frac{1}{12}\sum P_{st}^3}$$

Allowable compatibility level and planning level of flicker shows in table 3.1 and IEC characteristic curve for flicker is shown in Figure 3.6.

Table 3.1: Allowable level for flicker

	Compatibility level		Planning level	
	LV	MV	MV	HV & EHV
P_{st}	1.0	1.0	0.9	0.8
P_{lt}	0.8	0.8	0.7	0.6

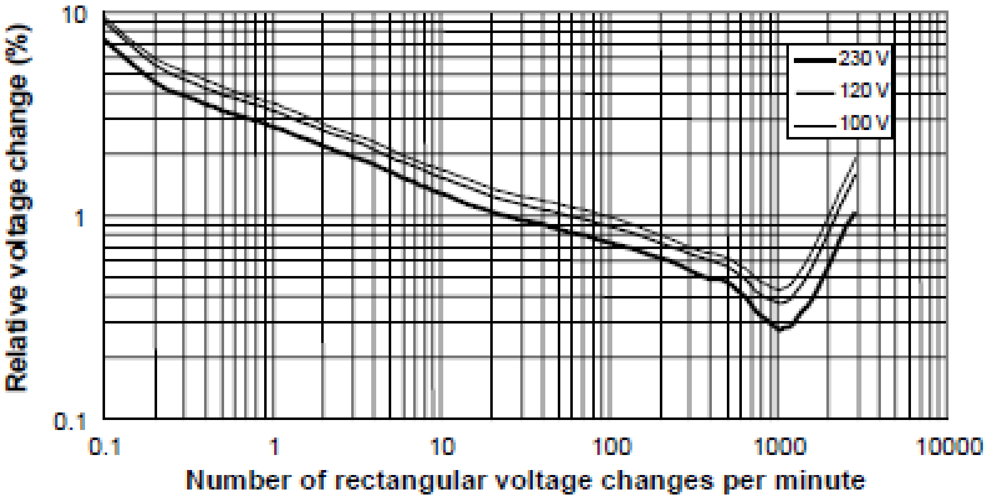


Figure 3.6: IEC Flicker curve

These are the major causes for Lamp flicker

- Intermittent types generators (e.g. wind turbines, solar plant).
- Capacitor switching, transformer on load tap changers (OLTC), step voltage regulators and other devices that alter the inductive component of the source impedance.
- Electric arc furnaces
- Static frequency converters
- Cycloconverters
- Rolling mill drives
- Main winders

Flicker is the major concern for power quality problems due to wind energy integration to the distribution network and it is limit the number of grid connected wind turbines. Flicker generates with the variation of generated power output from wind plant due to tower shadow effects, wind shear, and yaw error, misalignment of rotor blade angles, wind speed turbulence intensity, switching events and control system of the wind turbine

Mitigation techniques are required to prevent from lamp flickering.

- Increasing the fault level at the point of connection. Strengthening the system or reconnecting the offending load at a higher voltage level can achieve this.
- Decrease the reactive power flow through the network due to the load. This may be achieved through the use of a Static Var Compensator (SVC), STATCOM and will help reduce voltage sags.
- Strengthening the network reactive power compensation. A larger number of smaller capacitor banks distributed throughout a system will allow finer tuning of reactive power requirements

3.2 Waveform events

3.2.1 Harmonics

Harmonics are described by IEEE as sinusoidal voltages or currents having frequencies that are integer multiples of the fundamental frequency at which the power system is designed to operate. Harmonic waveforms with odd harmonic numbers are referred as “odd harmonics” and harmonic waveform with even harmonic numbers are referred as “Even harmonics”. Odd harmonics are additive and even harmonics are cancel out in the neutral conductor. Fourier series representation of a periodic waveform consisting DC component, fundamental and harmonic component can be shown as follows

$$F = F_0 + F_1 \cos(\omega t + \theta_1) + \sum_{h=2}^{\infty} (F_h \cos(h\omega t + \theta_h))$$

Main harmonic sources in wind plants are,

- Rectifier / Inverter system
- Thyristor soft starter devices
- Power factor compensation unit (capacitors, static var compensator)

3.2.2. Notching

Voltage Notching is described by IEEE as a recurring power quality disturbance due to the normal operation of power electronic devices, when current is commutated from one phase to another.

Voltage Notching is primarily caused by three phase rectifiers or converters that generate continuous DC current. As mentioned, the voltage notches happen when the current commutates from one phase to another. Subsequently, a momentary short circuit between two phases will occur during this period.

Moreover, the depth of the notch at any point in the system is influenced by the source inductance, the isolating inductance between the rectifier/converter, as well as the point being examined.

Voltage Notches introduce harmonic and non harmonic frequencies that are much higher than those found in higher voltage systems. Usually, these frequencies are in the radio frequency range, that cause negative operational effects, such as signal interference introduced into logic and communication circuits. Also, when of sufficient power, the voltage notching effect may overload electromagnetic interference filters, and other similar high frequency sensitive capacitive circuits.

The solution for voltage notching typically involves isolation of the critical and sensitive equipment from the source (i.e. rectifiers) of the power quality problem.

3.2.3. Transients

Transient over voltages in electrical distribution networks result from the unavoidable effects of lightning strikes and network switching operations. These over voltages have the potential to result in large financial losses due to damaged equipment and lost production. In a wind integrated system transients may occurs during cut in, cut out and other discrete switching operation of the wind turbine. Transient over voltages can be classified as two categories

- Impulsive transients resulting from lightning strikes
- Oscillatory transients resulting from network switching.

Chapter 04: Measurement of Power Quality at Wind Power Plants

Measurement taken from fluke 435-II power quality analyzer and analyzed measured data by power log 430-II software developed by fluke cooperation. Measurements were taken for 10 min interval for seven days at plant output. Limitations of power quality parameters set by considering,

- International electromechanical commissions (IEC) standard 61400-21:2008 ; Measurement and assessment of power quality characteristics of grid connected wind turbines,
- EN 50160 Voltage Characteristics in Public Distribution Systems
- IEEE 1159-2009: IEEE recommended practice for monitoring electric power quality.
- Grid connection requirement for wind power plants (Grid code) – Ceylon electricity board

Table 4.1 shows the technical specification of wind plant

Table 4.1: Technical specification of wind plant

POWER	
Rated Power	1500 kW
Cut in wind speed (10min. mean)	3 m/s
Rated wind speed (10min. mean)	12.5 m/s
Cut out wind speed (10min. mean)	22 m/s
Survival wind speed	52.5 m/s
Generator	Variable speed, Multi Pole synchronous with permanent magnet excitation
ROTOR	
Diameter	82m
Swept area	5325 sqm
Speed range (Variable)	9 to 17.3 rpm
TOWER AND FOUNDATION	
Hub height	85m
Design	Tubular,Four section
Foundation type	Floating foundation
CONTROL AND SAFETY SYSTEMS	
Control of output	Pitch Regulation
Speed control	Variable, Micro controller based
Low Voltage Ride Through (LVRT)	3 seconds
Primary brake system	Aerodynamic Brake, Single Pitch Control / Triple redundant
Pitch System	Electromechanical, Maintenance Free toothed Belt Drive (Patented)
Remote Monitoring	VPN, Visualization via web browser
GENERAL	
Number of turbines	16
Air density	1.18kg/m^3
Turbine Spacing	400 m in a single raw
Expected Plant Factor	30%
Total yield	60 GWh per annum

4.1 Voltage Events

4.1.1. Voltage variation

As per the standards and requirement of Grid code, operating voltage can be varied within (+/-) 6% of nominal voltage. Allowable limit as per the standard is 0.94 pu ≤output voltage of the plant (V_{plant}) ≤ 1.06 pu

If;

- $V_{plant} > 1.06$ pu; Overvoltage condition. Plant should remain connected with grid for 1 min and trip.
- $0.94 \text{ pu} < V_{plant} < 1.06$ pu; Voltage lies within operational limit. Plant should operate continuously
- $V_{plant} < 0.94$ pu; Under voltage condition. Plant should remain connected with grid for 1 min and trip.

Figure 4.1 shows the voltage variation of wind plant output during measurement period.

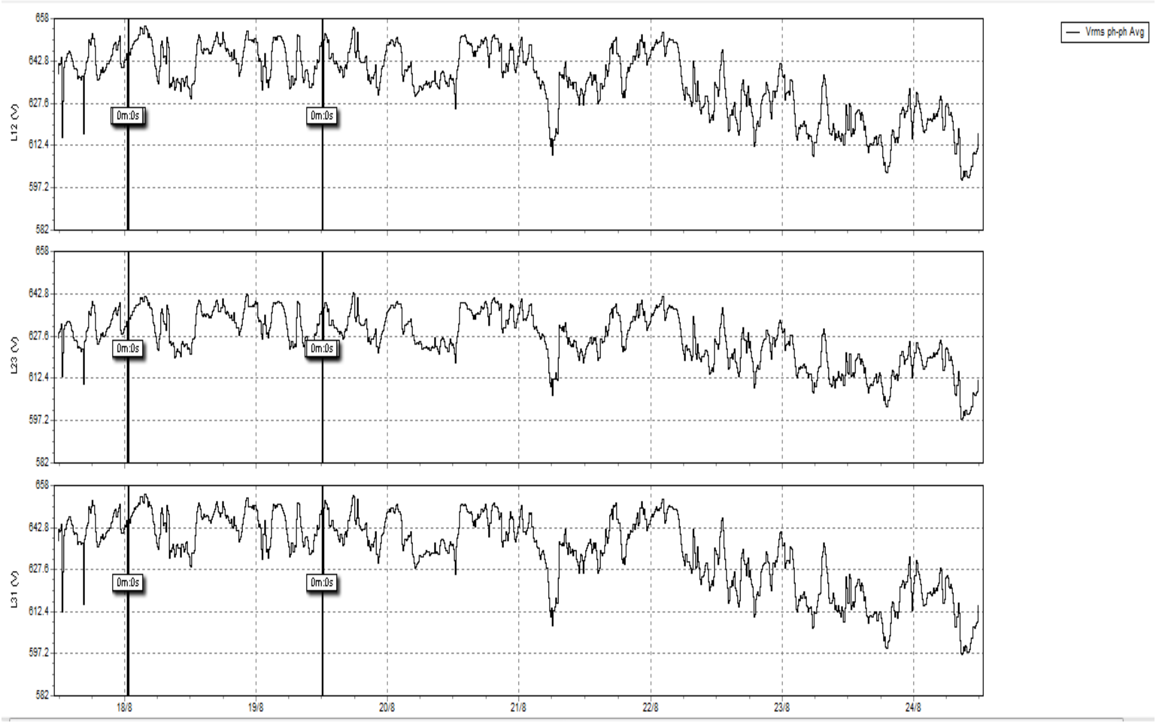


Figure 4.1: Phase to phase r.m.s average voltage of wind plant output

- Rated phase to phase output voltage of plant: 620 V
- Acceptable limit: 582.8V - 657.2V

According to the graph, even though there is high fluctuation of output voltage it shows that phase to phase r.m.s average voltage in wind plant outputs of all three phases are lies within acceptable limits as per the standards. Therefore no power quality issues rose due to voltage variation.

4.1.2. Voltage Dip, Swell and Interruption

When analyze the voltage dip, swell and interruption in an electrical system, it is very important to study of CBEMA curve and ITIC curve.

- CBEMA curve

CBEMA Curve was developed by the Computer Business Equipment Manufacturers Association in the 1970s to describe the tolerance of mainframe computer business equipment to the magnitude and duration of voltage variations on the power system. Also, the association designed the curve to point out ways in which system reliability could be provided for electronic equipment.

- ITIC curve

ITIC curve was developed by a working group of the CBEMA, which later changed its name to the Information Technology Industry Council (ITIC) in 1994. Even though it was primarily developed for 120V computer equipment just like the CBEMA curve, The ITIC curve has been applied to general power quality evaluation. Also, it is used as a reference to define the withstand capability of various loads and devices for protection from power quality problems. ITIC has defined three regions as prohibited region, no damaged region and no interruption in function region. If any measurement lies in prohibited region it may harm/ damage the equipment and if the measurement lies within no damage region, it creates lower efficiency of equipment or malfunction. No interruption in function region is the suitable region for the best operation of IT equipment

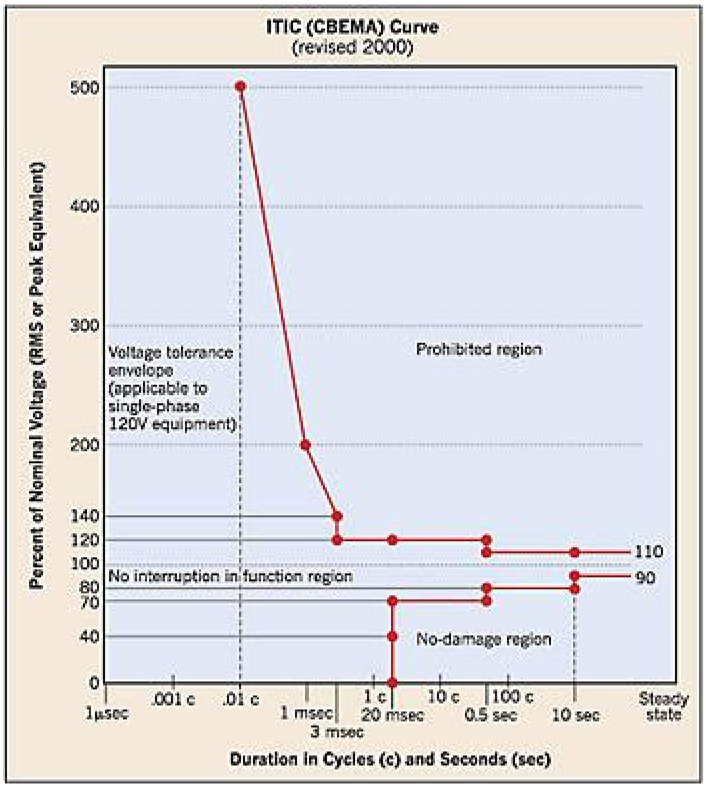


Figure 4.2: ITIC curve

Recorded voltage dip, swell and interruptions with CBEMA, ITIC curve shown in figure 4.3.

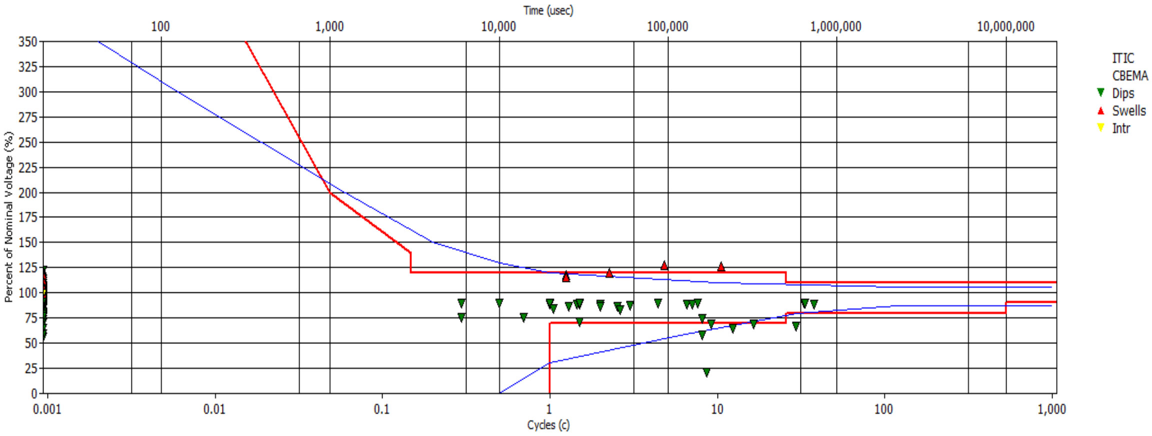


Figure 4.3: Voltage dip, swell and interruption with CBEMA,ITIC curve

- Voltage dip

Voltage dip/sag is occurred when 0.1 pu < V_{plant} < 0.94 pu duration less than 1 minute period of time. Throughout the measurement 47 numbers of dips were recorded while 6 numbers of voltage dips are within No damage region. In this region couldn’t get expected output from IT equipment by the result of lower efficiency or malfunction, but no damages result to the equipments.

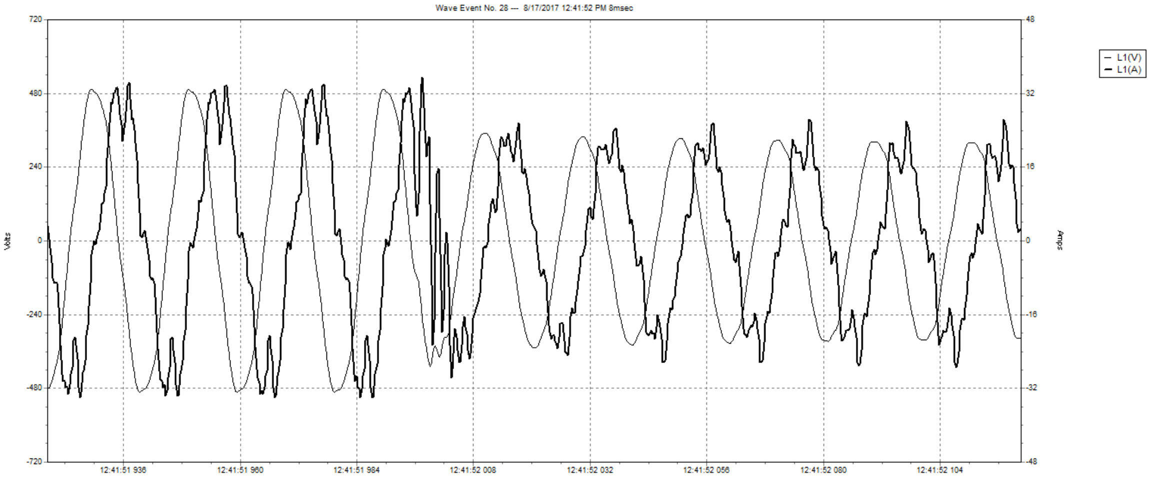


Figure 4.4: wave event of Voltage sag

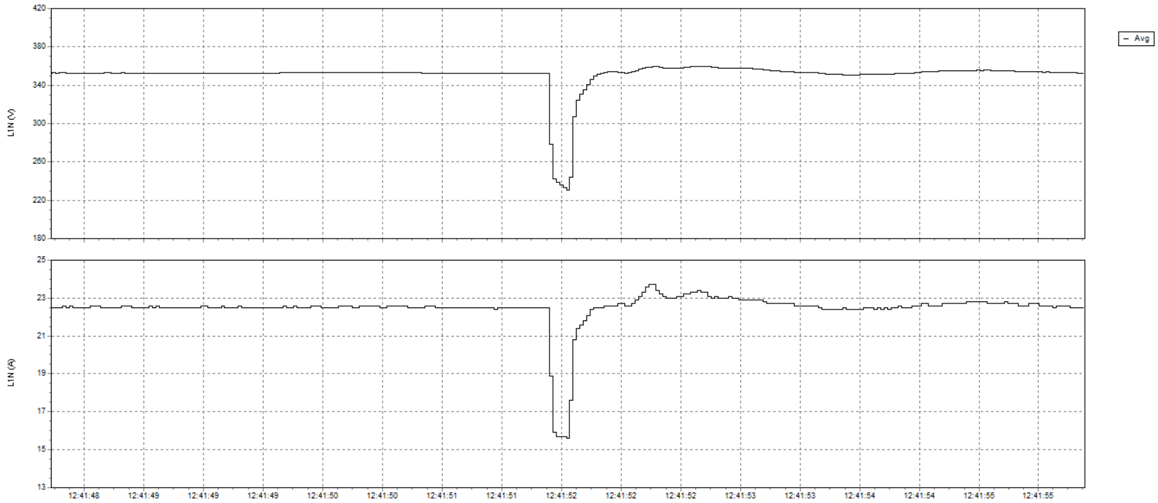


Figure 4.5: rms event of Voltage sag

- Voltage swell

Voltage swell is occurs when 1.06 pu < V_{plant} during 1 minute period of time. Throughout the measurement 5 numbers of swell were recorded and there was 2 event of voltage swell founded in prohibited region which is cause to damage IT equipment. A recorded wave event and rms event of Voltage swell are shown in Figure 4.6 and Figure 4.7.

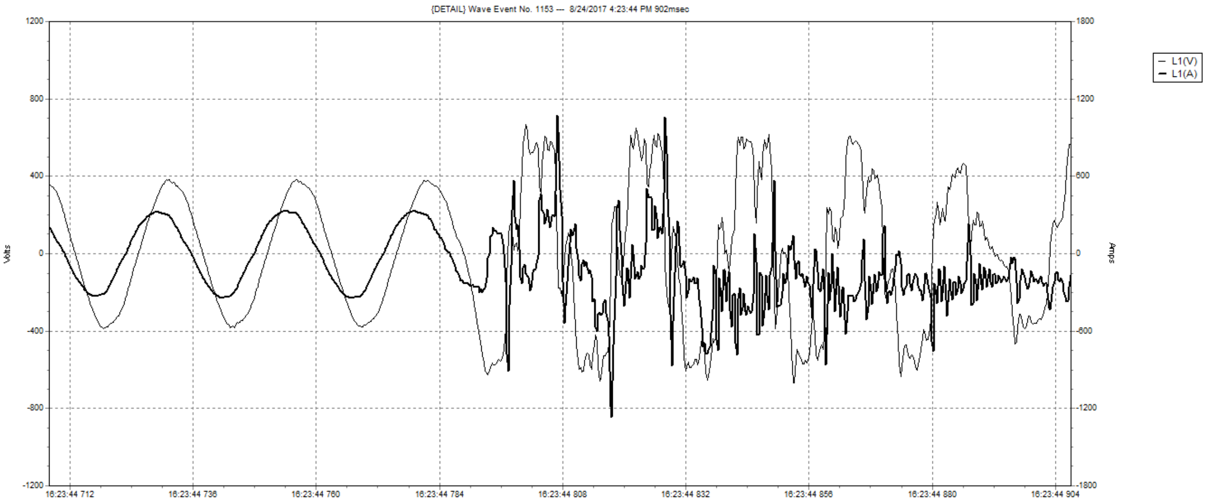


Figure 4.6: waveform event of a voltage swell

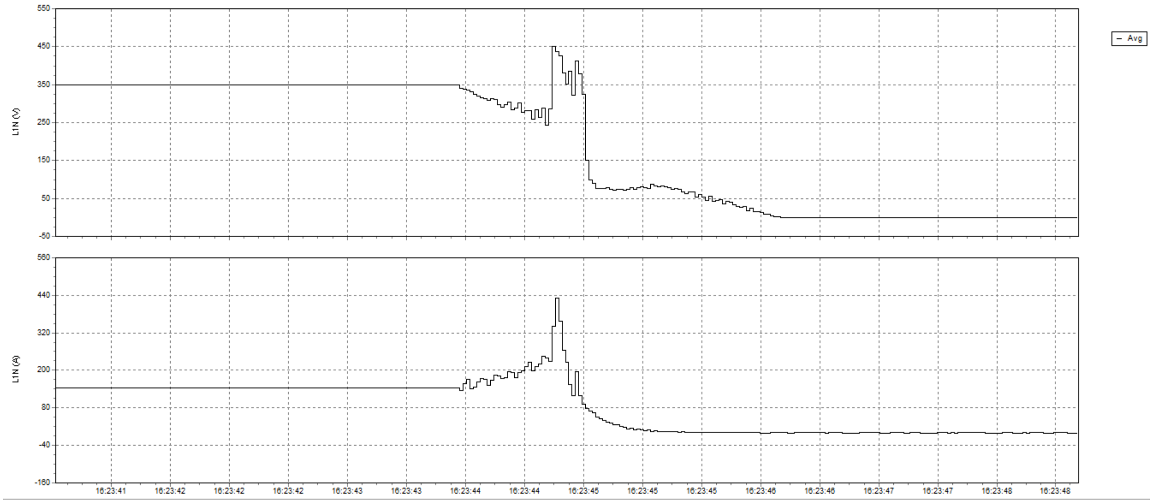


Figure 4.7 : rms event of a voltage swell

- Interruption

There are two interruption types naming short interruption and long interruption. Short interruption occurs when $V_{plant} < 0.1$ p.u. for the duration less than one minute and long interruption occurs when $V_{plant} < 0.1$ pu for the duration more than one minute. There was no short interruption and 4 numbers of long interruptions were recorded throughout the measurement period as shown in table 4.2.

Table 4.2: Recorded interruption

Date	Start time	End time	Duration	Interruption type
2017.08.18	00.37.09	00.40.24	3m 15s 479ms	Long Interruption
2017.08.19	12.05.37	12.08.34	2m 57s 14ms	Long Interruption
2017.08.24	16.23.46	16.59.36	35m 49s 977ms	Long Interruption
2017.08.24	17.04.05	17.06.33	2m 27s 399ms	Long Interruption

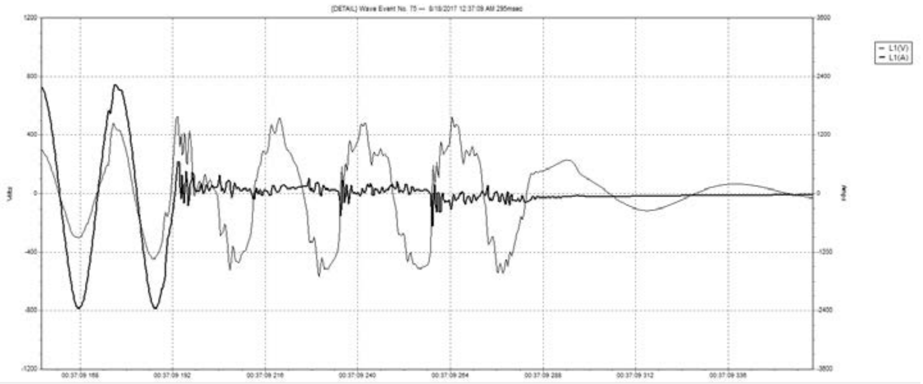


Figure 4.8: waveform event of interruption occurs

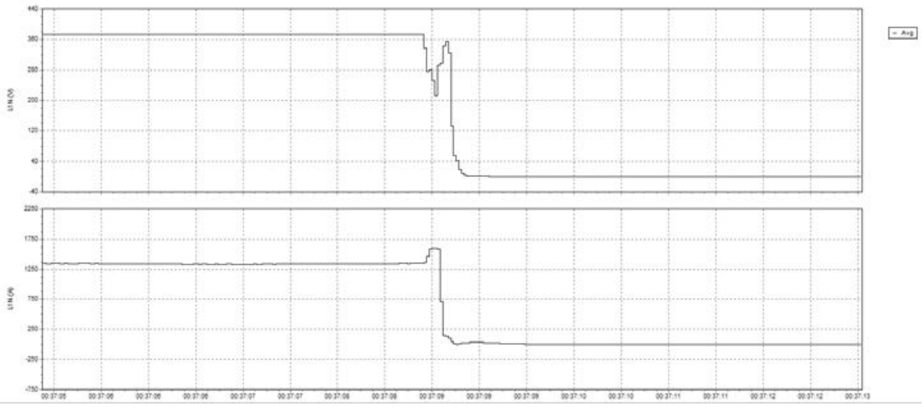


Figure 4.9 : rms event of interruption occurs

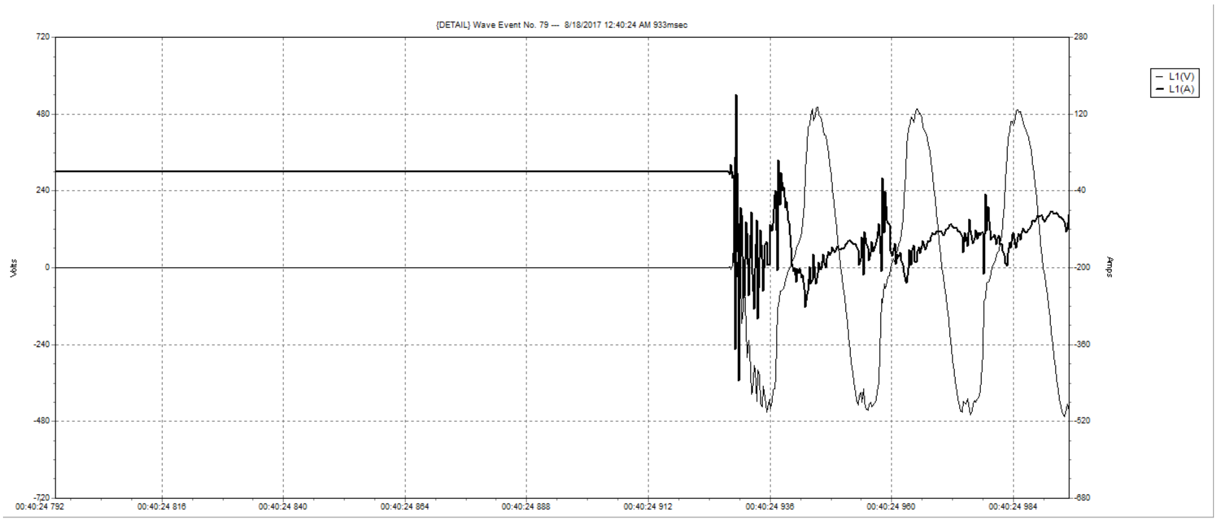


Figure 4.10: waveform event of ending interruption (starting of wind turbine)

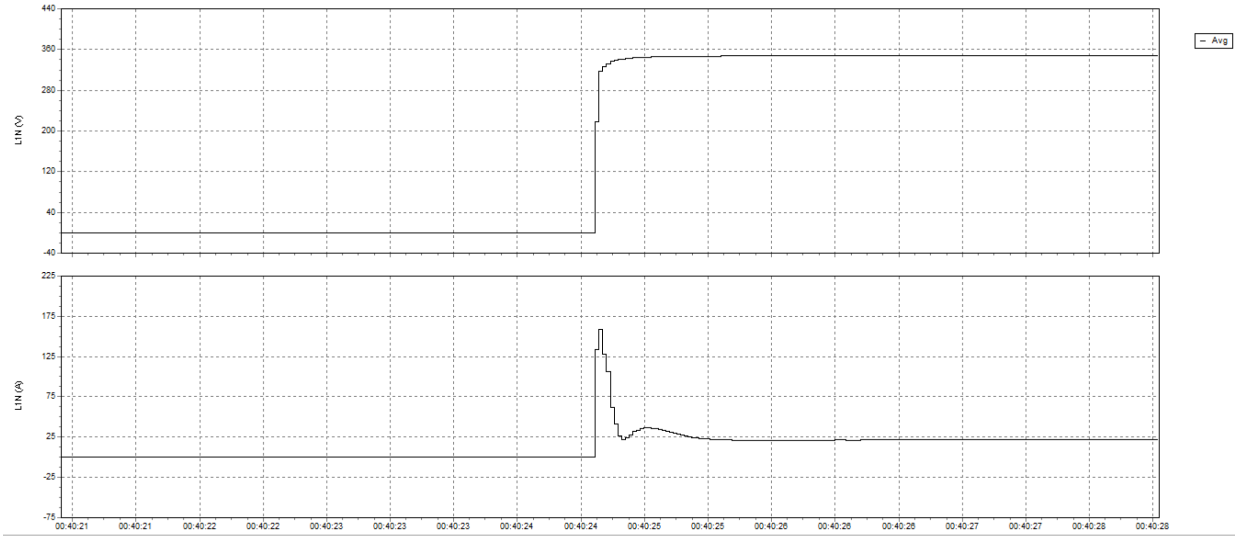


Figure 4.11: rms event of ending interruption (starting of wind turbine)

According to the measurement of voltage dip, swell and interruption with ITIC curve, it is identified following departures from standard.

- 6 numbers of voltage dip events within no damage region
- 2 numbers of voltage swell in prohibited region

4.1.3. Voltage unbalance

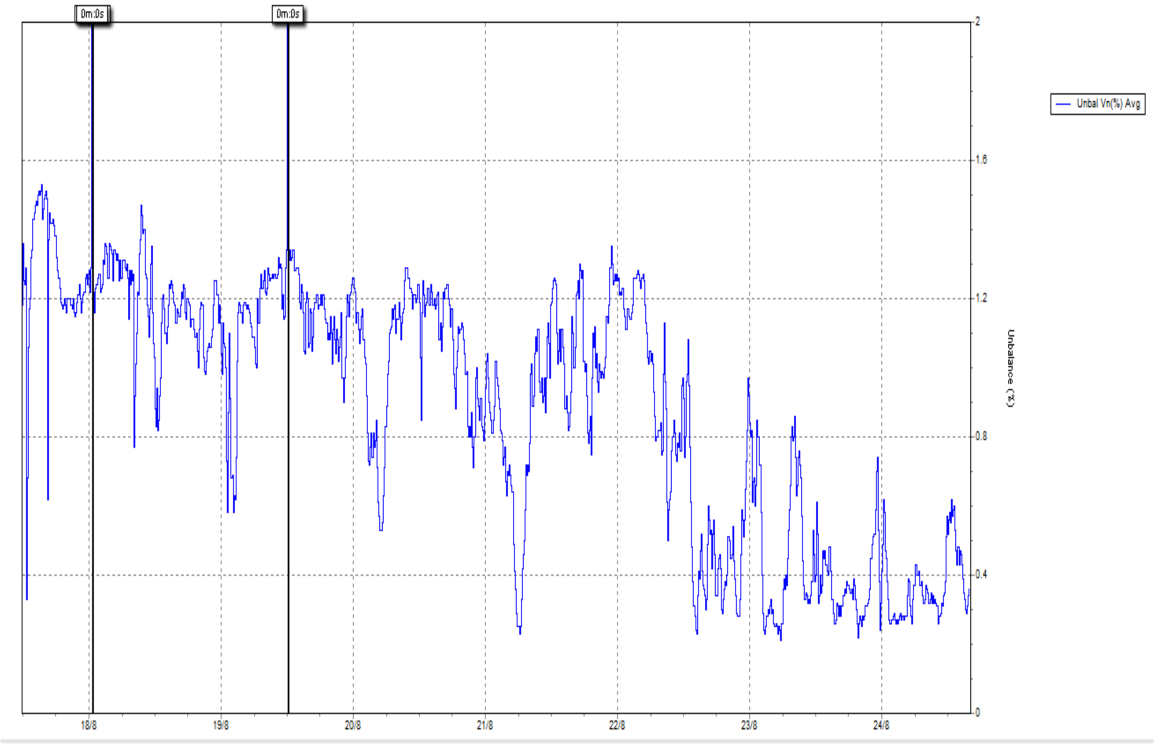


Figure 4.12: Negative sequence of voltage unbalance

According to the standards, negative sequence of voltage unbalance should lies within 0-2%. Figure 4.12 shows that the recorded measurement of negative sequence of voltage unbalance is within acceptable limit.

4.1.4. Flicker

Flicker meter is outlined in Australian standards of AS 4376 and AS 4377. As mentioned in previous chapter, there are two indexes for flicker measurements. Figure 4.13 shows that Short term flicker severity index (P_{st}) and Figure 4.14 shows that statistics of P_{st}.

- Short term flicker

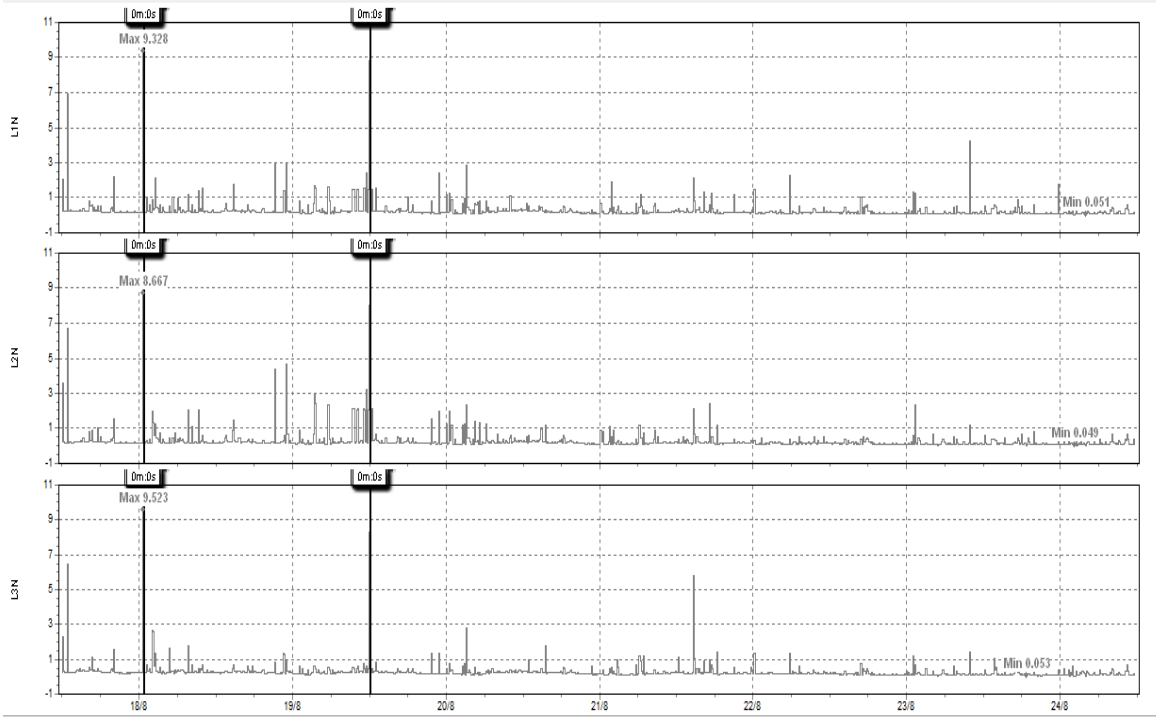


Figure 4.13: Short term flicker severity index (P_{st})

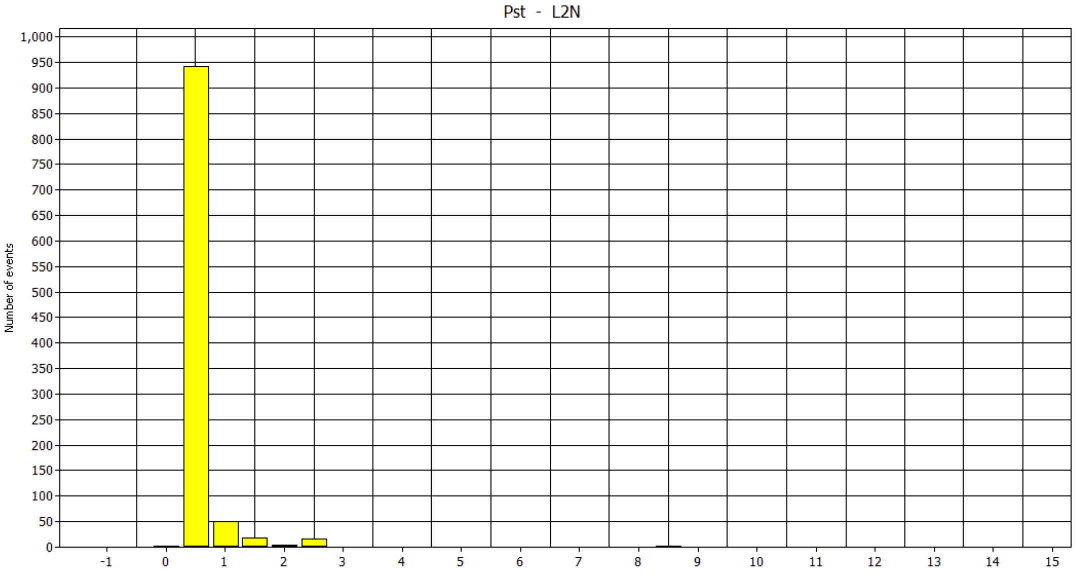


Figure 4.14: statistics of P_{st}

According to the measurements taken throughout the time period and statistics of P_{st}, it can be seen that the wind plant violate the condition of standard and grid code, $P_{st} < 1$.

- Long term flicker

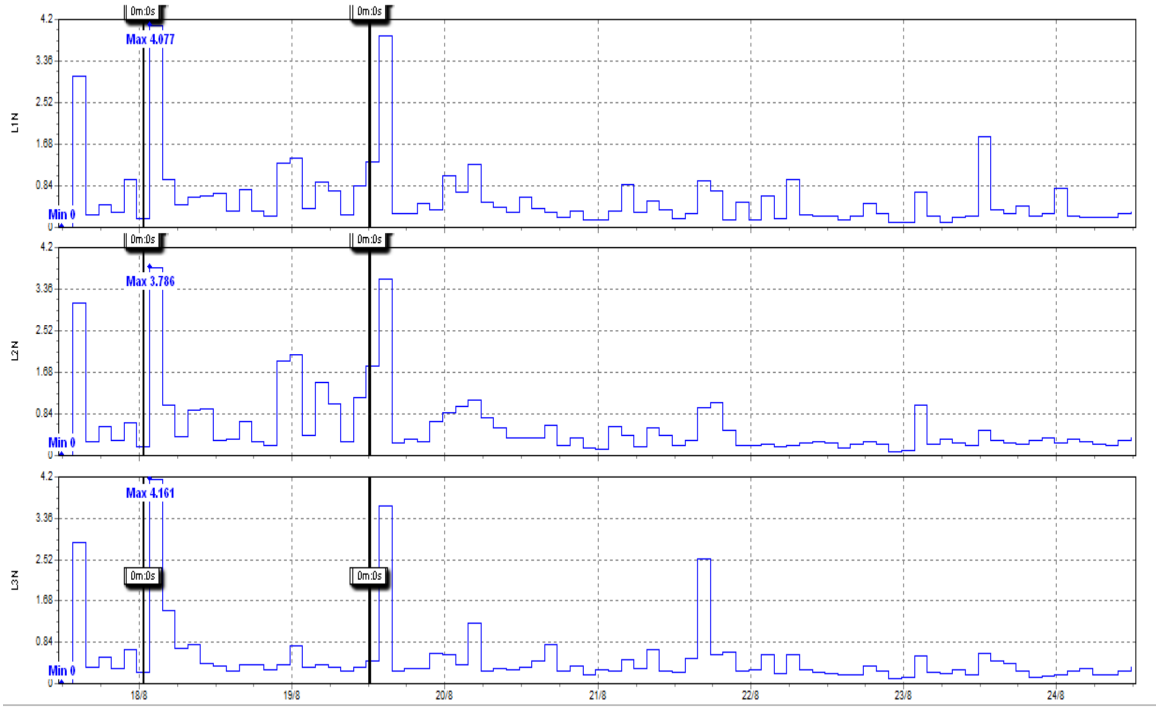


Figure 4.15: Long term flicker severity index (P_{lt})

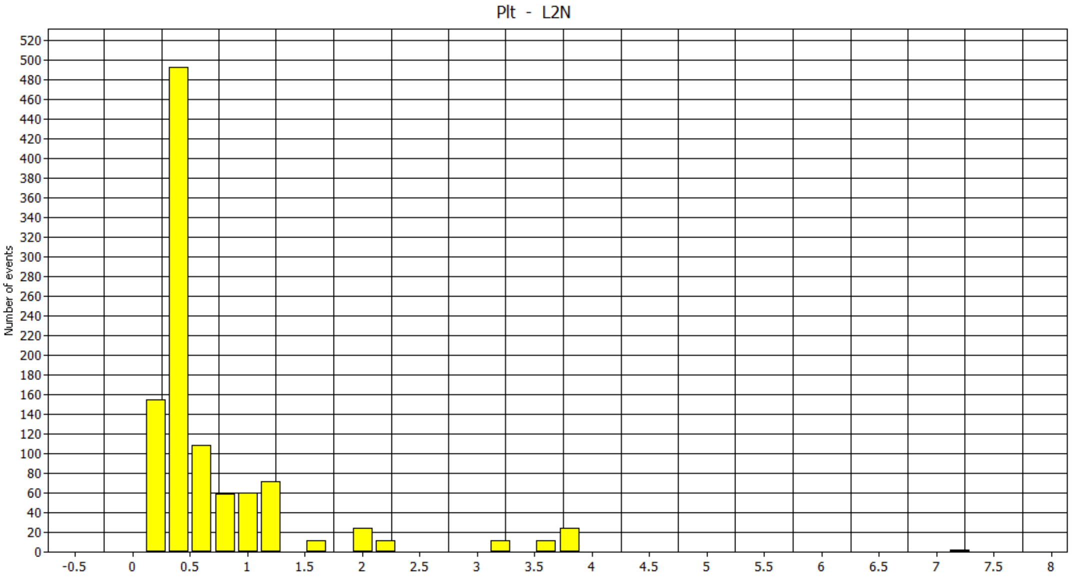


Figure 4.16: statistics of P_{lt}

According to the measurements taken throughout the time and statistics of P_{lt}, it can be seen that the wind plant violate condition of the standard $P_{lt} < 0.8$ also.

4.1.5. Transients

Throughout the measurement period, 14 numbers of transients were recorded. All are relevant interruption of the wind plant (during switching ON and OFF of the wind plant). Figure 4.17 and Figure 4.18 shows the waveform event and rms event of a transient recorded.

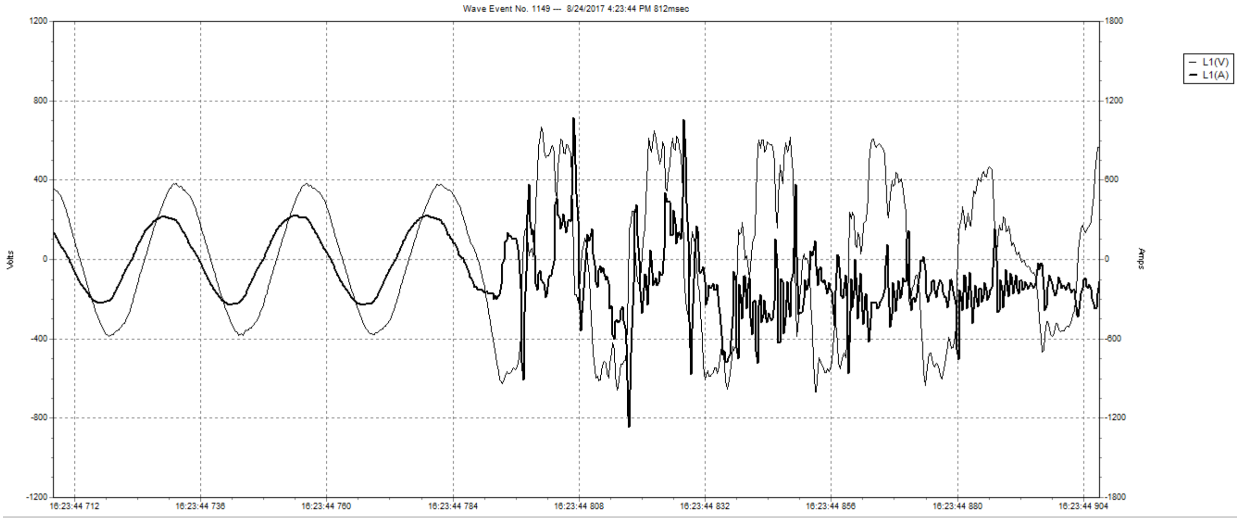


Figure 4.17: waveform event of a transient

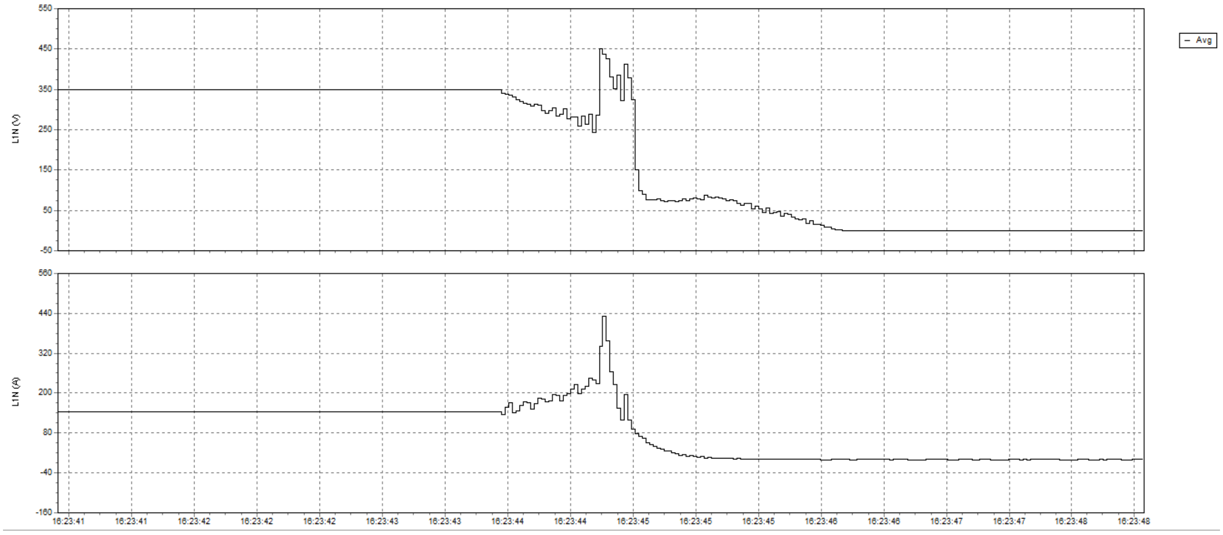


Figure 4.18: rms event of a transient

4.2. Frequency events

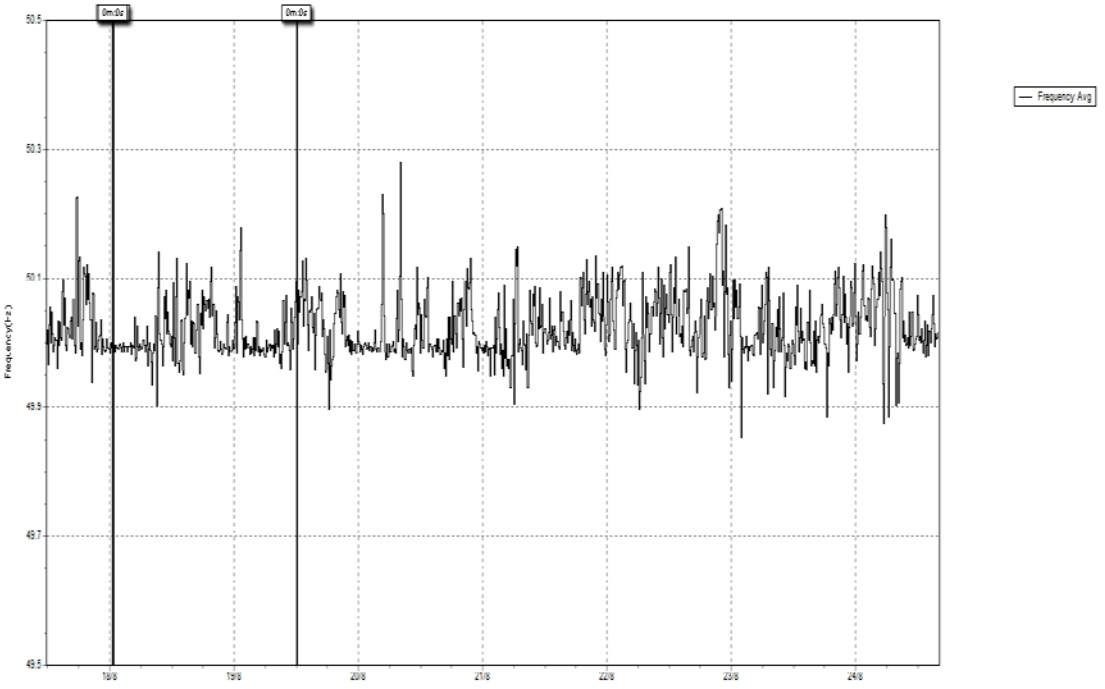


Figure 4.19: Average frequency

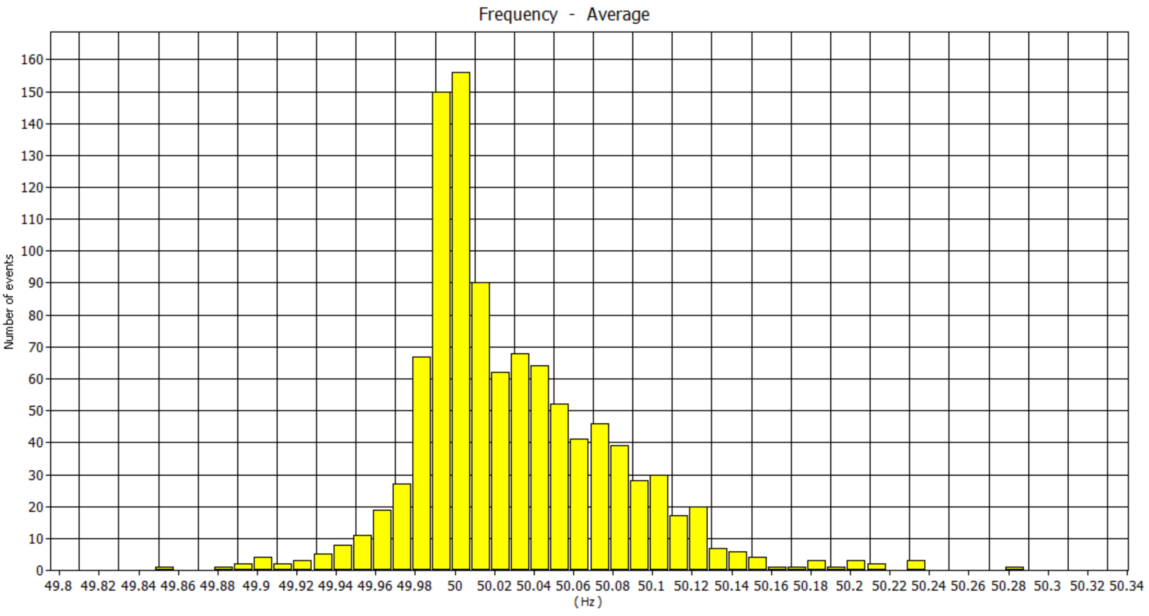


Figure 4.20: statistics of recorded frequency

CEB grid code allows only ±1% variation for frequency in normal operation (49.5Hz – 50.5 Hz). Recorded 50.28 Hz as maximum value and 49.853 as lowest through the measurements and all measurements are within acceptable limits.

4.3. Waveform events

4.3.1Voltage harmonic distortion

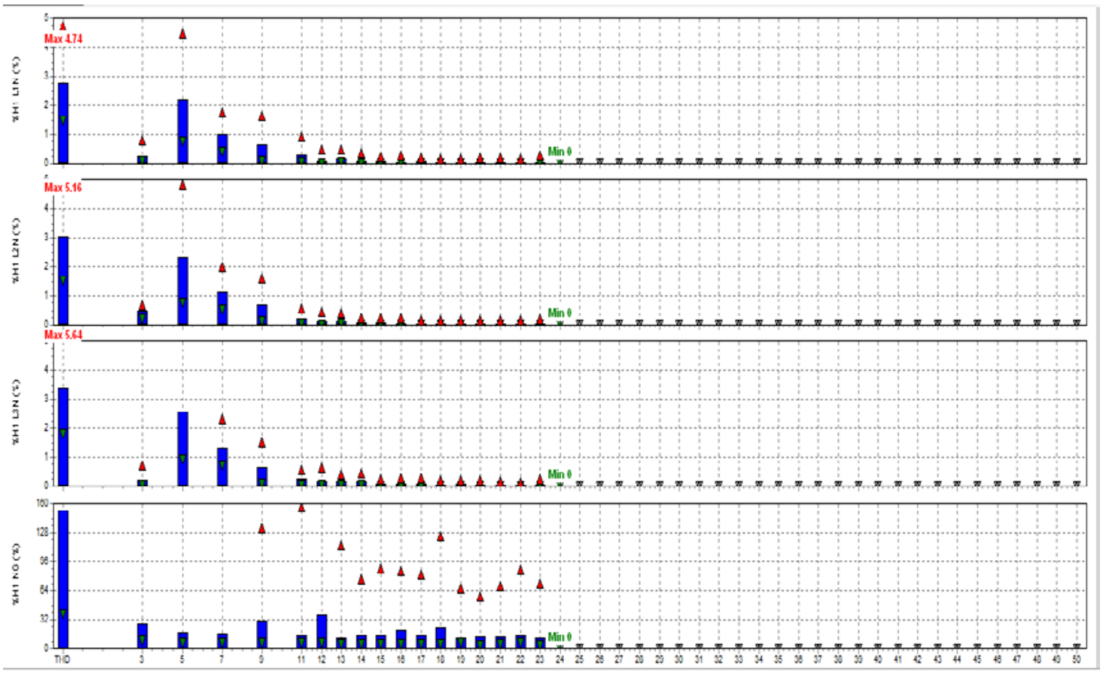


Figure 4.21: Spectrum of voltage harmonic

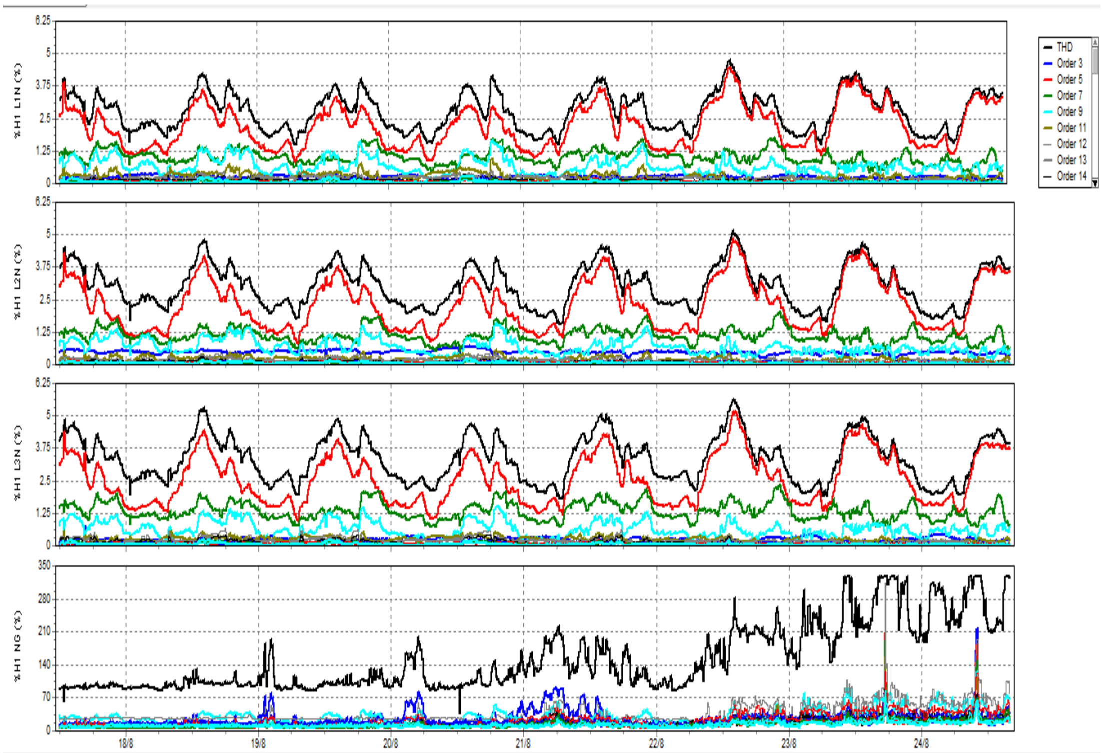


Figure 4.22: Time evolution of voltage harmonic

According to the measurements, total harmonic distortion of the voltage, all three phases lies within the limit. When study the time evolution of voltage, recorded departure of total harmonic of the voltage. (Exceeded the allowable limit of V_{thd}-5%)

4.3.2. Current harmonic distortion

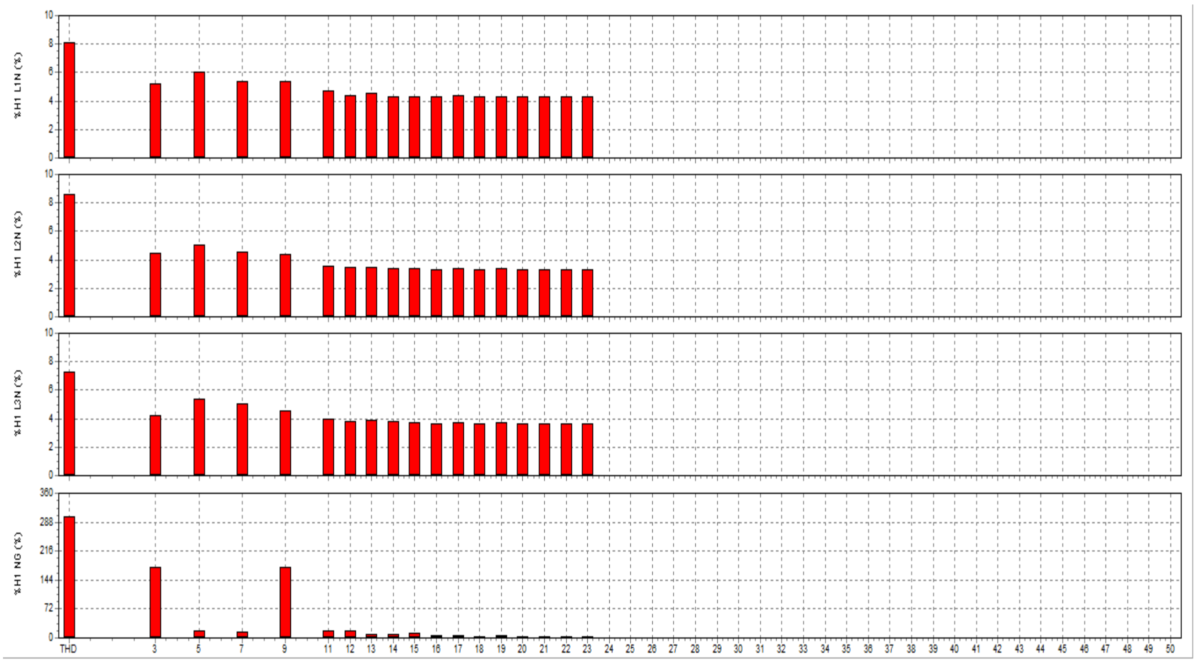


Figure 4.23: Spectrum of current harmonic

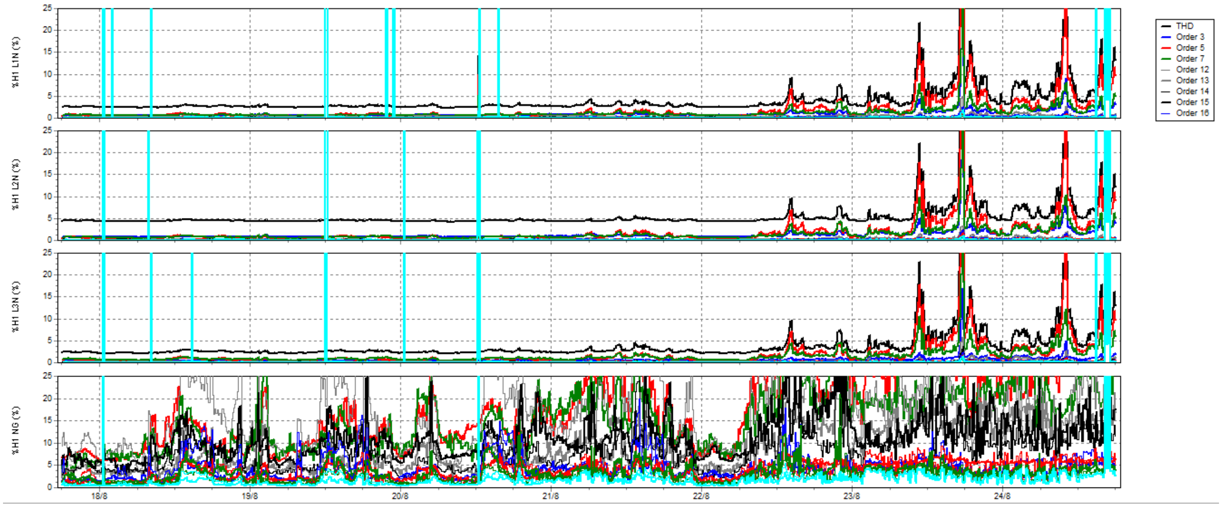


Figure 4.24: Time evolution of current harmonic

According to the measurements, all three phases violate the limit of total current harmonic distortion level and it exceeds its limit of 5%. When we study the graph of time evolution of current harmonic, it can be seen that for lower windy day, I_{thd} getting very high value and continuously violate the standard.

4.4. Power factor variation

CEB grid code states that “Generating Units shall be capable of continuously delivering the declared outputs at any point between the Power Factors of 0.8 lagging and 0.9 leading, in accordance with its reactive power Capability Curve, unless otherwise agreed in the Connection Agreement”

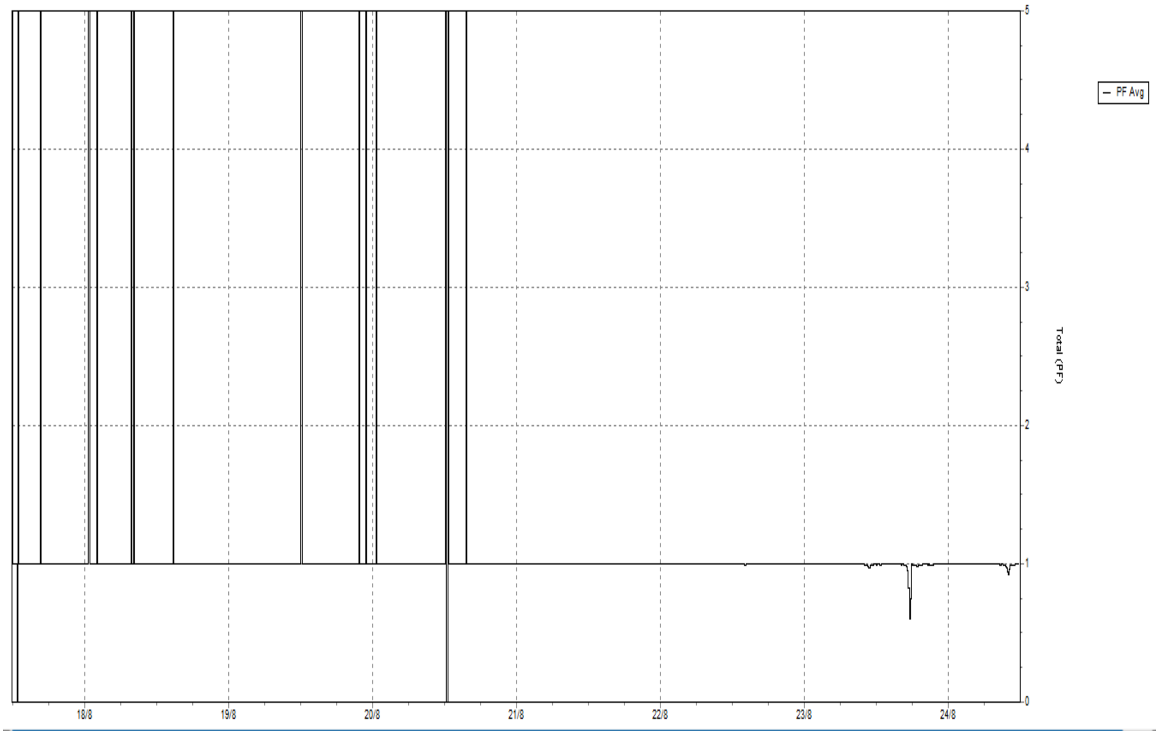


Figure 4.25: power factor variation

It can be seen that for some durations throughout the measurement, power factor is departure from its acceptable limit. For particular time period, Generated output power of the wind plant also very low due to low wind.

4.5. Average active, reactive and apparent power

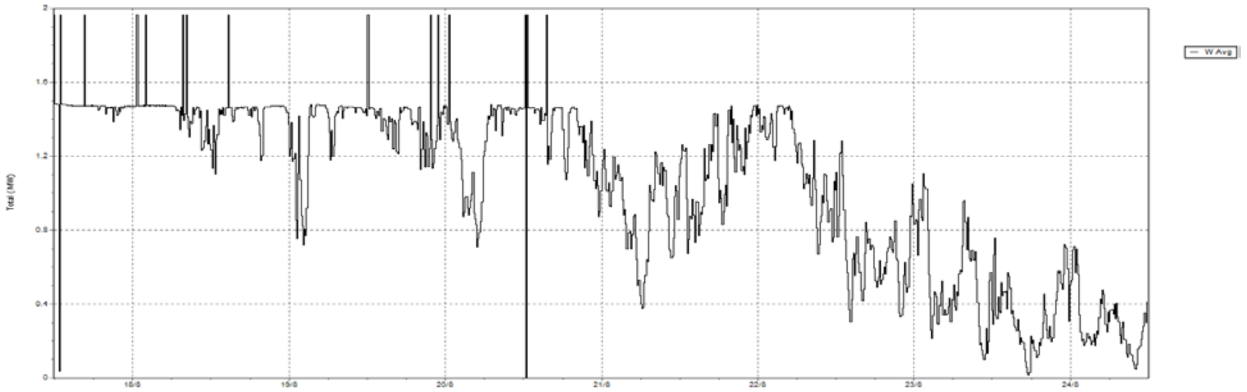


Figure 4.26: Average active power

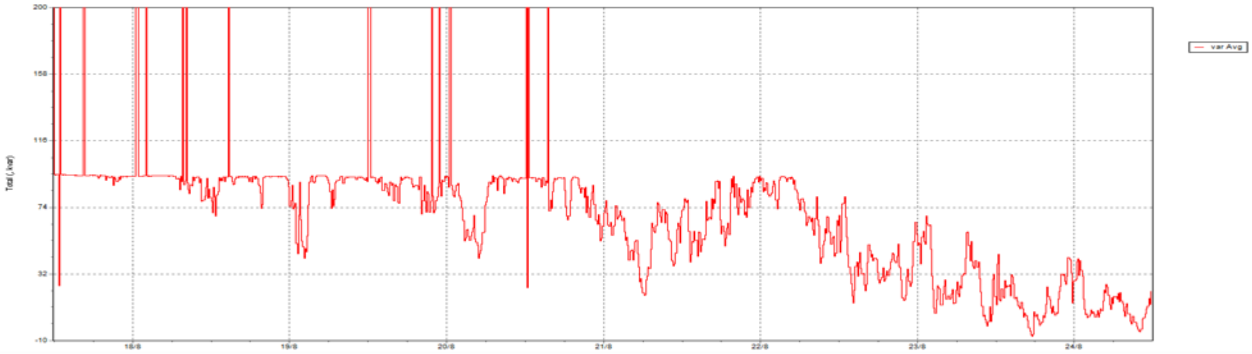


Figure 4.27: Average reactive power

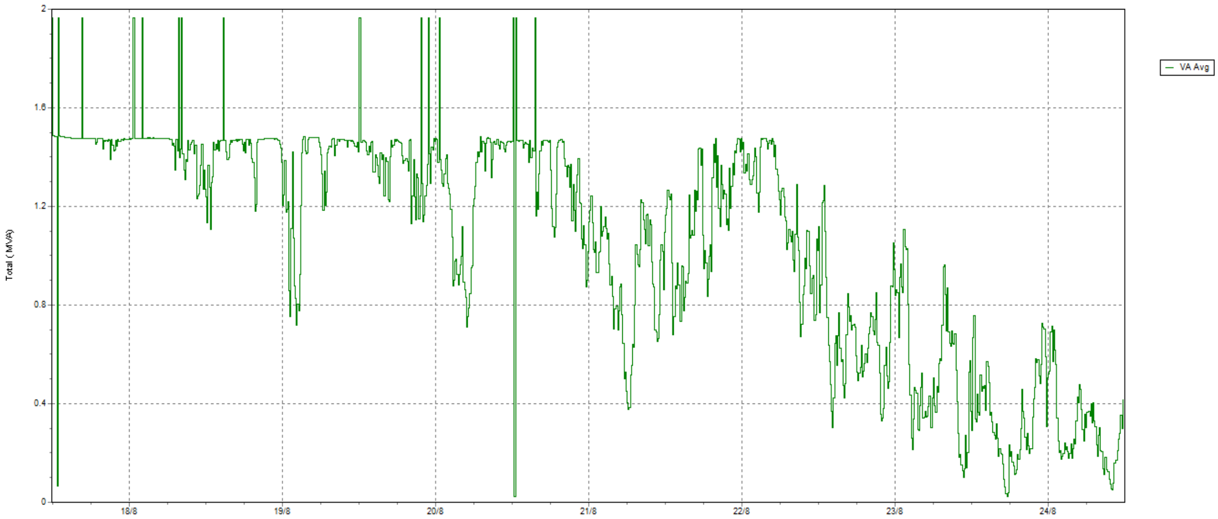


Figure 4.28: Average apparent power

Figure 4.26-28 shows average active, reactive and apparent power respectively. There are rapid variations due to intermittent nature of the wind.

Chapter 05: Evaluation of power quality measurements and improving techniques

According to the result and observation of data measurement and analysis in previous chapter, in this chapter evaluated power quality measurements and suggested possible power quality improvement techniques

5.1. Voltage Events

As per the measurements, there are four interruptions recorded and all are long interruptions. These interruptions occurred that accounts for 0.4% of the duration of measurement period due to network fault. Therefore it is difficult to avoid. 47 numbers of voltage sags have occurred immediately before or after interruption. Since this was occurred in line with interruptions, recorded sags can be considered as part of interruptions.

5.1.1. Static Var Compensator (SVC)

A SVC is a shunt connected power electronics based device which works by injecting reactive current into the load, thereby supporting the voltage and mitigating the voltage sag and Voltage flickering. The compensator normally includes a thyristor controlled reactor (TCR), thyristor switched capacitors (TSCs) and harmonic filters. SVCs may or may not include energy storage, with those systems which include storage being capable of mitigating deeper and longer voltage sags. Figure 5.1 shows a block diagram of a SVC. In addition to that SVC performs following functions.

- Voltage stabilization
- Reactive power compensation; improve power factor
- Increase voltage on the load bus
- Reduction of harmonics

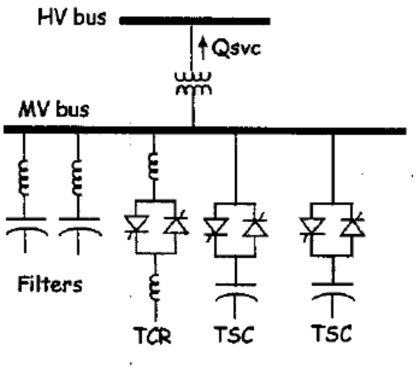


Figure 5.1: Block Diagram of a SVC

5.2 Waveform Event

5.2.1. Harmonics in voltage waveform

Total harmonic distortions of voltage for all measured harmonic orders are, below the allowable limit of V_{THD}. But, when analyze the time evolution of V_{THD} , in some instances V_{thd} exceed the allowable limit and that is not much affected to power quality issues.

5.2.2 Harmonics in current waveform

The total harmonic distortions of current for all measured harmonic orders are, exceed the allowable limit of I_{thd}. When go through the time evolution of current harmonic, it can be seen that for lower windy day, I_{thd} getting very high value and continuously violate the standard.

5.2.3. Harmonic mitigation techniques

The voltage and current harmonics should be controlled within allowable limit in order to maintain power quality as per the standards. Mainly there are two mitigating techniques of voltage and current harmonics in distribution sector.

- Harmonic Filtering
- Cancellation of harmonic

Harmonic filtering

- Active Harmonic Filter

An active harmonic filter is something like a boost regulator. The concept used in an active filter is the introduction of current components using power electronics to remove the harmonic distortions produced by the non linear load. Active harmonic filters are mostly used for low voltage networks. There are three types of active harmonic filters based on the way they are connected to the AC distribution network naming series filter, parallel filter and hybrid filter.

- Passive Harmonic Filter

A passive harmonic filter is built using an array of capacitors, inductors, and resistors. It can take the form of a simple line reactor or may use a series of parallel resonant filters to eliminate harmonics. Passive harmonic filters are also divided based on the way they are connected with the load.

According to the measurement on wind plant, identified current harmonic distortion and lamp flickering exceeds its allowable limit. Based on literature review of mitigation techniques, Static Var Compensator (SVC) provides solution to mitigate power quality issues on flicker and passive filter mitigate current harmonic distortion. Therefore, proposed to install SVC and passive filter at point of common coupling to overcome identified issues.

Chapter 06: PSCAD Modeling and Simulation

In chapter 04 (Measurement of Power Quality at Wind Power Plant), the measurement of power quality parameters were discussed and analyzed its variations with existing codes and standards, and in chapter 05 (Evaluation of power quality measurements and improving techniques), Power quality improvement techniques were discussed and It is suggested to adopt Static Var Compensator (SVC) and passive filter in order to prevent power quality disturbances of voltage events and harmonics respectively. In this chapter discuss PSCAD (Power System Computer Aided Design) modeling and simulation. Development of model and simulation results is explained as follows.

6.1. Development of PSCAD model

Wind plant output and network was developed by referring models in master library and actual plant parameters of wind plant were entered.

Complete model of PSCAD is as shown in Figure 6.1

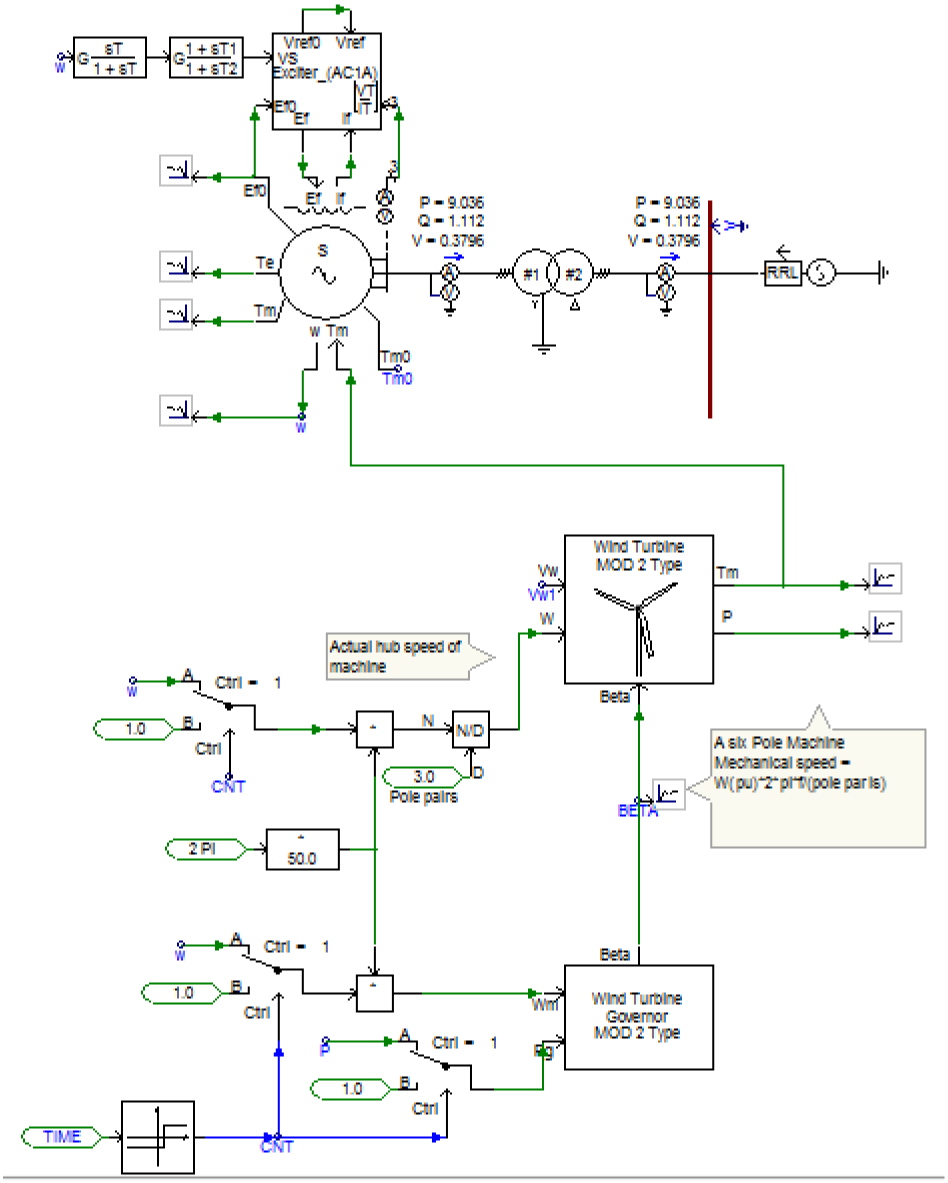
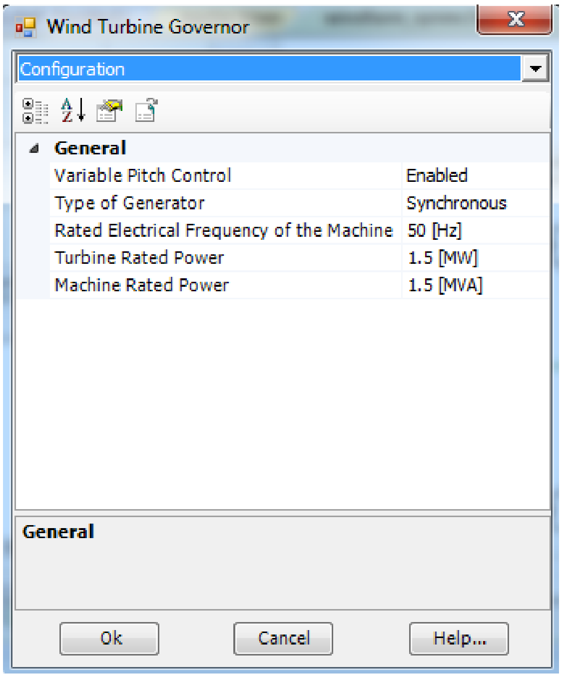


Figure 6.1: Complete PSCAD model

6.1.1. Wind turbine governor

Wind turbine governor regulates pitch angle of the wind turbine. Inputs of the model are Wm: Mechanical speed of the machine [rad/s] and Pg: Power output of the machine based on the machine rating [pu]. Beta: Pitch angle is the output of wind turbine governor. Relevant parameters of wind turbine governor are shown in Figure 6.2



General

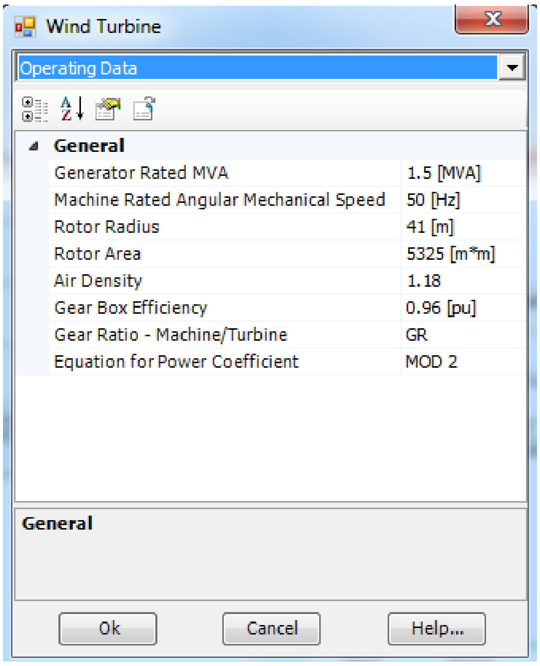
Variable Pitch Control	Enabled
Type of Generator	Synchronous
Rated Electrical Frequency of the Machine	50 [Hz]
Turbine Rated Power	1.5 [MW]
Machine Rated Power	1.5 [MVA]

General

Figure 6.2 : Technical Parameters of Wind turbine governor.

6.1.2. Wind Turbine

This component models a wind turbine. MOD 2 type present three blade configuration. Wind speed (Vw) and the mechanical speed of the machine connected to the turbine (W) is the inputs. Beta is the pitch angle of the turbine blades and it is the output of wind turbine governor. Tm and P are the output torque and power respectively in per-unit, based on the machine rating. Relevant technical parameters were entered as shown in Figure 6.3.



General

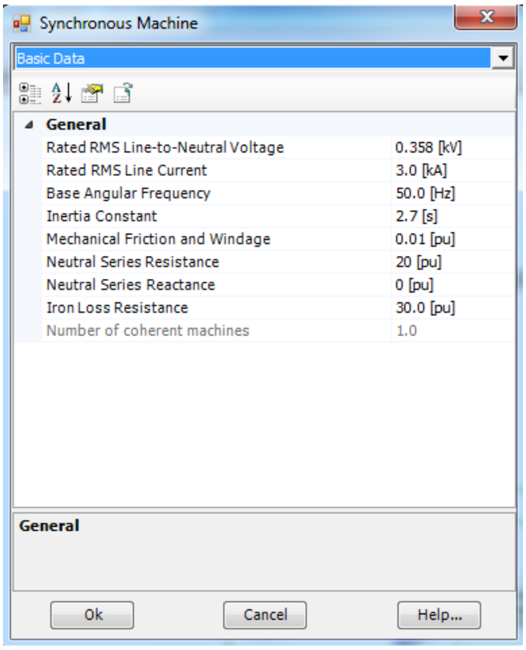
Generator Rated MVA	1.5 [MVA]
Machine Rated Angular Mechanical Speed	50 [Hz]
Rotor Radius	41 [m]
Rotor Area	5325 [m*m]
Air Density	1.18
Gear Box Efficiency	0.96 [pu]
Gear Ratio - Machine/Turbine	GR
Equation for Power Coefficient	MOD 2

General

Figure 6.3: Technical Parameter of Wind Turbine

6.1.3. Synchronous generator

Mechanical torque of the wind turbine is converted into electrical energy through synchronous generator. The speed of the machine is controlled directly by inputting a positive value into the w input of the machine, or a mechanical torque may be applied to the Tm input.



General

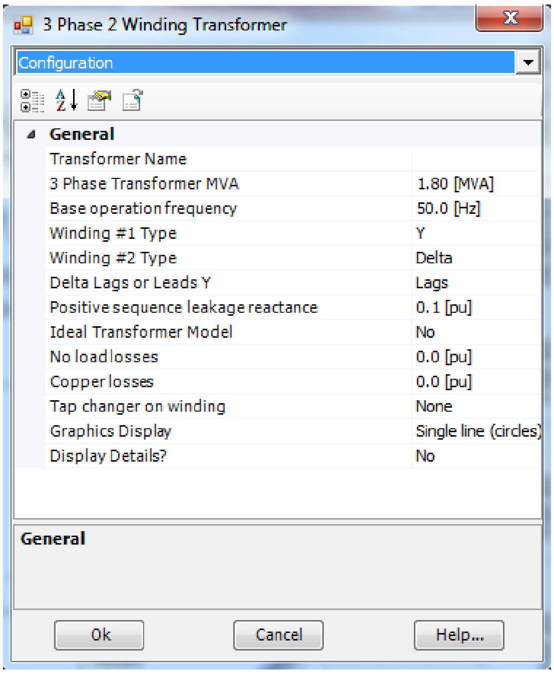
Rated RMS Line-to-Neutral Voltage	0.358 [kV]
Rated RMS Line Current	3.0 [kA]
Base Angular Frequency	50.0 [Hz]
Inertia Constant	2.7 [s]
Mechanical Friction and Windage	0.01 [pu]
Neutral Series Resistance	20 [pu]
Neutral Series Reactance	0 [pu]
Iron Loss Resistance	30.0 [pu]
Number of coherent machines	1.0

General

Figure 6.4: Technical Parameter of Synchronous Generator

6.1.4. Step-up transformer

Line to Line output voltage of wind plant is 620V and it is connected to 33kV Distribution network through 0.62kV/33kV step up transformer. Technical parameters of step up Transformer are shown in Figure 6.5 and Figure 6.6.

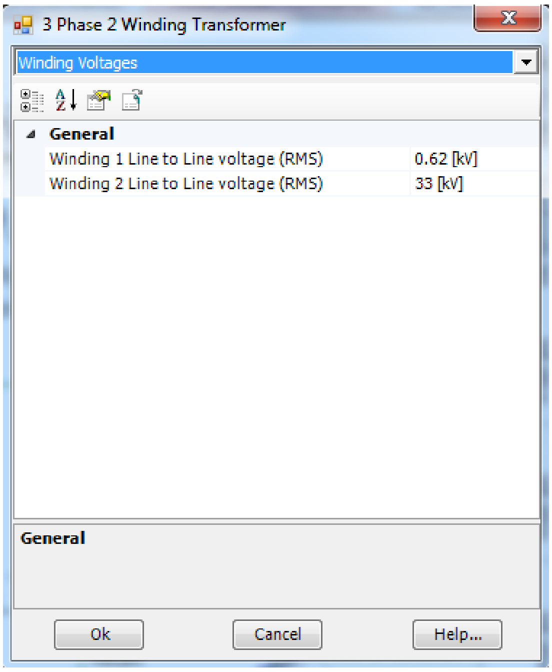


General

Transformer Name	
3 Phase Transformer MVA	1.80 [MVA]
Base operation frequency	50.0 [Hz]
Winding #1 Type	Y
Winding #2 Type	Delta
Delta Lags or Leads Y	Lags
Positive sequence leakage reactance	0.1 [pu]
Ideal Transformer Model	No
No load losses	0.0 [pu]
Copper losses	0.0 [pu]
Tap changer on winding	None
Graphics Display	Single line (circles)
Display Details?	No

General

Figure 6.5: Configuration of Step up transformer



General

Winding 1 Line to Line voltage (RMS)	0.62 [kV]
Winding 2 Line to Line voltage (RMS)	33 [kV]

General

Figure 6.6: Winding voltages of transformer

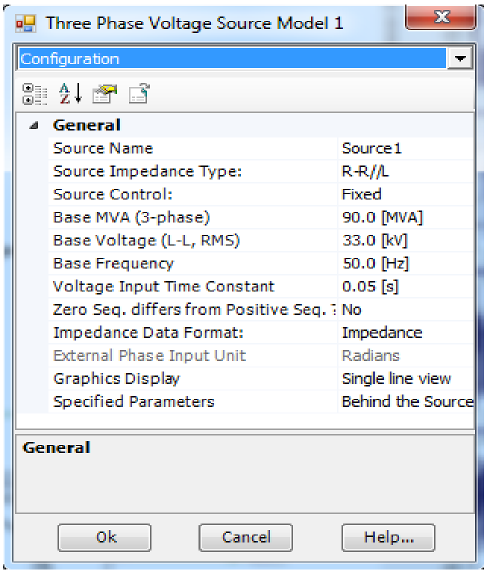
6.1.5. Distribution Network

Wind plant is connected to national grid through 33kV feeder. Equivalent grid substation was modeled through three phase voltage source by considering fault level of Kilinochchi substation. Table 6.1 shows Fault level of Kilinochchi grid for 33kV Bus and 132kV Bus.

Table 6.1: Fault level of Kilinochchi grid.

BUS	Fault Current (kA)	R (Ohm)	X (Ohm)	Impedance Angle
132 kV	2.73	7.03	26.57	75.19
33 kV	5.47	0.54	3.45	81.13

Technical parameters of Voltage source model are shown in Figure 6.7 and Figure 6.8.

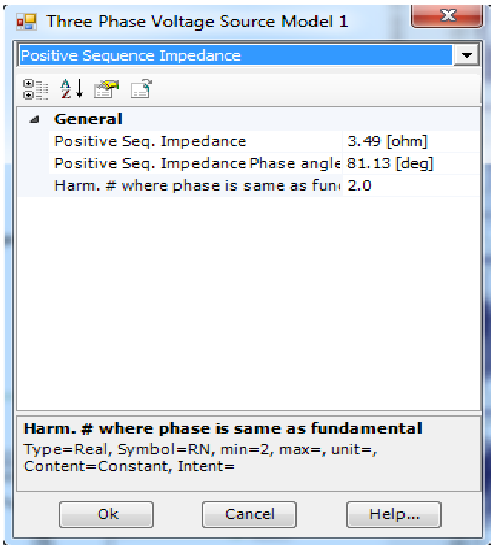


General

Source Name	Source1
Source Impedance Type:	R-R//L
Source Control:	Fixed
Base MVA (3-phase)	90.0 [MVA]
Base Voltage (L-L, RMS)	33.0 [kV]
Base Frequency	50.0 [Hz]
Voltage Input Time Constant	0.05 [s]
Zero Seq. differs from Positive Seq.	No
Impedance Data Format:	Impedance
External Phase Input Unit	Radians
Graphics Display	Single line view
Specified Parameters	Behind the Source

General

Figure 6.7: Configuration of Voltage source model



General

Positive Seq. Impedance	3.49 [ohm]
Positive Seq. Impedance Phase angle	81.13 [deg]
Harm. # where phase is same as fun	2.0

Harm. # where phase is same as fundamental
Type=Real, Symbol=RN, min=2, max=, unit=,
Content=Constant, Intent=

Figure 6.8 : Positive sequence Impedance of Voltage source model

6.1.6.Static Var Compensator (SVC)

Static Var Compensator (SVC) is used to mitigate voltage flickering and current harmonic. Model component of SVC is taken from master library of PSCAD. Diagram of SVC and control unit is shown in Figure 6.9.

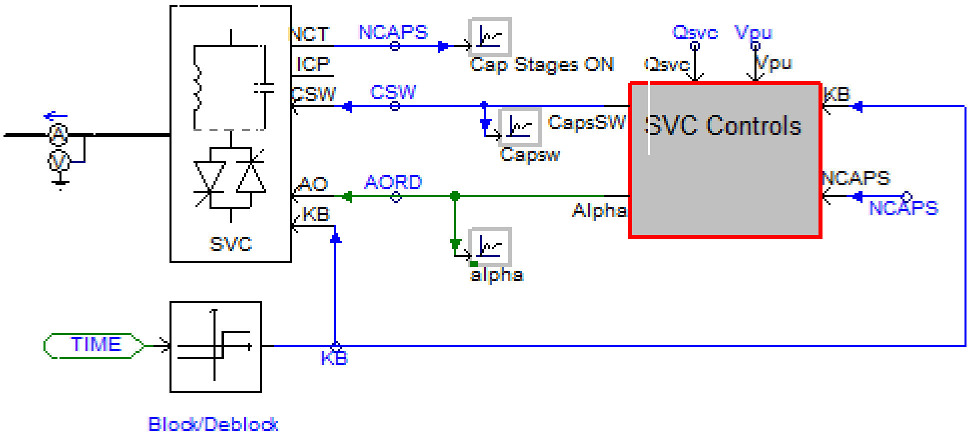
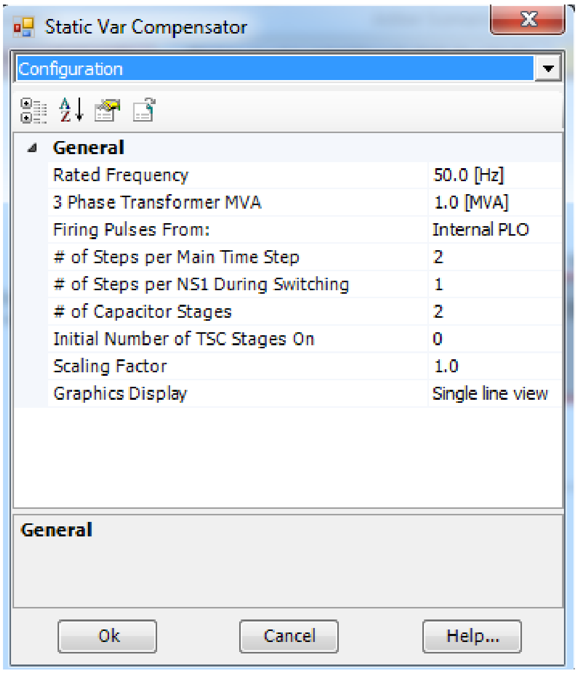


Figure 6.9: Diagram of SVC and Controller

Technical parameters of SVC are as shown in Figure 6.10.



General

Rated Frequency	50.0 [Hz]
3 Phase Transformer MVA	1.0 [MVA]
Firing Pulses From:	Internal PLO
# of Steps per Main Time Step	2
# of Steps per NS1 During Switching	1
# of Capacitor Stages	2
Initial Number of TSC Stages On	0
Scaling Factor	1.0
Graphics Display	Single line view

Figure 6.10.: Technical parameters of SVC

6.2. Model Validation

Model validation is very important and it is demonstrating that the developed model is a reasonable representation of the existing system. As per the equation of generated electrical power of a wind plant (P_e), P_e is depending on wind speed (V) since other factors are constant for a particular wind plant.

$$P_e = \eta_e . \eta_m . C_p . \frac{1}{2} . \rho . A . V^3$$

Then relevant wind speed (V) can be calculated for measured electrical power output by using following equation. Calculated wind speed (V) is used as the input of developed PSCAD model and it is shown in Figure 6.12.

$$V = \sqrt[3]{\frac{2 . P_e}{\eta_e . \eta_m . C_p . \rho . A}}$$

P_e – Electrical power output

η_e – Efficiency of electrical Generator (0.98 %)

η_m – Overall Mechanical efficiency of Drive train (0.98%)

C_p – Power coefficient (0.43)

ρ – Air Density (1.18 kgm^{-3})

A – Cross sectional area (5325 m^2)

Measured power output (MW) of a wind plant from 1500 hrs on 18.08.2017 to 1200 hrs on 19.08.2017 is shown in Figure 6.11.

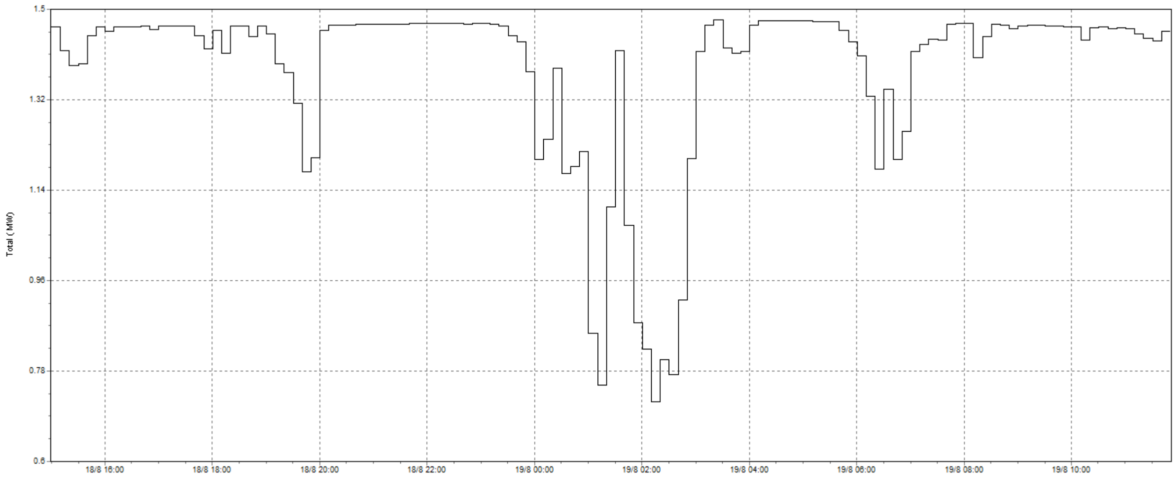


Figure 6.11: Measured power output of wind plant

Duration of 10 minutes is represent by 0.1S in PSCAD simulation.

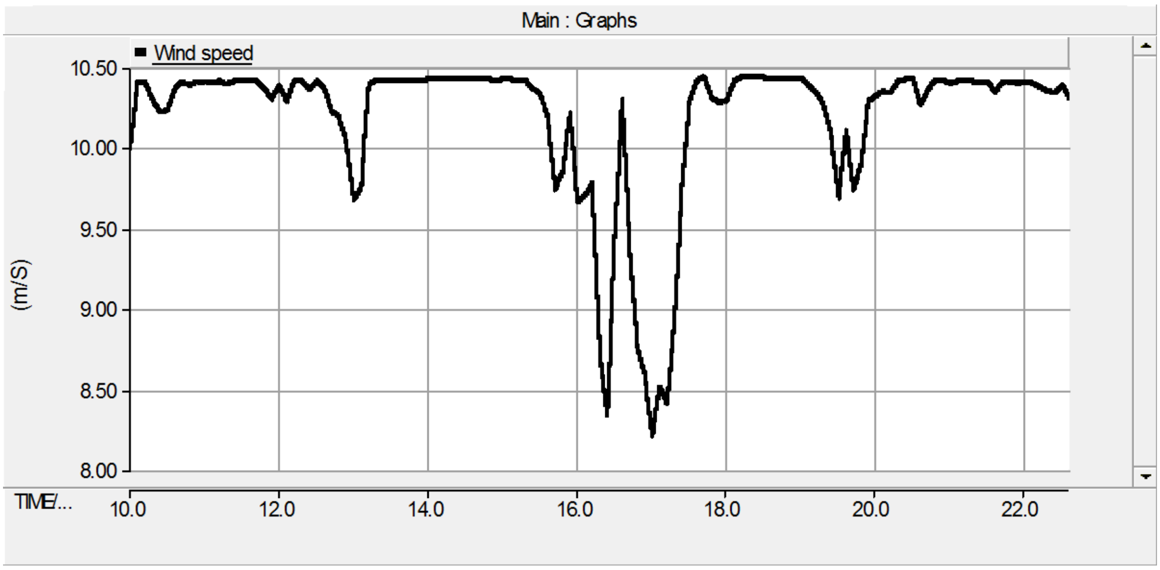


Figure 6.12: Calculated wind speed

Comparison between Measured and simulated Power output of wind plant is shown in Figure 6.13.

Comparison between Measured and simulated Voltage output of wind plant is shown in Figure 6.14.

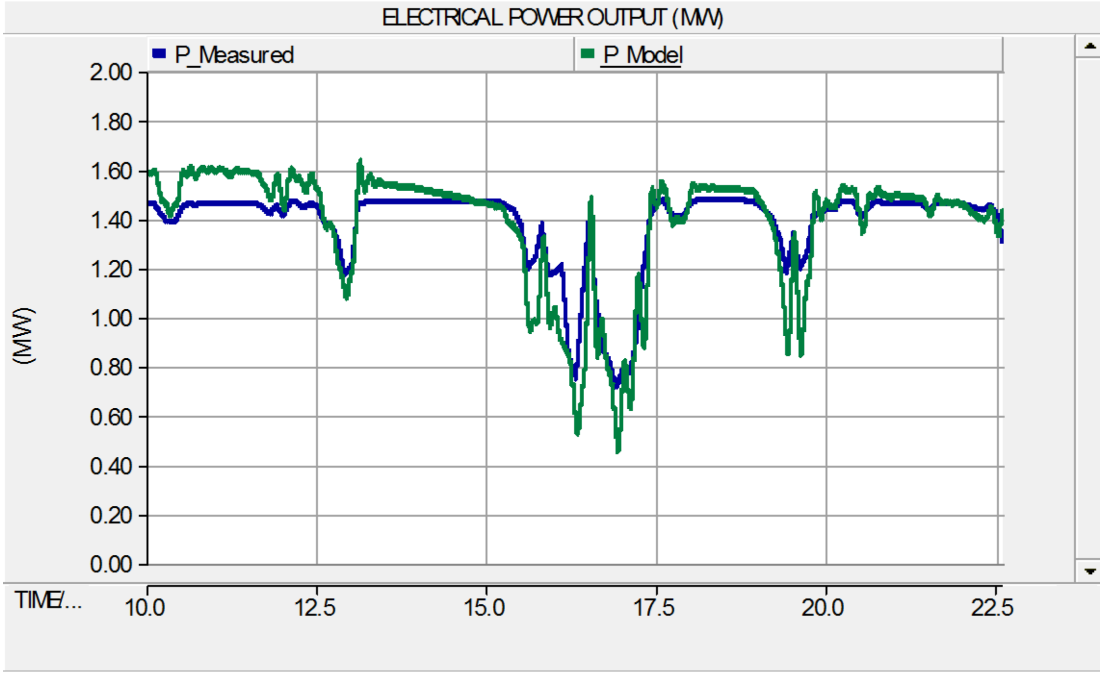


Figure 6.13: Comparison between Measured and simulated Power output of wind plant

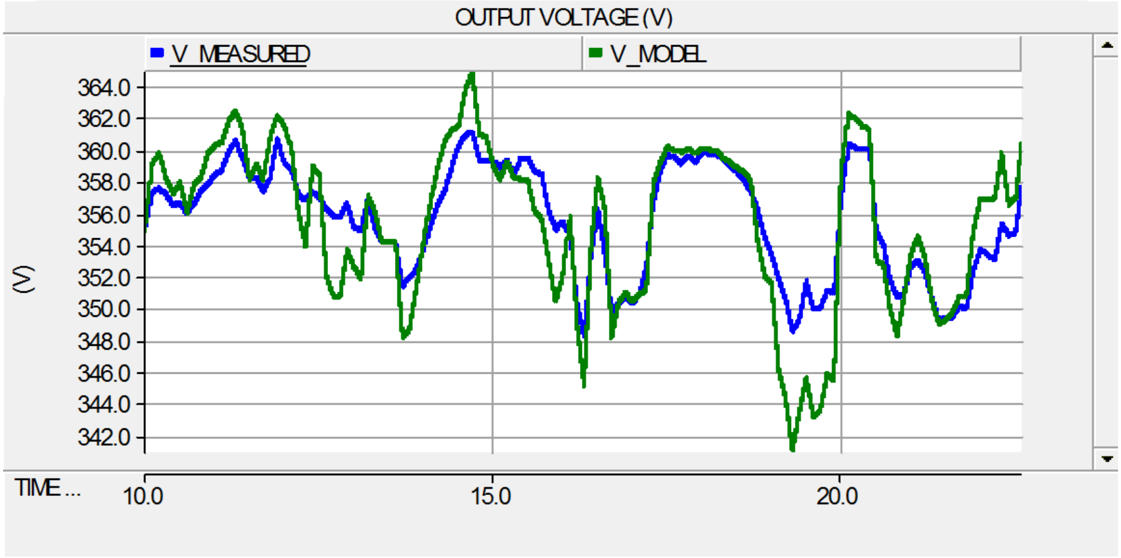


Figure 6.14: Comparison between Measured and simulated Voltage output of wind plant

For a variable speed turbine with full power electronics interface, it was much difficult to get a very good agreement between measurement and simulation responses. Since the controllers govern the responses in both active and reactive power, the challenge is to find the correct parameters for components and controls, and deciding the control strategy. Detailed information is required in order to obtain accurate results, however this is difficult to obtain from wind turbine manufacturers. However Figure 6.13 and Figure 6.14 show that the results taken from developed PSCAD model are in line with Power quality parameters, which was Measured at wind plant.

6.3. Simulation results

According to the measurement taken at wind plant, power quality issues on Current harmonic distortion and Voltage flicker were identified. Simulation results were obtained for identified power quality parameters.

6.3.1. Flicker

Comparison between simulated voltage output of wind plant with SVC (Static Var Compensator) and without SVC is shown in Figure 6.15.

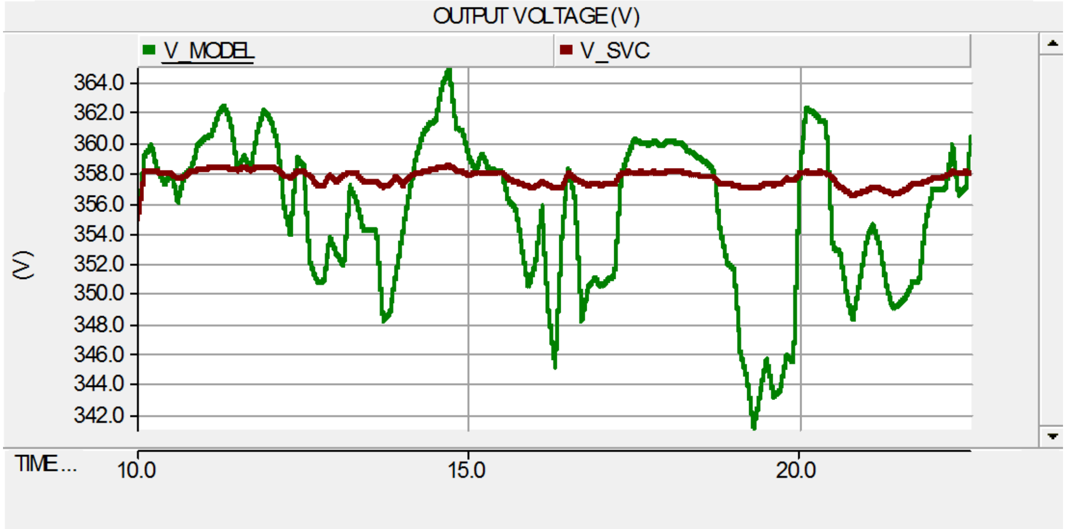


Figure 6.15: Comparison between simulated Voltage output of wind plant with SVC and without SVC.

The graphs shows that with adopting of SVC, mitigate the variation of output voltage and maintained nearly constant output voltage.

Figure 6.16 shows the Comparison of Measured Voltage output and simulated Voltage output of wind plant with SVC and without SVC.

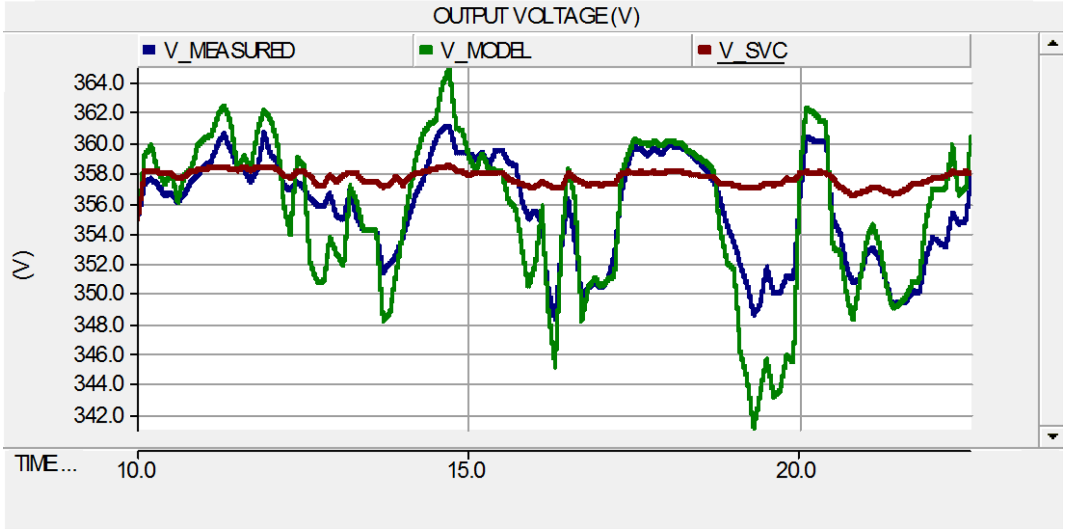


Figure 6.16: Comparison of Measured Voltage output and simulated Voltage output of wind plant with SVC and without SVC.

Sudden variation of the wind plant output voltage is caused to lamp flickering. This simulation model was proved that, with the presence of SVC at point of common coupling, mitigates sudden voltage variation and results nearly constant voltage output. Hence,power quality issues occurred due to flickering can be mitigated by adopting SVC at point of common coupling.

6.3.2. Current Harmonic distortion

Figure 6.17 and 6.18 shows that, Individual current harmonic and Current THD of wind plant without filters.

Figure 6.19 and 6.20 shows that, Individual current harmonic and Current THD of wind plant with filters.

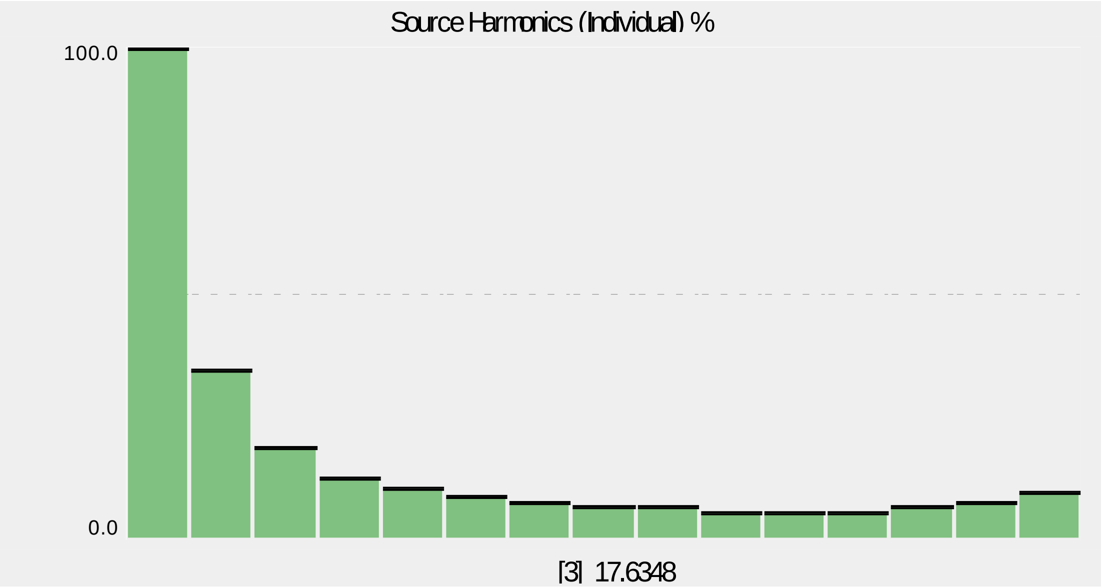


Figure 6.17 : Individual Current harmonic of wind plant without Filter (n = 1 to 15)

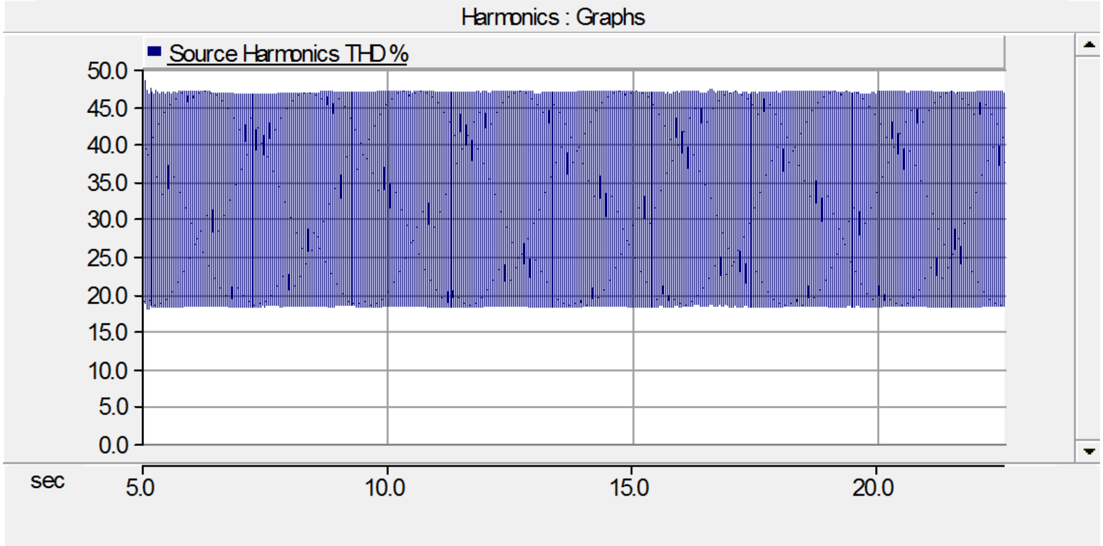


Figure 6.18 : Current THD of wind plant without Filter

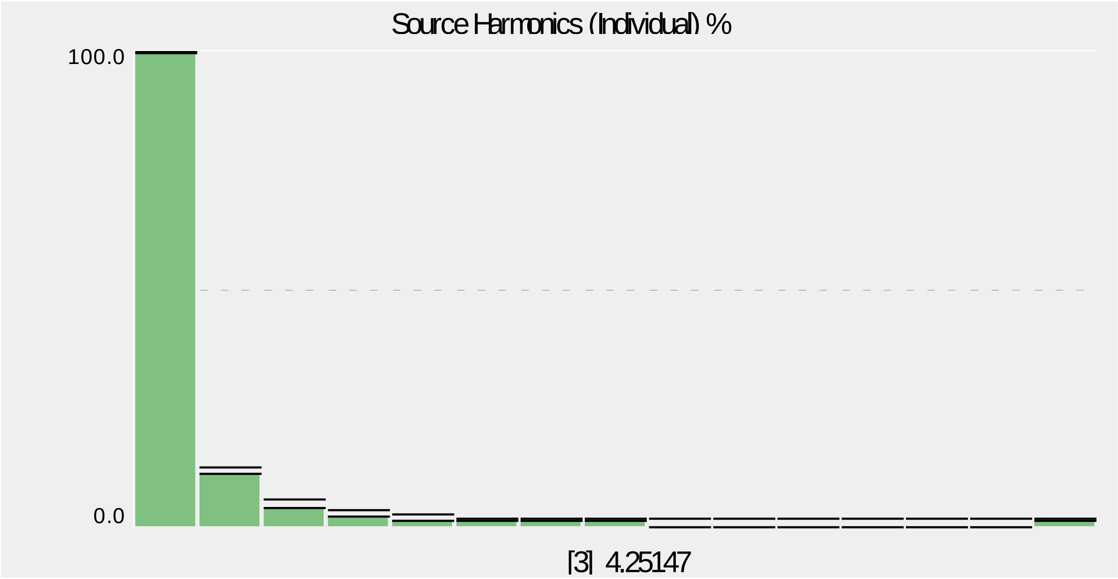


Figure 6.19 : Individual Current harmonic of wind plant with Filter (n = 1 to 15)

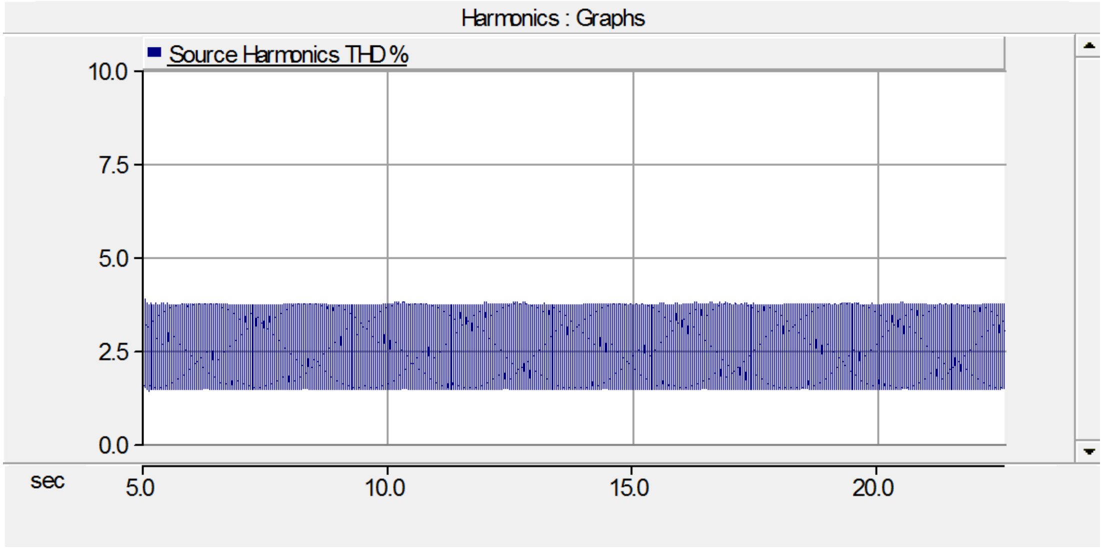


Figure 6.20 : Current THD of wind plant with Filter

Figure 6.19 and Figure 6.20 shows that Individual current harmonic and Current THD is reduced below 5% as standard requirement after adopting filter.

Static Var Compensator (SVC) provides improvement for power quality issues for voltage flickering and Passive Filter rectified current waveform distortion identified through the measurements. It has been proved through PSCAD simulation results.

Chapter 07: Discussion, Conclusion and Recommendation

7.1. Discussion

Wind energy is considered as a risky source for power quality disturbances such as voltage variation and fluctuation, lamp flickering, voltage unbalances, voltage and current harmonics, frequency variation, power factor variation, Reactive power injection and compensation from grid substation etc.. Ultimately these issues in distribution network lead to huge losses in economically and highly affect to personal and equipment safety.

With the government policy on renewable energy sector, expected high level wind integration to the distribution network. In order to provide quality power in line with standards, have to pay more attention on power quality of distribution network. Many of the research papers, journals and various proposals were studied for mitigating techniques of power quality issues in distribution network due to wind energy integration.

Data collection and measurements on wind power generation has been carried out for 10 minute average time duration. Power quality disturbances in lamp flickering and wave form distortions were identified.

After analyzing the measurements and evaluation of power quality mitigating techniques, suggested to install Static Var Compensator (SVC) and passive filter at the point of common coupling.

PSCAD model was developed by using actual parameters of wind plant. Simulation results of PSCAD show that, system is reduce total harmonic distortion and flickering with the presence of SVC.

7.2. Conclusions

- The recorded measurement of power quality parameters for considered wind plant is not in line with CEB grid code and relevant standard published by IEEE, IEC etc...
- Harmonic content is the critical factor of power quality issues. Higher level of current harmonic distortion was identified.
- During the study, Lamp flickering was identified as disturbances for power quality of distribution network.
- There is no appropriate mechanism for continuous monitoring of power quality parameters by both sides (CEB and wind power producer).
- Even though there are a lot of power quality improving techniques, in Sri Lanka these techniques were still not adopted and adequate attention was not paid on this.

7.3. Recommendations

- Should have to take remedial actions to improve the power quality for recorded disturbances.
- CEB and wind power producer should pay more attention on power quality issues due to wind plants. Both parties should have a mechanism to continuous monitoring of power quality parameters. After introducing proper mechanism for monitoring, it is required immediate response to clear monitored/recorded disturbances.

7.4. Provision for future research

- Main disadvantage of wind plant is Generated output power is varying rapidly. It is suggested to study on hybrid technology such as combination of wind plant and battery bank.
- Considerable amount of power quality issues arises with non linear load connected to the network. Therefore it is required to study and regularize the limitation of emission level of power quality disturbances to electrical/electronic equipment.

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