CHAPTER 1

INTRODUCTION

Existing distribution systems are designed to accept bulk power from the transmission network and distribute it to the loads. It is the utility's responsibility to generate, transmit and distribute the electricity to customers. This traditional structure is referred to as "centralized or regulated" electric power system. Though, it is generally agreed that the centralized electric power plants will remain the major source of electricity. However, centralized power plants face many challenges from different aspects such as high power loss, environmental pollution, and the need to update the energy infrastructure [1]. Over the last number of years, allowing small generation units known as distributed generators (DGs) to be connected at the distribution network is increasing significantly. This practice will move the conventional electric power plant from being regulated and centralized to deregulated power plants. Since distribution networks are designed without any generation at the customer side, integrating DGs into the distribution network can impact it positively or negatively.

This chapter presents the benefits and risks when connecting distributed generators to the existing distribution system. The chapter starts with an introduction on the structure of distribution networks and the concept of distributed generation. Then, the benefits of connecting DGs into distribution network and their impacts are presented. And lastly, an introduction to the islanding problem is given.

1.1. Conventional Electric Power Grid

Traditional power systems consist of four main Parts: Generation, Transmission, Distribution, and loads. In the generation phase, electricity is generally generated between 11 and 25 kV. Then, it is stepped up and transmitted via overhead lines from the generation units to remote areas of primary and secondary distribution systems where the voltage is stepped down. Figure 1.1 shows the different phases and their voltage ratings [2].

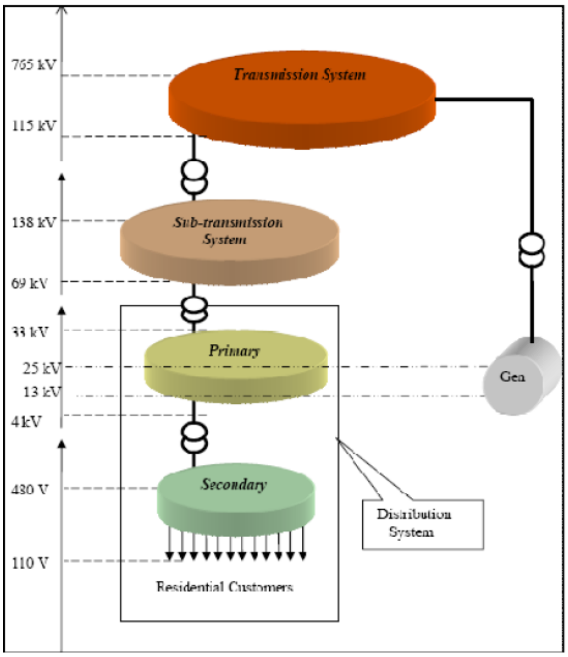


Figure 1.1: Different phases and their voltage rating in a traditional electric power grid.

1.2. Distributed Generators

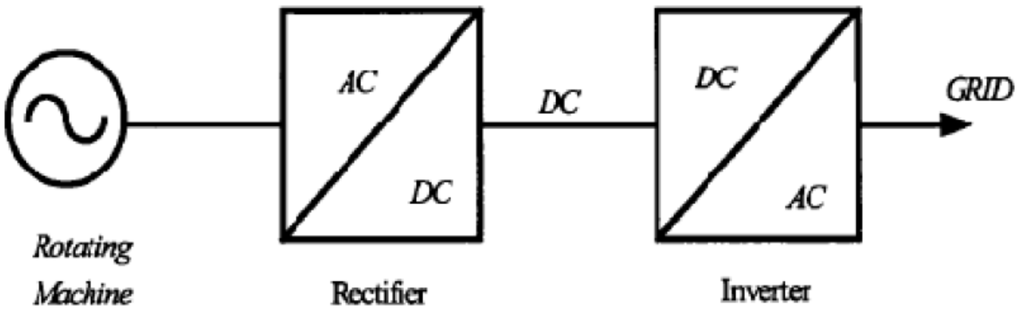
A Distributed Generator (DG) is an electric power source of typically 5kW to 20MW capacity connected directly to the distribution grid away from the main substation [2]. Distributed Generators can be divided according to the electrical interfaces into two main classes: Rotating machines type and inverter based type.

- **Rotating machine DG type:**

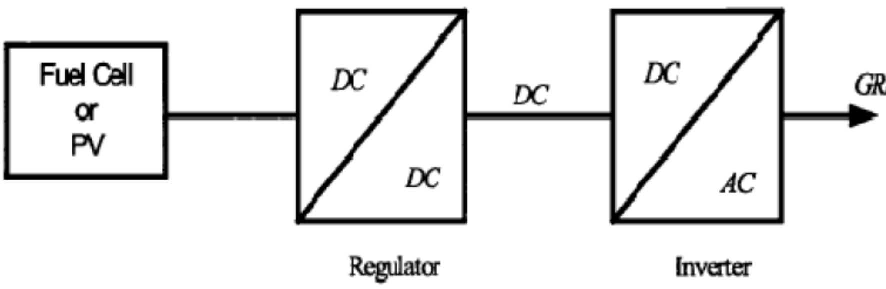
DG of rotating type include synchronous and induction generators. The synchronous type includes reciprocating engines (diesel and gas), mini hydro, small gas turbine, and some wind systems. Induction generators include wind systems and reciprocating engines which run on fuel to generate electricity. The reciprocating DG type suffers from some drawbacks such as noise, emissions and maintenance cost [3].

- **Inverter based DG type:**

The inverter based DG type relies on the inverter to convert the electricity from the DG to a form that can be supplied to the distribution network. The inverter is actually an interface between the system and the generator, the structure of this interface depends on the distributed generator type. DG could be rotating machine type or inverter based type as shown in Figure 1.2 [3]. If the source is a rotating machine operating at variable speed, such as those found in wind turbines and micro-turbines, the variable frequency AC voltage at the terminals of the generator is rectified and regulated to DC and then inverted to a fixed frequency AC current that is fed to the distribution network. On the other hand, if the distributed generation source has a varying DC voltage output, such as a photovoltaic array or fuel cell, the voltage may first be stepped up or down and pre-regulated by a DC/DC converter, or it may be fed directly to the DC to AC inverter. It is considered to be the most important functional block in the DG system since it is responsible for controlling the output active and reactive power of the DG.



(a)



(b)

Figure 1.2: Inverter interface topology for (a) rotating machine (b) fuel cell or PV DG.

Environmental concern is now driving the use of renewable and clean energy. Photovoltaic power generation is expected to play a big part due to their small scale and low maintenance characteristics. According to Chinese electric power institute a total of 350MW is generated by installed PV panels. Moreover, it is expected that PV panel will account for a total of 1.8 GW by 2020 and 600 GW by 2050 [4].

Over the past two decades, PV efficiencies, reliability, and manufacturing capabilities have improved. As a consequence, the cost of photovoltaic panels has fallen significantly in the recent years and can be expected to continue to fall. The cost of PV panels has decreased by almost 70 percent since 1980 and is estimated to decrease by another 70 percent from current levels by 2020 as shown in Figure 1.3. Due to the various advantages of PV generation, the DG considered in this thesis is PV panels [5].

Distributed generator can be classified according to their technology into three main classes, namely, renewable, non-renewable and storage devices as shown in Figure 1.4.

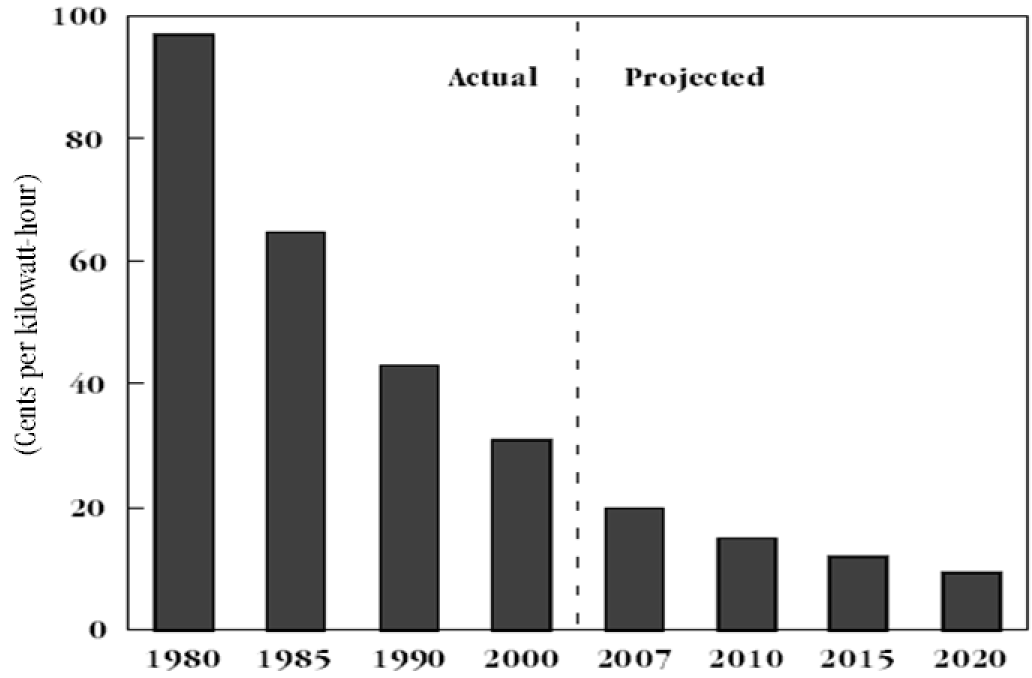


Figure 1.3: Cost of photovoltaic electricity.

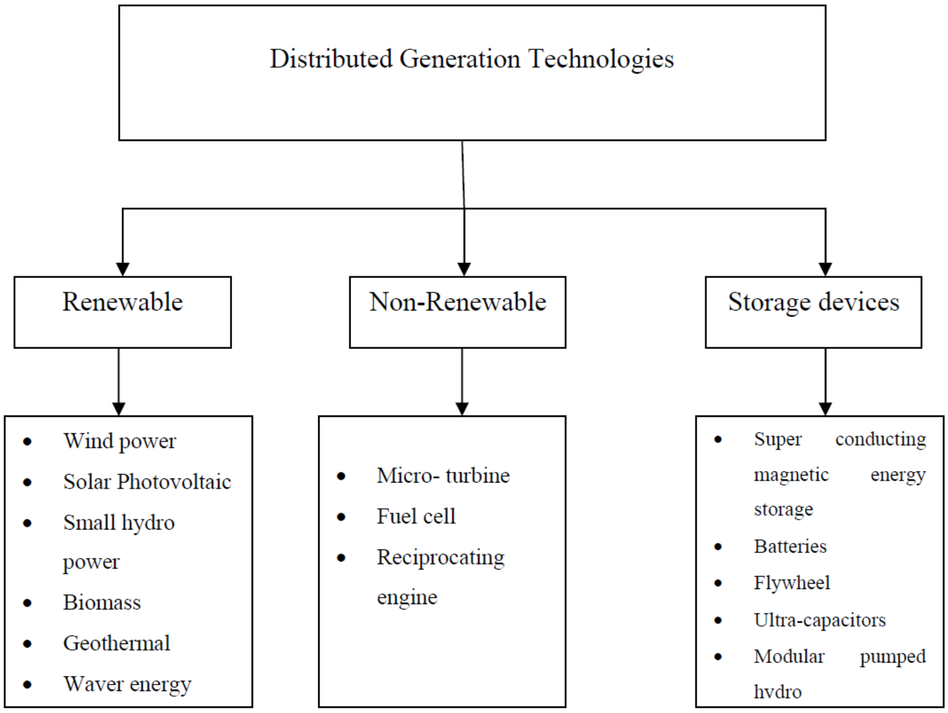


Figure 1.4: Distributed generation technology classification.

1.3. Benefits of Connecting DGs into Existing Distribution Network

Connecting DGs into the existing electric power grid has many benefits such as:

- Power peak shaving: Distributed generation operation during peak demand periods (Peak Shaving) contribute in supplying demand power during these high demand periods hence reducing the amount of electricity purchased during the peak price periods. In this way, distributed generation contributes in avoiding electricity price fluctuations. This is considered the major driver for distributed generation installation in US [1].
- Network reliability: Installing Distributed generators enhance the reliability of the system by providing a back- up in case of power interruption [1].

- Voltage control: Other than producing real power distributed generators provides reactive supply (absorption and injection) to achieve voltage control.
- Power quality: Distributed generation can assist in solving power quality problems, such as voltage sags, as the installation of a DG increase the voltage level in the network. Moreover, distributed generation can also contribute in the power factor correction [1].
- Transmission and Distribution Deferral: In some locations, where load goes beyond transmission line's capacity, addition of DG will be more economical than constructing distribution lines.

1.4. Technical Challenges when Connecting DGs into the Existing Distribution System

Distribution power systems are radial in nature. Power flows in one direction from the utility to the load. Most protection, monitoring, and control devices are designed based on this unidirectional flow of power. Hence, integrating distributed generators into the existing distribution power system will give rise to many problems such as: voltage regulation, fuse-recloser coordination, unintentional islanding, and increase the system's fault level [6]. Among all the above mentioned problems unintentional islanding is one of the most important concerns when integrating DG into the grid [7]. Islanding phenomenon is the situation where the distribution system containing both distributed generator and loads is separated from the main grid as a result of several reasons such as electrical faults and their subsequent switching incidents, equipment failure, or pre-planned switching events like maintenance. Figure 1.5 shows a typical hybrid distribution system with two distributed generators connected to it [7]. Due to one of the reasons mentioned earlier circuit breaker "CB1" was tripped and a power island was formed.

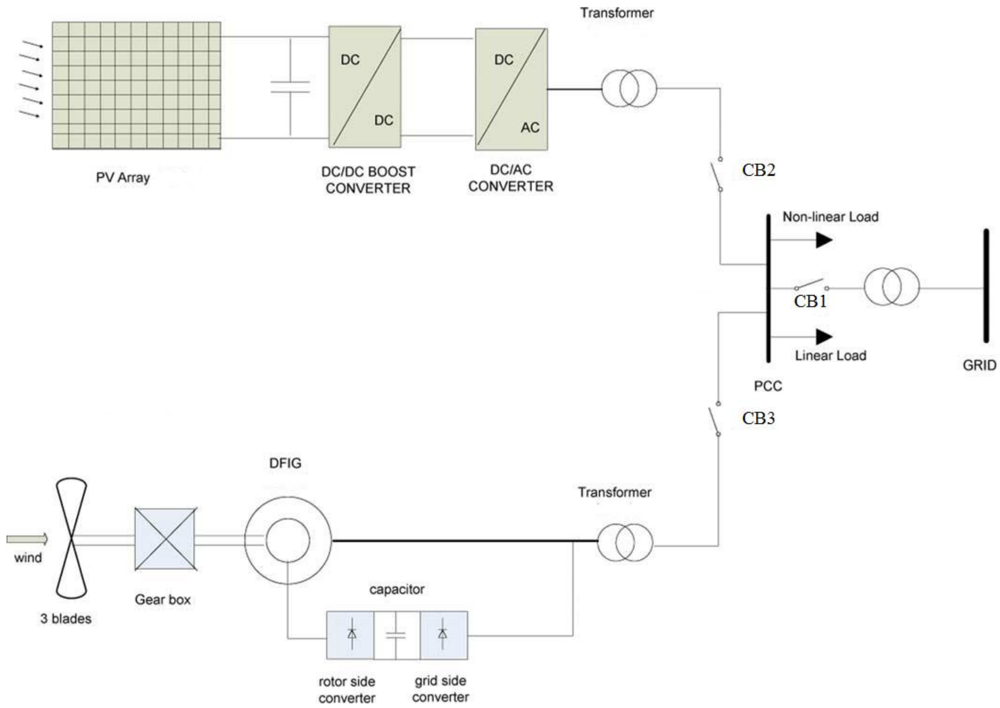


Figure 1.5: Typical hybrid distribution system with distributed generators

Unintentional islanding has the following implications on the electric power system.

- The voltage and frequency provided to the loads in the islanded system can vary significantly since the utility is no longer controlling the voltage and frequency, creating the possibility of damage to customer equipment [7].
- Islanding may create a hazard for utility line-workers or the public by causing a line to remain energized that may be assumed to be disconnected from all energy sources [7].
- The distributed generators in the island could be damaged when the island is reconnected to the grid due to the out-of-phase reclosing which can inject a large current to the generators. This is because the generators are likely not in synchronism with the system at the instant of reconnection [7].

For safe operation unintentional islanding should properly detected. According to IEEE Standard 1547-2003 and IEEE Standard 929-2000, DG units are normally disconnected from the AC line when the grid is not present [8].

1.5. Problem Statement

Presently, there are many methods which may be used to detect the islanding situation of DG(s). Passive methods such as under/over voltage and under/over frequency work well when there is an imbalance of power between the loads and the DG(s) present in the power island. However, these methods fail to detect the islanding condition if there is a balance of power supplied and consumed in the island. Various active methods which attempt to create a power imbalance so that the island may be detected also exist. However, these methods can degrade the quality of the power supplied by the DG and their ability to detect the island may be diminished when there are multiple DGs supplying power to the same island. The active methods may also require knowledge of the currents being drawn by the loads. Utility installed methods such as power line carrier communication require extra equipment and therefore may be expensive.

Proposed is an islanding detection method based on implementing the Wavelet Transform (WT) of the negative sequence voltage signal at the point of common coupling (PCC). A decision whether an islanding or not has occurred is obtained the trained ANN. The Artificial Neural network (ANN) model trained by these WT indices, which understands the pattern of input feature vector, will help to classify them. A number of simulated negative sequence voltage signals are acquired from the system modeled in MATLAB Simulink. The acquired negative sequence voltage signals have mainly two classes: non-islanding and islanding. Simulated non-islanding cases include normal operation, temporary single line to ground (SLG), Line to Line (LL) fault and switching of non linear load at PCC on the distribution network. On the other hand, the islanding cases simulated, include opening of circuit breaker at PCC which cause islanding at different times. Wavelet analysis is a developed mathematical tool for signal processing. The basic concept in wavelet transform (WT) is to select an appropriate wavelet function "mother wavelet" and then perform analysis using shifted and dilated versions of this wavelet. In WT a windowing technique with variable-sized regions is used. Wavelet analysis allows the use of long windows where low-frequency information (approximation) is required, and short windows where high-frequency information (detail) is required.

The energy content and standard deviation (SD) of the detail coefficients for the negative sequence voltage waveforms acquired are calculated for the obtained two different frequency levels and selection of these levels is based on the expected harmonic frequency range occurs during a disturbance. A well trained ANN has the capability of learning complex mapping, linear or nonlinear, from the input space to the output space. This will improve the accuracy of prediction.

The algorithm starts by collecting 1 second sampled data window for each signal. Then, a WT analysis is carried out and the energy content and SD in the details of the obtained negative sequence voltage waveforms are calculated. This data is used as feature vector to train ANN. Once trained, for a new feature vector, a decision will be made on what kind of event happened, by ANN.

1.6. Thesis objectives and contribution

The capabilities of a conventional passive islanding detection technique are verified using computer simulation. The technique considered in this thesis is Detection of Harmonics (DH). It was found that DH has the problem of false tripping since it is hard to set an appropriate threshold that provides islanding detection, abrupt variations on load change and failure in discriminating Islanding with Power Quality (PQ) issues. Therefore, this passive technique is not capable of detecting and classifying the events of disturbance. The main objective of this thesis is to design reliable, fast, and accurate islanding detection approach which work well in case of matched power situation and in the presence of multiple DGs that can fulfill the inabilities of a conventional method. Another objective is to select an appropriate discriminative feature which will successfully detect islanding. Proposed is a WT-ANN based islanding detection technique in which the negative sequence voltage signal at the PCC will be acquired and then decomposed into different frequency bands using Discrete Wavelet Transform. The energy content and SD of the wavelet details will be calculated and fed to a trained ANN. A decision whether an islanding or non-islanding event will be obtained using the trained ANN. Once trained, ANN will be able to predict the event by understanding the pattern of input feature vector. The proposed method has the potential to detect islanding conditions reliably in the presence of multiple DG islands. It is based on local cost effective measurements. Using Microsoft Azure Machine Learning Studio, a cloud platform by Microsoft, the trained model is deployed as a Web Service. A GUI is built using Python, from which we can connect to the Microsoft server, to get the prediction of the event happened in system whenever needed by sending the feature vector as a Web Request. This feature can be used for continuous monitoring of the system. In addition of being fast and cost effective, the proposed technique has no negative impact on the power quality unlike proposed active techniques.

1.7. Thesis outline

The thesis is organized in 5 chapters as described below:

Chapter 2 presents a literature review on the previous work conducted in the area of islanding detection. The principle of operation, the benefits, and the drawbacks of each method are discussed.

Chapter 3 explains with the performance of Detection of Harmonics passive technique. It begins with the theory behind this passive technique and a description of the system model used for all the simulations in this work. The results of the implemented technique is then presented and discussed to show the limitations of this technique.

In chapter 4 the proposed Wavelet Transform – ANN based islanding detection technique is fully described. The theory and working of Discrete Wavelet Transform (DWT) is followed by an overview of artificial neural network (ANN) architecture. The training process of ANN is then explained. The methodology of the proposed technique is fully explained.

Chapter 5 is regarding the presentation and discussion of simulation test results showing the proper operation of Wavelet Transform – ANN technique, followed by discussion of the results.

Chapter 6 discusses the implementation of the trained model is done using Microsoft Azure Machine Learning Studio and Python GUI.

Chapter 7 concludes and summarizes the important contributions and findings of the proposed Wavelet Transform – ANN base islanding detection technique. Finally, suggestions for future work are identified.

CHAPTER 2

LITRATURE REVIEW

A critical requirement for grid connected DG is islanding detection. According to IEEE std. 1546, the DG should be disconnected once an islanding event is declared. Several islanding detection techniques have been proposed in the literature. An overview of various islanding detection methods, principles of operation, their strengths and drawbacks are introduced in this chapter.

2.1 Review of Established Islanding Detection Methods

Islanding detection methods may be divided into two main categories: remote methods and local methods. Remote techniques are based on the communication between the utility and the distributed generators. On the other hand, local techniques are based on the data available on the distributed generator side. Local techniques can be further classified into passive and active methods [9] as shown in Figure 2.1.

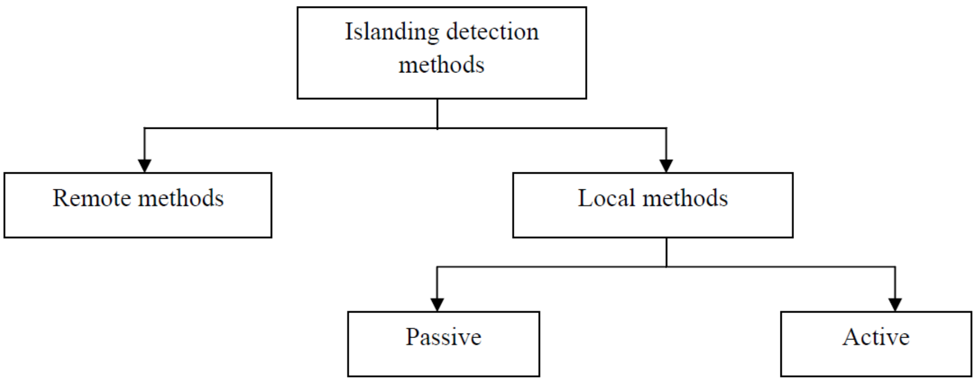


Figure 2.1: Classification of islanding detection methods

2.1.1 Remote islanding detection techniques

Remote islanding detection techniques are based on the information transferred through the communication between the utility and the DG. Upon detecting the islanding event, the communication signal is sent to trip DG units. Fig. 2.2 shows the basic operating principle of remote islanding detection techniques.

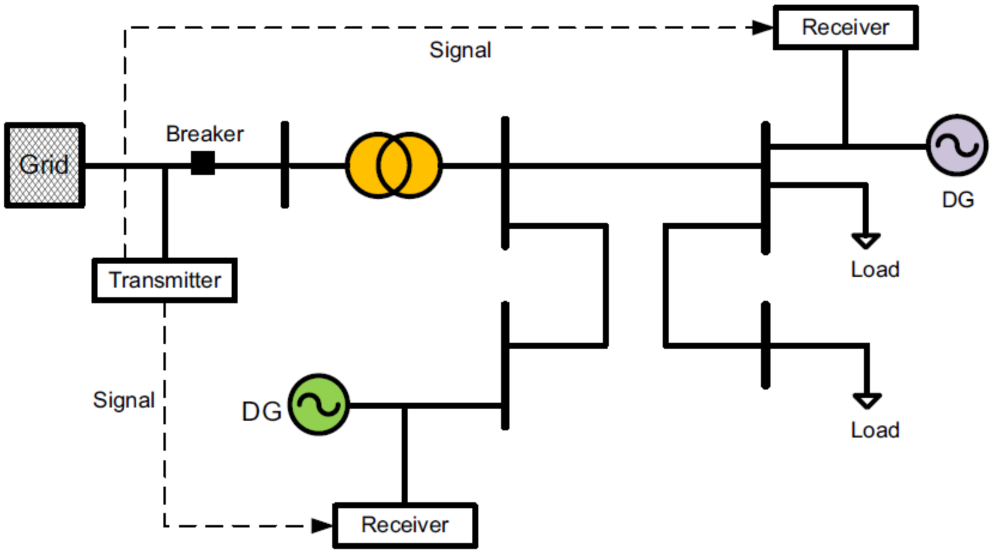


Figure 2.2: Remote islanding detection scenario

It can be observed that the transmitter is placed at the grid's side, while the receiver is placed on each DG side, and communication is carried out through a power line carrier. During steady state operation when the circuit breaker is connected, the receivers at the DG side continuously receive signals. However, when the distribution network is islanded, the receiver will not receive the signal due to the broken communication medium. Hence, islanded is detected. This type of communication for islanding detection is known as power line signaling scheme [10-12]. Another communication medium is the use of Supervisory Control and Data Acquisition (SCADA) system for islanding detection. This type is known as the transfer trip scheme [13]. Remote islanding detection techniques have better reliability than local techniques; however, these techniques are complex and costly, especially for small distribution networks [14]. The practical implementation of transfer trip scheme or power line signaling scheme costs around $80,000–$250,000 for a single DG installation [15]. Furthermore, these techniques highly rely only on the communication means. Thus, any communication failure may lead to malfunctions throughout the system. Due to these reasons, remote techniques are not recommended for small DG systems [16]. Hence, local (passive and active) techniques are widely used for islanding detection.

2.1.2 Active islanding detection techniques

The principle of active techniques is based on the usage of high frequency signals or some other means to slightly perturb the system variables, such as voltage and frequency to detect the islanding. The main concept behind active techniques is when the distribution system is connected to the grid; the addition of perturbation will cause a small variation in system parameter. However, in the islanded mode, the system will observe a significant variation in system parameter, which will lead to the detection of islanding. The examples of active islanding detection techniques include slip mode frequency shift algorithms (SMFSA) [17], active frequency drift (AFD), and active frequency drift with positive feedback methods [18], automatic phase shift algorithm [19], negative sequence current injection [18], negative sequence voltage injection [20], changing of the injected current and monitoring its voltage at the PCC [21]. Most of the active techniques are employed for inverter-based distributed generations. Apart from this, most of the active islanding detection techniques are generally proposed only for current controlled sources. Active islanding detection techniques have the advantage that their non-detection zone is very small, and can detect islanding even in perfect match of generation and load demand. However, their main problem is that these techniques introduce perturbation in the system at the regular intervals of time that are unnecessary during most of the operating conditions, which often degrade the quality of power. Furthermore, active technique takes large time to detect islanding compared to passive techniques [22].

2.1.3 Passive islanding detection techniques

Passive islanding detection techniques use system parameters measurement (voltage, frequency) at the DG terminals or point of common coupling for islanding detection. These measurements are compared with a predetermined threshold value for the purpose of detecting islanding. Passive techniques are very cost effective, as they do not require large modifications in the protection system [23]. Few common passive techniques include the rate of change of frequency [24], rate of change of output power [25], change of source impedance [26], harmonic distortion [25,26] and voltage magnitude variation [27].

The passive techniques have the advantage of not affecting the power quality of the distribution network. Hence, power quality issues, such as electrical noise, spikes, and voltage dip do not exist in these techniques. However, passive techniques suffer from large non-detection zone (NDZ), which is the range (in terms of power difference between DG and load) where an islanding detection technique fails to detect islanding. Furthermore, these techniques need special care while setting the thresholds values. Setting up of low threshold value may result in nuisance tripping, while high threshold value setting may fail to detect islanding. The passive technique drawbacks can be overcome by active islanding detection techniques. Detection of Harmonics is the conventional technique used in this thesis to compare the performance with Wavelet based approach.

CHAPTER 3

DETECTION OF HARMONICS METHOD

3.1 Theory of Detection of Harmonics Method

There are several ways to calculate the harmonic content in a voltage or current signals. The most common way is to calculate the total harmonic distortion (THD) which is calculated according to equation (3.1):

$$THD = \frac{\sqrt{\sum_{h=2}^{H} V_h^{\,2}}}{V_1} \times 100 \tag{3.1}$$

Where V_h is denoted for all the harmonic components except for the fundamental and V_1 is the fundamental frequency component. There are two main sources of harmonics in typical distribution systems. The first source includes power electronic converters such as three phase inverter while the second source includes devices that exhibit non-linear relationship between the voltage and current such as transformers.

This method involves monitoring the THD of the voltage or current signal at the point of common coupling. During grid connected mode, the distorted current which includes the harmonics will flow from the inverter out to the utility since the grid has lower impedance compared to that of the load. The current containing the harmonics will interact with the low impedance grid producing small amount of distortion in the voltage signal. However, when the grid is disconnected, the current containing the harmonics will be forced to flow into the load which has high impedance producing larger amount of distortion in the voltage signal compared to the amount produced under grid connected mode. If the THD was large enough it will exceed the threshold and islanding will be detected. The simulation of the study is conducted in MATLAB/ Simulink on a Hybrid Distribution System explained on the following section.

3.2 Hybrid System

The hybrid system under consideration consists of a PV plant rated at 250 kW with constant irradiance of 1000 W/m^2 and a Wind plant is rated at 1.5 MW with constant wind speed of 12 m/s. The PV array consists of 86 parallel strings. Each string has 7 Sun Power SPR-415E modules connected in series. The converter is modeled using a 3-level IGBT bridge PWM-controlled. The inverters choke RL and a small harmonics filter C are used to filter the harmonics generated by the IGBT Bridge. A 250-kVA 250V/25kV three-phase transformer is used to connect the inverter to the utility distribution system. The grid is modeled as a typical North American distribution grid. It included two 25-kV feeders, loads, grounding transformer and an equivalent 120-kV transmission system.

A 1.5 MW wind turbine connected to a 25 kV distribution system exports power to a 120 kV grid through a 30 km, 25 kV feeders. Wind turbines using a doubly-fed induction generator (DFIG) consist of a wound rotor induction generator and an AC/DC/AC IGBT-based PWM converter. The stator winding is connected directly to the 60 Hz grid while the rotor is fed at variable frequency through the AC/DC/AC converter. The DFIG technology allows extracting maximum energy from the wind for low wind speeds by optimizing the turbine speed, while minimizing mechanical stresses on the turbine during gusts of wind.. The reactive power produced by the wind turbine is regulated at 0 MVAr. Both are connected to grid through a PCC. Fig. 3.1 shows the layout of the system. The grid voltage is 25 kV. Islanding is simulated by opening the 'CB1' circuit breaker. Hybrid System loading is an important parameter at Islanding situations. Load is connected at PCC.

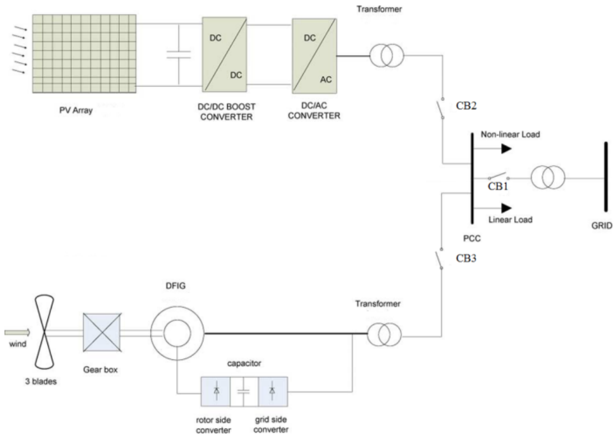


Figure 3.1: Hybrid system layout

Figure 3.2 shows the simulation diagram drawn in MATLAB/Simulink which is used for all the simulations in this thesis. PV model and Wind model is explained in following sub sections.

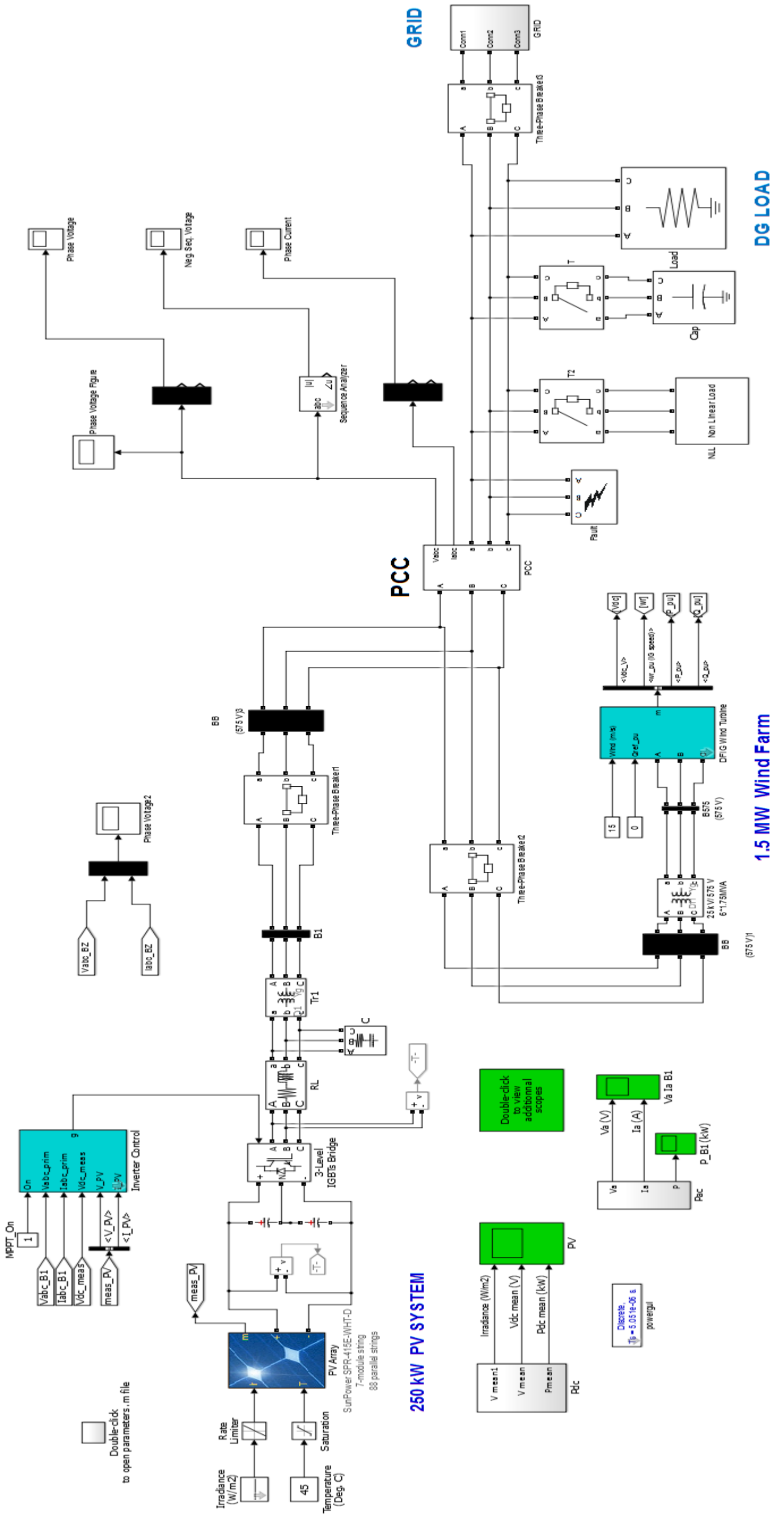


Fig. 3.2: Simulation Diagram

3.2.1 PV Model

The solar energy conversion into electricity takes place in a semiconductor device called a solar cell. A solar cell is a unit that delivers only a certain amount of electrical power. It is the basic unit of solar PV array/panel. They are combined in series and parallel to achieve the required voltage and current level. A PV cell is a p–n junction semiconductor that generates current when exposed to light. The mathematical model of PV cell is useful for simulation purpose to reveal the voltage, current and power behavior under different operating conditions [28]. The basic theory involved in working of an individual PV cell is the Photoelectric effect according to which, when a photon particle hits a PV cell, after receiving energy from sunbeam the electrons of the semiconductor get excited and hop to the conduction band from the valence band and become free to move. If the energy of photon of light is greater than the band gap, then the electron is emitted and the flow of electrons creates current. Movement of electrons create positive and negative terminal and also create potential difference across these two terminals as shown in Fig 3.3. When an external circuit is connected between these terminals an electric current starts flowing through the circuit.

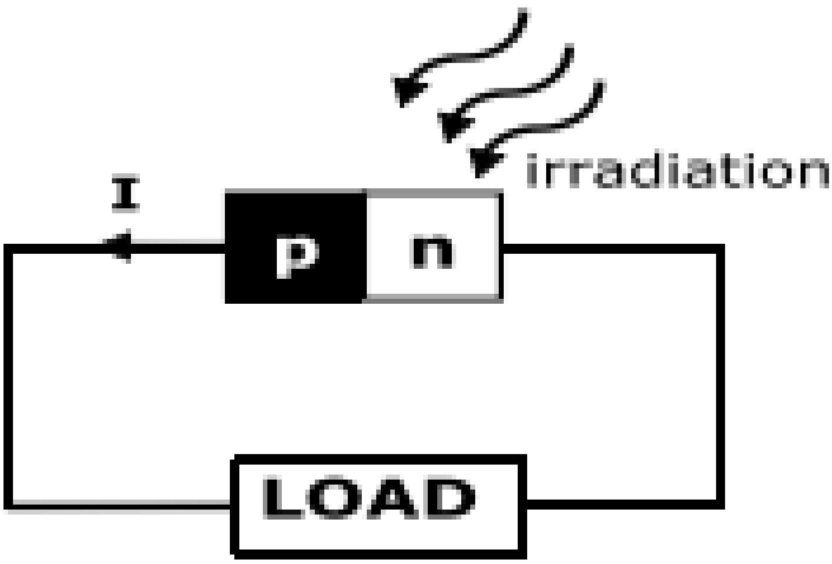


Fig. 3.3: Working of a PV cell

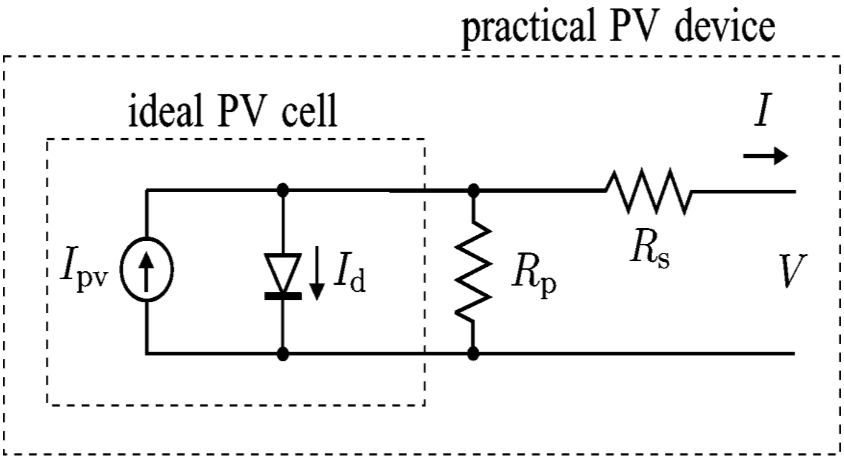


Fig. 3.4: Single-diode model of the theoretical PV cell

The basic equation describing the I–V characteristic of the ideal PV cell is

$$I = I_{pv,cell} - \underbrace{I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right]}_{I_d} \tag{3.2}$$

where, $I_{pv,cell}$ is the current generated by the incident light which is directly proportional to the Sun's irradiation, I_d denotes the Shockley diode equation, $I_{0,cell}$ denotes the reverse saturation current or leakage current of the diode, q is the electron charge , ie, $1.60217646 \times 10^{-19}$ C, a is the diode ideality constant, k is the Boltzmann constant ,ie, $1.3806503 \times 10^{-23}$ J/K and T indicates the temperature of the p–n junction in Kelvin. Practical arrays are composed of several connected PV cells and the basic equation requires inclusion of several other parameters,

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + R_s I}{V_t a}\right) - 1\right] - \frac{V + R_s I}{R_p} \tag{3.3}$$

where I_{pv} is the photovoltaic (PV) current and I_0 is the saturation current of the array and the thermal voltage of the array $V_t = N_s kT/q$ with N_s cells connected in series, R_s and R_p are the equivalent series and parallel resistances of the array. The light-generated current of the PV cell depends on the solar irradiation and temperature according to the following equation,

$$I_{pv} = (I_{pv,n} + K_I \Delta_T)\frac{G}{G_n} \tag{3.4}$$

where $I_{pv,n}$ is the light-generated current at the nominal condition in amperes (usually 25°C and 1000 W/m^2), $\Delta T = T - T_n$ (T is the actual temperature and T_n is the nominal temperature in Kelvins), G and G_n are the irradiation on the device surface and the nominal irradiation respectively(watts per square meters). The diode saturation current I_0 may be expressed as shown

$$I_0 = \frac{I_{sc,n} + K_I \Delta_T}{\exp((V_{oc,n} + K_V \Delta_T)/aV_t) - 1} \tag{3.5}$$

where $V = V_{oc,n}$, $I = 0$, $I_{pv} \approx I_{sc,n}$, K_I and K_V are the current and voltage coefficients respectively.

The power produced by a single PV cell is not enough for general use. Thus connecting many PV cells in series (for high voltage requirement) and in parallel (for high current requirement) results in the attainment of the desired power. Generally a series connection is chosen. This set of arrangement is known as a module. The modules consist of transparent front side, encapsulated PV cell and back side. The front side material is usually made up of low-iron and tempered glass. The efficiency of a PV module is less than a PV cell. This is due to the fact that some radiation is reflected by the glass cover and frame shadowing etc. A Photovoltaic array is an interconnection of modules which in turn is made up of many PV cells in series or parallel. The power produced by a single module is seldom enough for commercial use, so modules are connected to form array to supply the load. The connection of the modules in an array is same as that of cells in a module. Modules can also be connected in series to get an increased voltage or in parallel to get an increased current. In urban areas, generally the arrays are mounted on a rooftop. Fig 3.5 shows the hierarchy of a photovoltaic system.

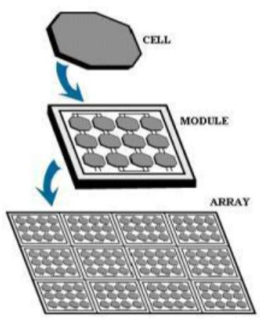


Fig. 3.5: Photovoltaic Hierarchy

3.2.2 Wind Energy

Wind is the by-product of solar energy. Only a small fraction of the sun's energy reaching the earth is converted into wind. The surface of the earth heats and cools, creating atmospheric pressure zones which force the air flow from high- to low-pressure areas. Wind power is the use of air flow through wind turbines to mechanically generate power for electricity. Wind power, as an alternative to burning fossil fuels, is plentiful, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation, uses no water, and uses little land. The net effects on the environment are far less problematic than those of non-renewable power sources. Wind farms consist of many individual wind turbines which are connected to the electric power transmission network. Onshore wind is an inexpensive source of electricity, competitive with or in many places cheaper than coal or gas plants. Offshore wind is steadier and stronger than on land, and offshore farms have less visual impact, but construction and maintenance costs are considerably higher. Small onshore wind farms can feed some energy into the grid or provide electricity to isolated off-grid locations [29].

3.2.2.1 Wind Turbine

A wind turbine is a rotary engine that captures power from a fluid flow (the wind) using aerodynamically designed blades and convert it into useful mechanical power. The available power depends on the wind speed but it is important to be able to control and limit the power at higher wind speeds so as to avoid the damage of the unit. The power limitation may be done by some of the three following methods, namely stall control (the blade position is fixed but stall of the wind appears along the blade at higher wind speed), active stall (the blade angle is adjusted in order to create stall along the blades) or pitch control (the blades are turned out of the wind at higher wind speed). Wind turbines are classified into two general types, namely Horizontal and Vertical axis. A horizontal axis turbine has its blades rotating on an axis parallel to ground and a vertical axis machine has its blades rotating on an axis perpendicular to ground. There are different available designs for both types and each type has certain advantages and disadvantages. However, compared to horizontal axis type, vertical axis machines are used less commercially.

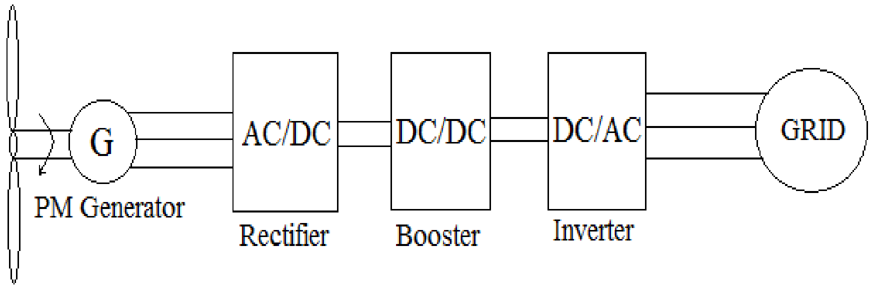


Fig. 3.6: WECS block diagram

Fig. 3.6 is the block diagram of Wind Energy Conversion System (WECS). A wind turbine converts kinetic energy of air i.e., wind power into mechanical power i.e., rotating motion of the turbine that can be used directly to run the machine or generator. The MATLAB model of a wind turbine is shown in Fig.2.6. Power captured by wind turbine blade is a concomitant of the blade shape, the pitch angle, speed of rotation and radius of the rotor. The equation for the power generated is shown below.

$$P_W = \frac{1}{2} C_p(\lambda, \beta)\rho A V^3 \qquad (3.6)$$

where ρ is the density of air (typically 1.225 kg/m^3), A is the area swept by rotor blades, V is the wind speed, C_p is the coefficient of power conversion and β is the pitch angle.

3.3 Simulation Results

Following waveforms are taken at Islanding and Non-Islanding situations for 50% loading of Hybrid System rating (0.8 MW). THD is calculated for the first cycle after Islanding instant. Simulation time is 1.2 seconds. Islanding period is from 0.5 to 0.7 seconds.

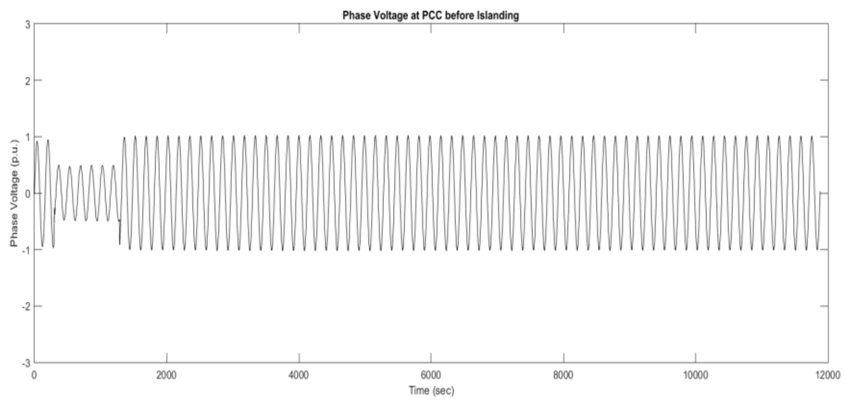


Figure 3.7: Phase Voltage at PCC before Islanding

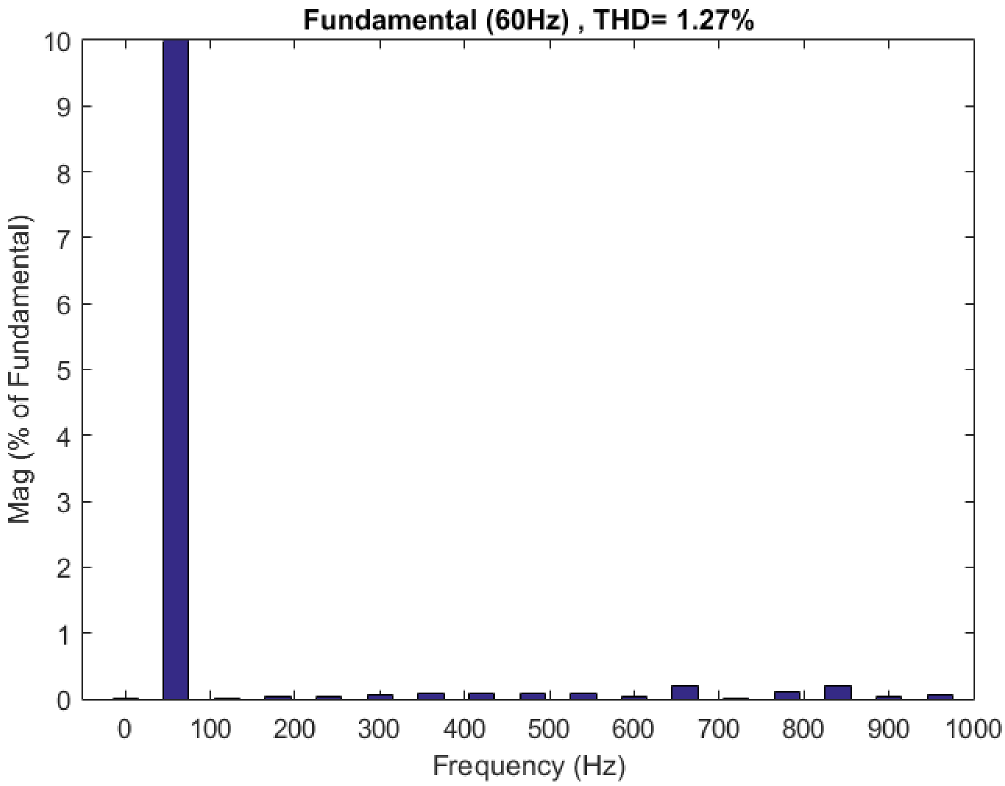


Figure 3.8: THD of Phase Voltage at PCC before Islanding

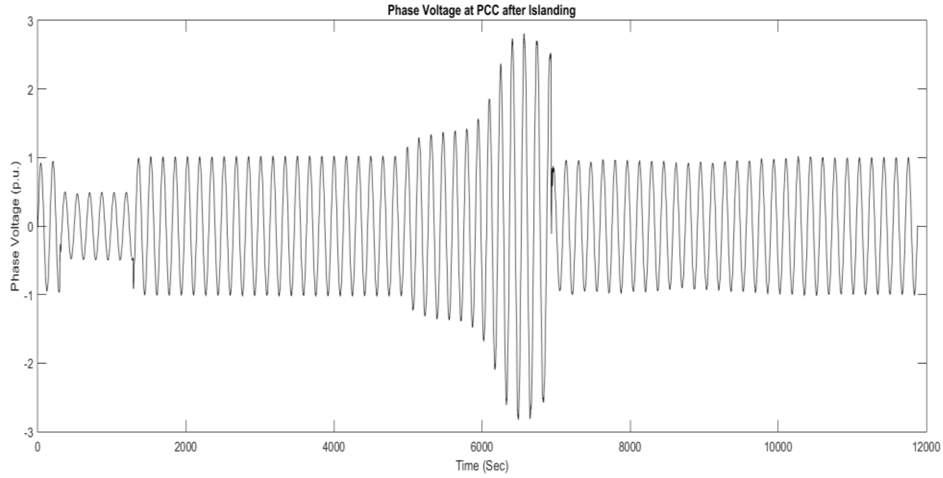


Figure 3.9: Phase Voltage at PCC after Islanding

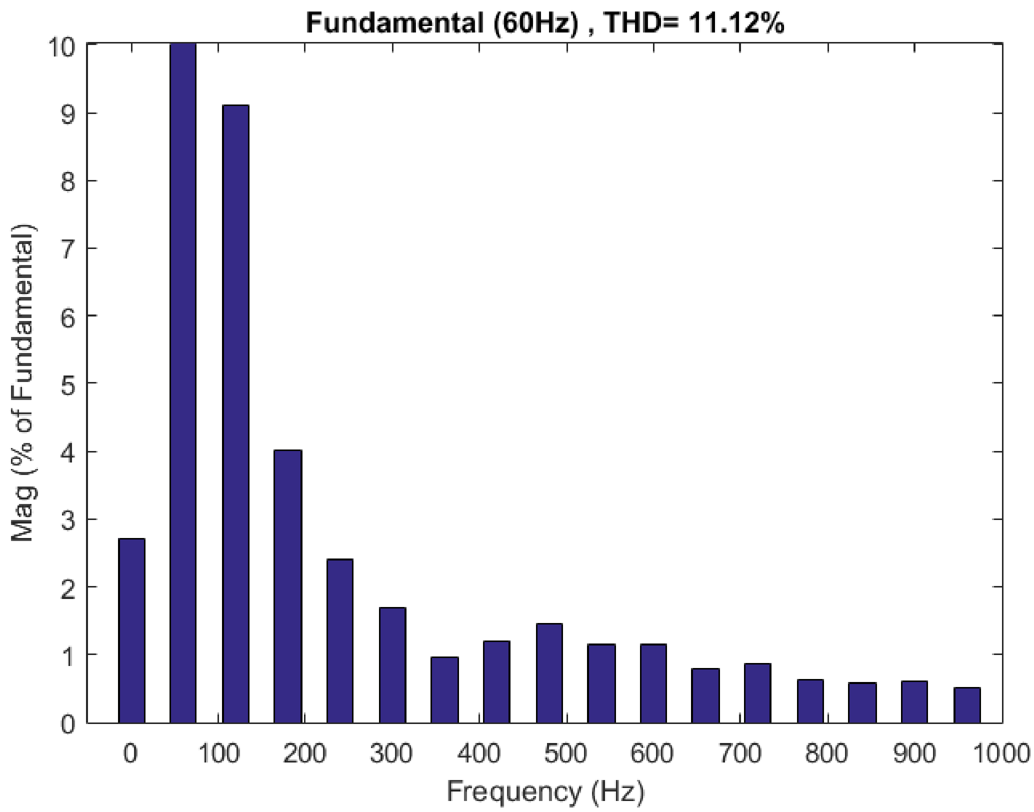


Figure 3.10: THD of Phase Voltage at PCC after Islanding

The value of THD before Islanding was 1.27 % which is increased to 11.12 % after Islanding indicates the disturbance in the system. Thus THD is capable of detecting the disturbances in the system.

Table 3.1 shows the performance of THD in various loading of Hybrid Distribution System during Islanding. Loading is in the range of 50 % to 100 % rated load.

Table 3.1 Performance of THD in various loading during Islanding

Loading in MW	THD before Islanding (%)	THD after Islanding (%)
0.875	1.2665	11.1161
1	1.1347	8.0497
1.3	0.953	3.3066
1.75	0.7766	4.1653

Table 3.2 shows the Performance of THD (%) during different disturbances happened at PCC at different loadings.

Table 3.2 Performance of THD in various loading at various disturbances

Loading (MW)	Grid Connected	Islanding	L-G Fault	L-L Fault	Non - Linear Load Switch
0.875	1.2665	11.1161	3.5811	6.0342	62.3332
1	1.1347	8.0497	3.5966	6.0166	62.2358
1.3	0.953	3.3066	3.7453	5.9751	61.8576
1.75	0.7766	4.1653	3.9311	5.8795	61.3211

From table 3.1 and 3.2 we can make following inferences

- THD changes abruptly with loading during Islanding
- Due to the abrupt change in value, it is hard to fix a threshold for detection
- THD fails to differentiate PQ events from Islanding.