Islanding and Power Quality Improvement in Hybrid Distributed Generation

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Abstract: *Islanding and Power Quality(PQ) Issues in Hybrid Distributed Generation (DG) System consists of Photovoltaic(PV) system and Wind Power Plant connected to grid through a Point of Common Coupling(PCC), are detected and classified, using Wavelet Transform and Artificial Neural Networks. Wavelet Transform indices are extracted from the Negative Sequence component of the voltage signal at PCC to detect the disturbances. A feature vector is modeled with WT indices and loading of DG system to train Artificial Neural Network. . The proposed method is compared with a conventional method. The results demonstrate the advantages of Wavelet over conventional method in detection and classification of disturbances in the system and robustness in application of Machine Learning (ML) Classifier. The trained ANN is deployed as a Web Service using Microsoft Azure Machine Learning Studio. It enhances the implementation feasibility of proposed method.*

Keywords: *Machine Learning, Web Service, Distributed system, Photovoltaic cell, DC Generators.*

I. INTRODUCTION

The bulk power from the transmission network is intended to be received by existing distribution systems, which then distribute it to the loads. Electricity generation, transmission, and distribution to customers are the responsibility of the utility. The term "centralised or regulated" electric power system is used to describe this conventional setup. The centralised electric power plants will reportedly continue to be the main source of electricity, though, as is generally accepted. The need to update the energy infrastructure, high power loss, and environmental pollution are just a few of the challenges faced by centralised power plants [1]. The number of small generation units known as distributed generators (DGs) that can connect to the distribution network has significantly increased over the past few years. By using this method, centralised and regulated conventional electric power plants will become deregulated power plants. The integration of DGs into the distribution network can have either a positive or negative effect because distribution networks are created without any generation at the customer side. The advantages and disadvantages of connecting distributed generators to the current distribution system are discussed in this chapter. An introduction to the concept of distributed generation and the structure of distribution networks opens the chapter. The advantages of integrating DGs into the distribution network and their effects are then discussed. Finally, a brief overview of the islanding issue is provided.

The four main components of conventional power systems are generation, transmission, distribution, and loads. Electricity is typically generated between 11 and 25 kV during the generation phase. The voltage is then stepped down after being transmitted via overhead lines from the generation units to far-flung regions of the primary and secondary distribution systems. Figure 1 displays the various phases and their respective voltage ratings. [2].

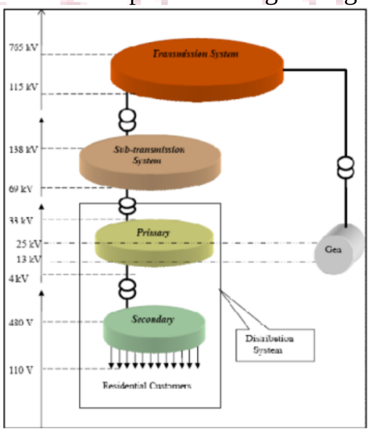

Figure 1: Different phases and their voltage rating in a traditional electric power grid.

II. PROBLEM STATEMENT

Currently, there are numerous techniques that can be used to identify the DG's islanding situation (s). In situations where there is an imbalance of power between the loads and the DG(s) present in the power island, passive methods like under/over voltage and under/over frequency work well. If the amount of power supplied and consumed on the island is balanced, these methods do not identify the islanding situation. There are also numerous active strategies that aim to create a power imbalance in order to make the island detectable. However, when there are multiple DGs providing power to the same island, these techniques may be less effective at detecting the island and can degrade the quality of the power provided by the DG. The active methods might also need to know how much current the loads are drawing. Utility installed techniques like power line carrier communication demand additional equipment and may be pricey. The implementation of the Wavelet Transform (WT) of the negative sequence voltage signal at the point of common coupling is the foundation of the proposed islanding detection method (PCC). The taught ANN determines whether or not an islanding has taken place. They will be classified with the aid of the Artificial Neural Network (ANN) model trained by these WT indices, which recognises the pattern of the input feature vector. The system that is represented by MATLAB Simulink is used to acquire a number of simulated negative sequence voltage signals. There are primarily two types of acquired negative sequence voltage signals: non-islanding and islanding. Normal operation, temporary single line to ground (SLG), line to line fault, and switching of non linear load at PCC on the distribution network are examples of simulated nonislanding situations. On the other hand, the simulated islanding cases include the PCC's circuit breaker being opened, which results in islanding at various times. A developed mathematical tool for signal processing is wavelet analysis. Choosing a suitable wavelet function, or "mother wavelet," and then performing analysis using shifted and dilated versions of this wavelet are the fundamental principles of wavelet transform (WT). A windowing method with variable-sized regions is applied in WT. Long windows can be used in wavelet analysis when low-frequency information (approximation) is needed, and short windows can be used when high-frequency information (detail) is needed.

III. LITERATURE REVIEW

Kumar et al. [1] outlines a control strategy that uses voltage feedback-based reactive power support from the existing DGs to reduce the impact of an induction motor starting on the network voltage. The theoretical framework is validated through the presentation of simulation studies. It is demonstrated that DGs can quickly restore the motor starting transient voltage dip thanks to the voltage controller's quick response.

Zhang et al.[2] outlines a common distributed cooperative voltage control strategy for grid-following (GFL) and grid-forming (GFM) DGs. A novel range-consensus-based distributed control algorithm and a unified modelling technique make up the suggested methodology. The modelling approach uses power coupling and extended state observer (ESO) to combine various internal dynamics and control architectures of DGs, allowing for the development of a single distributed controller to handle the voltage regulation of various DGs. The suggested distributed algorithm introduces deviation-based states rather than a consensus state to converge the voltages to an expected range, making the algorithm more in line with the grid code's voltage control standard than the common state consensus ones. Additionally, the algorithm's local feedback design enhances the system's anti-interference performance. The stability of the suggested method is confirmed by the Lyapunov technique. Finally, a hardware-in-the-loop (HIL) test and several simulation results are used to verify the effectiveness of the suggested scheme.

Gupta et al. [3] focuses on the multimode operation of a photovoltaic (PV) array, a battery, the grid, and a charging station (CS) based on a diesel generator (DG) set for supplying continuous charging and uninterruptible supply to the household loads. In this CS, a single voltage source converter runs the CS in an islanded mode, the grid connected mode, and the DG set connected mode (DGM) and completes a variety of tasks, including managing power between various energy sources and charging electric vehicles (EVs), extracting the most power possible from the PV array, regulating the voltage and frequency of the generator, compensating for harmonic currents in nonlinear loads, and compensating for intentional reactive power. The PV array and a storage battery serve as the main power sources for the control of charging station (CS). The charging station uses a squirrel cage induction generator-based DG set as a last resort when neither of these two sources is available. The size of the DG is reduced because the DG set is operated so that it can produce up to 33% more power than its rated capacity without going over the rated current in the windings. Additionally, the generator's voltage and frequency are controlled at their rated values without the use of a mechanical speed governor. The CS complies with the IEEE 1547 standard in all operating modes and achieves the total harmonic distortion of voltage and current.

Puchalapalli et al.[4] The PV array and a storage battery are used to provide the majority of the power for the control of charging station (CS). In the absence of these two resources, the charging station uses a DG set based on a squirrel cage induction generator as well as grid power. However, by operating the DG set so that it can produce up to 33% more power than its stated capacity without going over the rated current in the windings, the DG set's size is reduced. Furthermore, the generator's frequency and voltage are maintained at their specified levels without the use of a mechanical speed governor. The CS achieves total harmonic distortion of voltage and current in accordance with the IEEE 1547 standard in all operational modes. Through rotor side VSC control and bidirectional buck/boost dc-dc converter control, respectively, the maximum power from wind and solar is extracted. To get the most power out of a solar PV array, a modified perturb and observe algorithm is presented. Additionally, the control of load side VSC is made to maximise DG fuel usage. The reference DG power output for ideal fuel consumption is determined using a new generalised concept. A bidirectional converter's impact on load variation and an unbalanced nonlinear load connected at the point of common coupling are two situations that can be modelled and simulated using the SimPowerSystems toolbox of MATLAB. The DG currents and DFIG stator currents are discovered to be sinusoidal and balanced.

Kumar et al. [5] Presents a grid-based electric vehicle (EV) charging station (CS) is used to provide the continuous charging in islanded, grid-connected, and DG set connected modes. It consists of a solar photovoltaic (PV) array, a battery energy storage (BES), a diesel generator (DG) set, and an EV charging station (CS). The main purpose of the CS is to charge the EV battery using a BES and a solar PV array. However, the CS intelligently uses power from the grid or DG set in the event that the storage battery is empty and the solar PV array generation is not available. To achieve maximum fuel efficiency under all loading conditions, the power from DG sets is drawn so that it always operates at 80% to 85% loading. Additionally, without a mechanical speed governor, the CS controls the generator voltage and frequency in conjunction with the storage battery. Additionally, it guarantees that even under nonlinear loading, the power drawn from the grid or DG set has a power factor of unity. In order to achieve continuous charging, the grid/generator voltage and the point of common coupling voltage are synchronised. To improve the CS's operational efficiency, the CS also performs active/reactive power transfers from vehicles to the grid, homes, and other vehicles. The prototype created in the lab is used to experimentally validate the CS's operation.

Ye et al.[6] proposes a comprehensive optimization model for restoring an unbalanced distribution system following widespread power outages brought on by extreme events. Dispatched distributed generators (DGs), renewable DGs (primarily wind and solar), and energy storage systems are among the various types of distributed energy resources (DERs) that the model can coordinate the control actions of (ESSs). The model also takes topology flexibility into account by reconfiguring dynamic islands. Additionally, the best dispatch model for repair teams and mobile emergency generators is suggested in order to take advantage of the distribution systems' installed DERs' restoration capabilities. The integrated optimization model is linearized into a mixed-integer linear programming form, which is amenable to being successfully solved by commercial solvers like Cplex and Gurobi. The effectiveness of the suggested model was validated by numerical results on IEEE 123 and 8500 node test feeders, which also highlighted the need to coordinate numerous flexible resources.

Mahpatra et al. [7] For a high penetration/hybrid diesel wind-based energy storage system, a control algorithm was put forth with two scenarios in order to maintain the dynamic stability of power flow and regulate frequency throughout the entire power system. The findings demonstrate that, when compared to earlier research and publications, the transient time of wind power flow and the frequency fluctuation rate are significantly decreased when using an integral-derivative (I-D) controller. A storage system (battery) was used to minimise the loss of power generated by the wind turbine and store excess energy without sending it to the secondary/dump load (DL) in order to regulate the network frequency. When there is a high load demand, the excess wind energy is delivered to the battery.

Lai et al.[8] the massive current-controlled voltage source inverter (CCVSI)-based distributed generators (DGs) in an ac microgird will be dispatched and shared using an innovative distributed event-driven control strategy. When compared to continuous-time feedback control, the proposed distributed power sharing control strategy successfully lowers the frequency of controller updates because it is fully distributed and only driven at their own event time. In addition, each CCVSI-based DG only needs to measure local voltage and current from itself and some of its closest neighbours (but not all) for distributed power sharing control at the most recent event-driven time using low-bandwidth communication links, and then updates the control inputs to restore the active and reactive powers to desired values to further reduce the consumption of computing and communication resources to some extent.

Kumar et al. [9] compares conventional UPQC, UPQC-DG, and UPQC-independent DG (UPQC-IDG) in detail in terms of their respective power losses and improves the criteria for choosing the ideal configuration to be used effectively based on requirements and economically viable options. In this study, the power losses for various steady-state and dynamic operating conditions are compared between UPQC, UPQC-DG, and UPQC-IDG. Conduction losses, filtering losses, and switching losses are all included in the power losses in every arrangement and were discovered through simulation and empirical research. The computer simulations used in the comparative research were done in MATLAB/Simulink and real-time simulation was done using Opal-RT.

Kumar et al.[10] Investigation is conducted into the coordinated operation of a tidal turbine generator (TTG), a newly emerging and underutilised DG, a diesel engine generator (DEG), and plug-in hybrid electric vehicles (PHEVs), all of which are built on an underutilised autonomous high-voltage system (HPS). The first implementation of the proposed quasi-oppositional harmony search algorithm (QOHSA) based model predictive control (MPC) strategy achieves the coordinated operation of various control loops, such as the blade pitch control loop of TTG, supplementary control loop of DEG, and power control loop of PHEVs. Its performance is compared to that of the coordinated performance achieved using QOHSA tuned conventional controllers and other known optimization algorithms in order to demonstrate the superiority of the proposed QOHSA tuned MPC method in mitigating frequency deviation following disturbance. According to the findings, frequency fluctuation can be greatly decreased using the suggested method when there are various load disturbances. The suggested approach is capable of addressing model mismatches as well as various variations of disruption signals or noise entering the system.

Hridaya et al.[11] suggests a hierarchical coordinated control, which includes primary control level (PCL) and power management system (PMS) for the coordinated operation of the power sources in dc-SMGs. The following characteristics are made possible by the coordination between the PCL and the PMS: The primary speed regulation (PSR) of the diesel generator (DG) and the primary voltage control (PVC) of the dc circuit are included in the PCL first. By including a virtual impedance loop, the PVC can achieve dynamic/steady load power sharing, and the PSR of the DG adjusts the rotation speed to match the standard. Second, the PMS has secondary voltage recovery control and an optimum speed reference setting that enable variable-speed operation of the DG in accordance with its best energy efficiency characteristic, which also enhances power quality.

Kizito et al.[12] the location, assignment, and quantity of renewable distributed generators (DGs) in a utility-based microgrid operating independently from the main grid during a large-scale grid disturbance are optimised using a single-source capacitated facility location coverage problem (SS-CFLCP). Traditional analytical methods for DG placement within microgrids typically emphasise maximising cost reductions, increasing voltage profile, and minimising power and electric energy losses. A budgetary restriction for installing the DGs is also included in the proposed SS-CFLCP model, making it more realistic and applicable for a utility business. The efficacy of the suggested model is demonstrated through the use of a case study involving solar/photovoltaic-based DGs.

Kumar et al. [13] To provide precise harmonic power sharing and voltage harmonic correction in islanded microgrids, suggest an improved DG VIC. The proposed VIC is built on straightforward integral controllers with just two controllable components and no knowledge of the load currents or feeder impedances. A small-signal state-space model is used to analytically analyse the control performance and assess the stability and dynamics of the system. Results from simulations and experiments verify the method's viability and efficacy.

Zhou et al.[14] examines the power distribution and voltage control problems in isolated single- and three-phase microgrids (S/T-MGs), where both sources and consumers are unbalanced, and takes into account the possibility of hostile cyberattacks on the sensors of distributed generator (DG) units. The issue is formulated as a distributed containment control problem after each DG unit is first modelled as a heterogeneous linear dynamic agent with disturbances brought on by sources and loads. After that, a distributed adaptive observer is designed in order to create an attack-resistant distributed secondary control method that will ensure that the S/T-MGs will perform satisfactorily in terms of power sharing and voltage control asymptotically. This method allows for the neutralisation of the impact of cyber-attacks while maintaining bounded voltage synchronisation and system reliability.

Gupta et al. [15] based on dc integration at a shared dc bus, suggests a dc droop-based hierarchical control for the PV-BES-DG system. The dc integration removes the PV's scaling constraint and makes the hybrid system easier to manage than its ac counterpart. To guarantee optimal load sharing between DG and BES, a secondary control based on an optimal regulator is also proposed. Additionally, a power management scheme (PMS) is created to guarantee the standalone system's dependable operation during source and load power imbalances as well as under crucial BES state-of-charge limit conditions. Additionally, the PMS limits the use of DG below a specified low-level usage. In addition, a small signal stability study is provided to examine the impact of droop and the ideal regulator gain on the stability of the system.

Ling et al.[16] offers a dispatchable droop control method that can be used in isolated ac microgrids to control numerous distributed generators (DGs). The suggested approach achieves pseudo hierarchical control by using first-order inertia elements, allowing the DG to autonomously distribute the load on a smaller time scale and comply with the dispatch order on a larger time scale. The suggested approach combines active power management and frequency restoration control on the one hand. On the other hand, it can regulate the voltage or the reactive power regulation depending on the circumstance. Even if the provided power control examples are impractical, the suggested method is still applicable.

Meena et al.[17] outlines a design-oriented modelling method to examine the Q-V control loop of distributed generators that form grids (DGs). The proposed strategy, in contrast to earlier modelling techniques, takes into account all typical grid-forming DG operation modes. The models in islanded single-DG mode and islanded multi-DG mode can be obtained through the suggested formulas, regardless of the type of inner control scheme that is used, once its state-space model in grid-connected mode is set. We evaluate and compare the two main Q-V control schemes of grid-forming DGs—the voltage/current double loop-based control and the reactive power loop-based control—using this innovative framework using corresponding reduced-order models. To emphasise the distinctive characteristics between control schemes and operation modes, closed-loop pole analyses of both control schemes in all three operation modes are examined.

Han et al.[18] Four voltage sag generators (VSGs), including generator-based, shunt impedance-based, transformer-based, and full converter-based VSGs, are reviewed and compared. A systematic overview of the causes, classification of voltage sag phenomena, and voltage sag emulating methods is also provided. In order to study the LVRT performance of the WT system under grid voltage sag conditions, a closed-loop detection platform based on real-time digital simulator (RTDS) for the converter controller of a permanent magnet synchronous generator (PWSG) set is introduced. Finally, the use of VSG in RES is discussed, along with possible future study directions.

Kumar et al.[19] suggest a grid-forming (GFM) inverter distributed voltage control strategy for isolated AC microgrids. The output voltage of distributed generators (DGs) is taken into account as the control variable in an optimization problem with technological limitations on voltage and reactive power output capacity and an objective function that trades off voltage regulation and reactive power sharing. In order to overcome the difficulties caused by the formulation's non-separable objective function, unavailability of the global average voltage, and globally coupled reactive power constraints, a distributed primal-dual gradient-based algorithm has been created.

Liu et al.[20] To analyse the different dynamic performance of VSG-based IIDG in each operating state, suggest a unified modelling approach. For any VSG control method, the suggested unified formulas can be used to derive the state-space models of the islanded-single-DG and islanded-multi-DG modes from the GC mode. With the obtained models, we analyse the distribution and sensitivity of the closed-loop poles and explore the step responses both analytically and experimentally for several different kinds of VSG control in various operation modes. These studies highlight the inherent distinctions and relationships between each operation mode's VSG-based IIDG dynamics.

IV. METHODOLOGY

Theory of Detection of Harmonics Method

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.

Hybrid System

The hybrid system under consideration consists of a PV plant rated at 250 kW with constant irradiance of 1000 W/m2 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. 2 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.

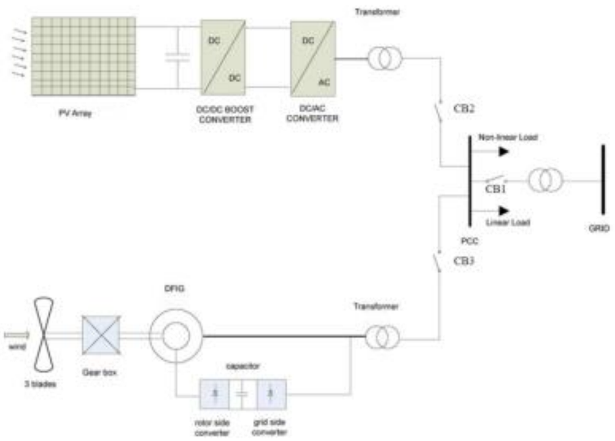

Figure 2: Hybrid system layout

Figure 3 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.

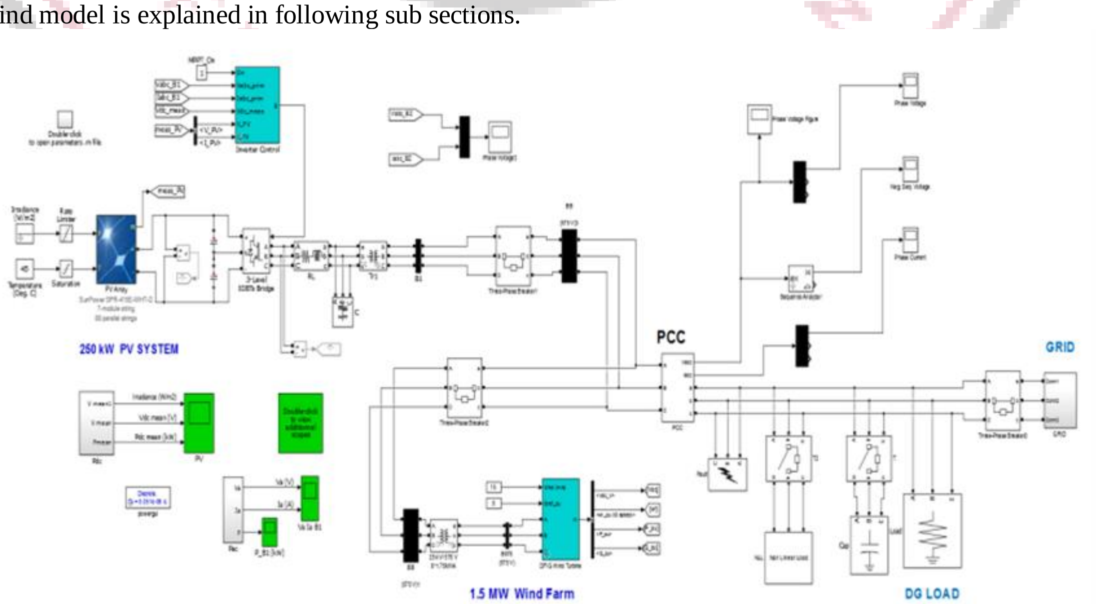

Fig. 3: PV model

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 4. When an external circuit is connected between these terminals an electric current starts flowing through the circuit.

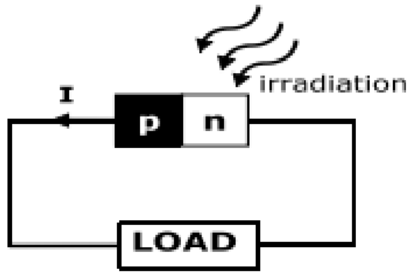

Fig. 4: Working of a PV cell

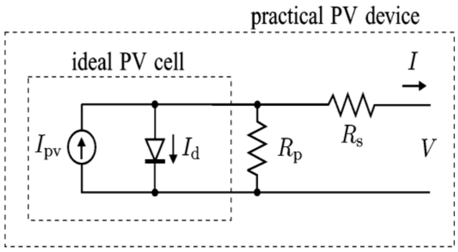

Fig. 5: Single-diode model of the theoretical PV cell

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 6 shows the hierarchy of a photovoltaic system.

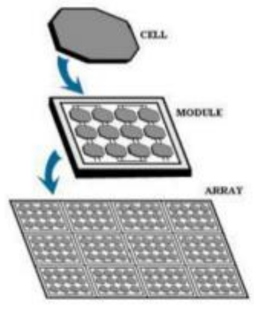

Fig. 6: Photovoltaic Hierarchy

PROPOSED ISLANDING DETECTION TECHNIQUE

The proposed technique is based on the identification of the transients associated with islanding, and differentiating them from the transients associated with non-islanding events such as faults, switching, etc. In this chapter, the proposed Wavelet Transform - ANN based islanding detection technique is explained. The chapter starts with an introduction to wavelet transform including its theory and choice of mother wavelet. Section two gives an overview of ANN followed by an explanation of the training process. Section three presents the methodology of the proposed Wavelet Transform ANN technique.

Wavelet Transform

Real time transients classification of power transients is very challenging since the high frequency content superimposed on the power frequency signals are usually aperiodic, short term and non stationary waveforms. Wavelet transform is proposed in order to extract discriminative features which will help in differentiating between transients associated with islanding event and those created from any other event such as switching of capacitor bank and temporary fault.

Wavelet transform (WT) is an effective mathematical tool which has been widely used in many engineering applications such as speech and image processing. WT has found many numerous applications in the power systems field some of the applications are power system protection, power quality, and partial discharge. Unlike Fourier transform (FT) which transforms the signal from the time domain to the frequency domain. The WT extract the frequency components of the signal while preserving the time domain properties. The theory of WT will be explained in the following section.

Theory of Wavelet Transform

Traditionally, the FT has been used extensively in signal processing to analyze stationary or time-invariant signals. In FT the analyzed signal is decomposed into a combination of sinusoidal waves having different frequencies. The FT is defined in (1).

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-j2\pi ft}dt \qquad (1)$$

Equation (1) defines the Fourier transform X f ( ) at the specific frequency f to be the time integral over all time of the product of a given signal xt() with a complex sinusoid at the specified frequency f . If the signal has a strong component at the particular frequency f , the FT will be significant. Otherwise it will be negligible. When the utility grid isolates, it can be seen that variations within the decomposition coefficient of the voltage signals contain useful signatures. Filters of different cut-off frequencies are used to analyze the signal at different scales. The signal is passed through a series of high pass filters to analyze the high frequencies, and it is passed through a series of low pass filters to analyze the low frequencies. Hence the signal (S) is decomposed into two types of components approximation (C) and detail (D). The approximation (C) is the high scale, low-frequency component of the signal. The detail (D) is the low-scale, high-frequency components. The decomposition process can be iterated, with successive approximations being decomposed in turn, so that one signal is divided into many lower resolution components which is called the wavelet decomposition tree and is shown in Fig. 7.

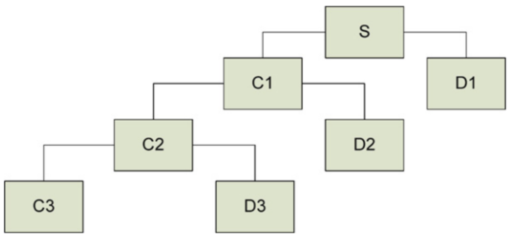

Figure 7: Wavelet decomposition tree.

As decompositions are done on higher levels, lower frequency components are filtered out progressively. The wavelet transform not only decomposes a signal into frequency bands, but also, unlike the Fourier transform, provides a non-uniform division of the frequency domain (i.e., the wavelet transform uses short windows at high frequencies and long windows for low frequency components). Wavelet analysis deals with expansion of functions in terms of a set of basis functions (wavelets) which are generated from another wavelet by operations of dilatations and translations. Given a function vt() , its continuous wavelet transform (CWT) can be calculated as

$$CWT(v,x,y) = \frac{1}{\sqrt{a}}\int_{-\infty}^{\infty} v(t)\varphi^{*}\frac{(t-y)}{x}dt \qquad (2)$$

Where x and y are scaling (dilation) and translation (time shift) constants, respectively, and ψ is the wavelet function. Wavelet transform of sampled waveform can be obtained by implementing the discrete wavelet transform as:

$$DWT(v,x,y) = \frac{1}{\sqrt{x_0^m}}\sum_{k} v(t)\frac{(n-kx_0^m)}{x_0^m} \qquad (3)$$

Where the parameters x and y in Eq. 2 are replaced by 0 m x and 0 m kx , k and m being integer variables. In a standard DWT, the coefficients are sampled from the CWT on a dyadic grid. A scaling function φ()t is associated with the wavelet function process multi-resolution analysis (MRA) of the taken signal. The scaling function of one level can be represented as a sum of a scaling function of the next finer level and is given by:

$$\varphi(t) = \sum_{n=-\infty}^{\infty} h\,(n)\sqrt{2}\,\varphi\,(2t-n) \qquad (4)$$

The wavelet function can be expressed in terms of the scaling function by:

$$\varphi(t) = \sum_{n=-\infty}^{\infty} h_1\,(n)\sqrt{2}\,\varphi\,(2t-n) \qquad (5)$$

Where hk( ) and 1 h k( ) represent the scaling function and wavelet function and are related by the expression:

$$h_1(k) = (-1)^k h(1-k) \qquad (6)$$

Choice of mother wavelet

In wavelets applications, the choice of appropriate mother wavelet plays an important role in the analysis. Different basis functions have been proposed. These include Haar, Morlet, Mexican, Daubechies, etc. In the present work, the db4 wavelet (with four quadrature filter bank) shown in Figure 8, 9 and 10 has been used as the mother wavelet for analyzing the transients associated with islanding. Db4 is a short wavelet and therefore it can efficiently detect transients.

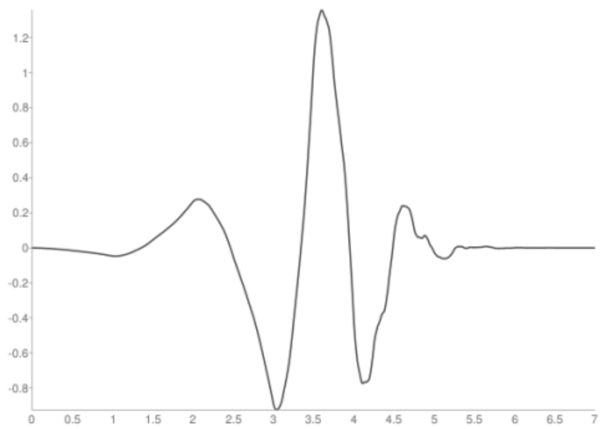

Figure 8: Wavelet Function of db4

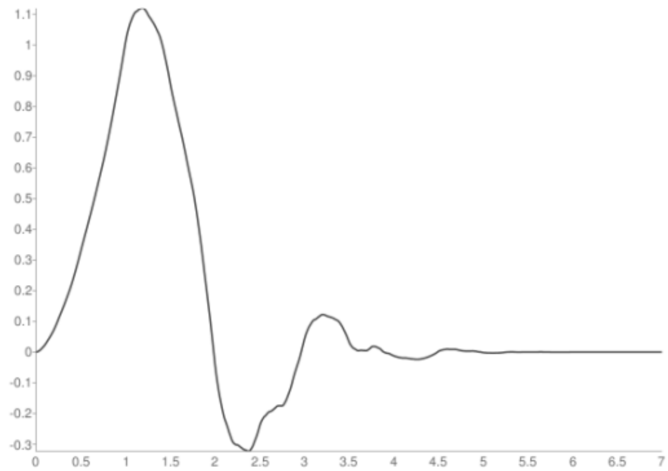

Figure 9: Scaling Function of db4

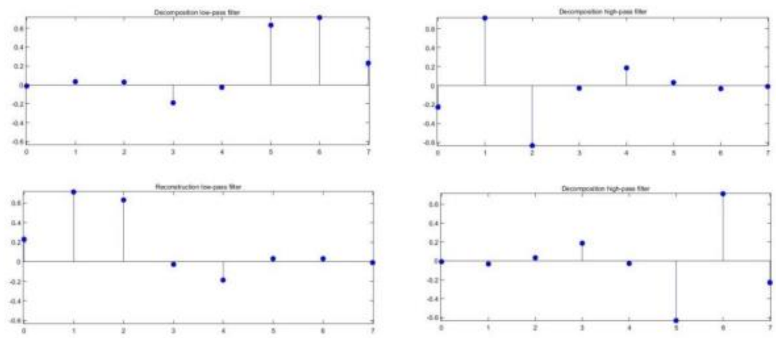

Figure 10: Quadrature Filter Bank of db4

Methodology

The proposed method utilizes and combines wavelet analysis and artificial neural network. Wavelet transform is capable of decomposing the signals into different frequency bands. It can be utilized in extracting discriminative features from the acquired negative sequence voltage signal. The features are then fed to a trained ANN model which if well trained is capable of detecting islanding and differentiating between islanding events and any other events that have transients such as switching or temporary fault. In the proposed technique, prescribed events are simulated. The negative sequence voltage signal at the PCC are acquired in order to be analyzed using WT. Negative sequence component is one of the key indicators which quantify the presence of any disturbances in the voltage signal retrieved at point of common coupling (PCC) . Thus, in this thesis, the negative sequence component of the voltage signals retrieved at PCC is considered for analysis towards effective detection of islanding and PQ events. The negative, positive and zero sequence component of the voltage signal at PCC can be expressed by symmetrical component analysis as:

$$V_n = \frac{1}{3}(v_a + \lambda^2 v_b + \lambda v_c) \qquad (7)$$

$$V_p = \frac{1}{3}(v_a + v_b + \lambda^2 v_c) \qquad (7)$$

$$V_z = \frac{1}{3}(v_a + v_b + v_c) \quad (7)$$

where Va , Vb and Vc are the three-phase voltages retrieved at the PCC and Vn , Vp and Vz are the negative, positive and zero sequence voltages, respectively, and λ = 1 120 ∠° is the complex operator. The negative sequence component of the extracted voltage signal at PCC is obtained by passing it through the three-phase sequence analyzer block in MATLAB/Simulink. Out of these three sequential components, it is only negative sequence component of the voltage signal, considered in this study because it reflects the information under disturbance condition. Quantification of the negative-sequence voltage at PCC is carried out which provides high degree of immunity to noise, for detection of islanding event and other disturbances, thus enable better performance. The discriminative features are then captured and fed to a trained ANN model. A general block diagram of the proposed method is illustrated in Figure 11.

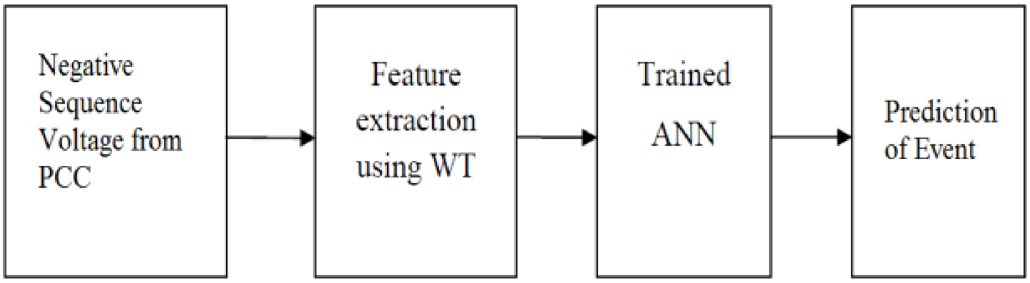

Fig. 11: General methodology block diagram.

The system under study is simulated in MATLAB/Simulink as discussed in chapter two. The system model contains two DGs. Two different sets of data which correspond to the two different classes (islanding and non-islanding) are simulated in Simulink. The simulated non-islanding cases include normal condition i.e. grid connected DG without any disturbances, temporary single line to ground (SLG), line to line to ground (LLG) and Non-Linear Load Switching at PCC. Negative Sequence Voltage signals for the different mentioned cases are then acquired from the PCC. WT will be carried out on the obtained negative sequence voltage signals to extract the features. The purpose of feature extraction is to identify specific signature of the negative sequence voltage waveforms that can detect islanding and differentiate between islanding and any other transient condition. Fig. 12 shows the change in frequency levels before and after Islanding. Frequency range from 60 Hz to 250 Hz has strengthened significantly after Islanding. Frequency levels below fundamental frequency are ignored.

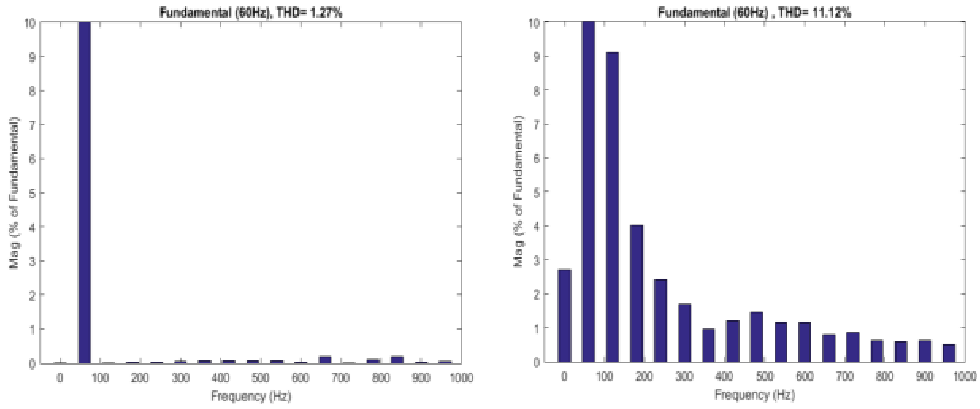

Fig.12: Comparison of Harmonic Distribution Before (Left) and After (Right) Islanding

V. Simulation Results and Data Collection

This section consists of the waveforms obtained on computer simulation of various events at MATLAB/Simulink and the data collected in those disturbances to train ANN. Simulation time is 1.2 seconds. Disturbances are introduced from 0.5 to 0.7 seconds.

Normal Operation

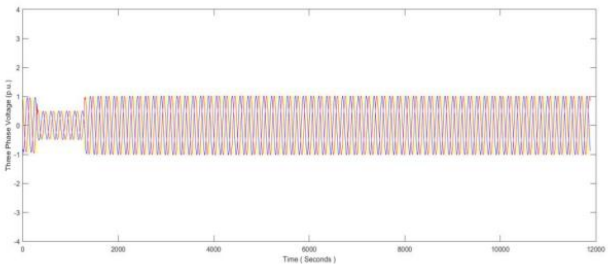

Fig. 13: Three Phase Voltage at PCC during normal conditions

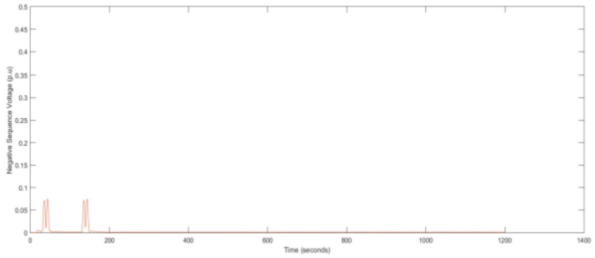

Fig.14: Negative Voltage at PCC at normal conditions

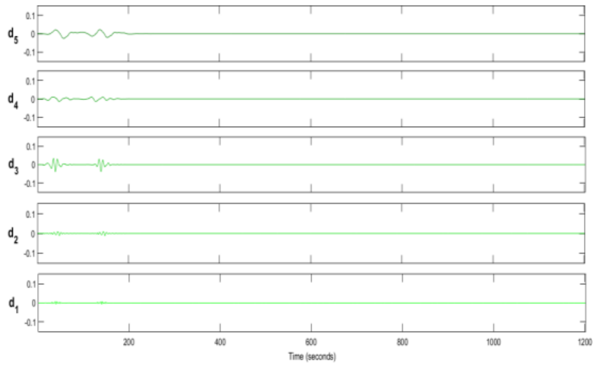

Fig.15: Details of Wavelet Transform at normal conditions

Table 1: Feature Vector for ANN Training of Normal Operation

Feature Vector					Label
Loading (MW)	SD3	SD4	E3	E4	
0.875	0.00011473	0.00014444	0.00130841	0.00119563	1
1.015	0.00011594	0.00015432	0.00132418	0.00128137	1
1.295	0.00010763	0.00017652	0.00123171	0.00146062	1
1.505	0.00011485	0.00019470	0.00131076	0.00160678	1
1.75	0.00012745	0.00022712	0.00145480	0.00187444	1

Islanding

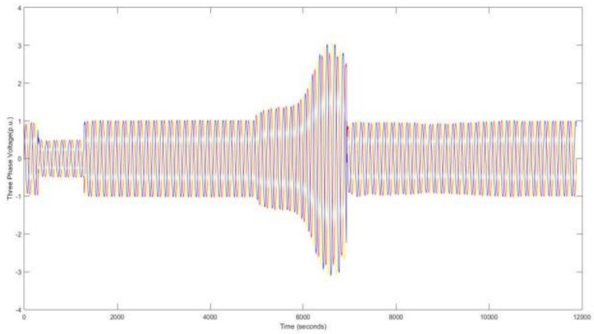

Fig.16: Three Phase Voltage at PCC at Islanding

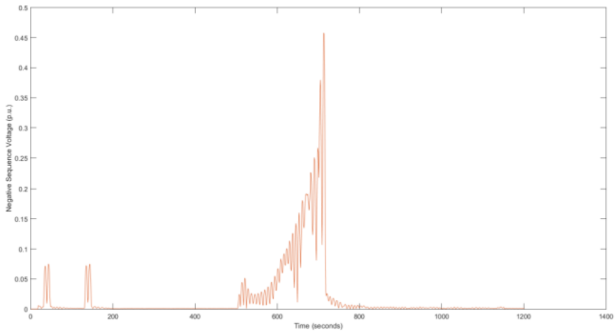

Fig.17: Negative Voltage at PCC at Islanding

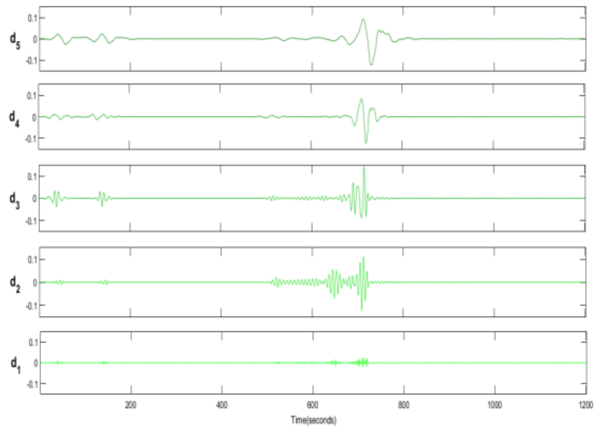

Fig.18: Details of Wavelet Transform at Islanding

Table 2: Feature Vector for ANN Training of Islanding

Feature Vector					
Loading (MW)	SD3	SD4	E3	E4	Label
0.875	0.03401753	0.03705120	0.39045041	0.30587180	2
1.015	0.03204665	0.04406543	0.36693973	0.36386052	2
1.295	0.02510713	0.02957596	0.29207070	0.24395503	2
1.505	0.00600586	0.00491463	0.06873916	0.04055274	2
1.75	0.00583276	0.00608325	0.06664993	0.05016677	2

L-G Fault

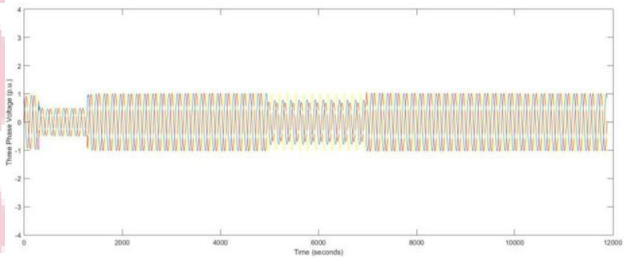

Fig.19: Three Phase Voltage at PCC at L-G Fault

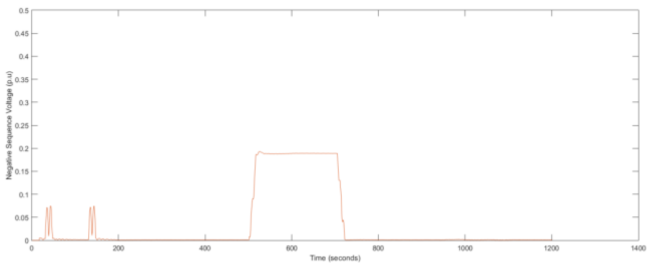

Fig.20: Negative Voltage at PCC at L-G fault

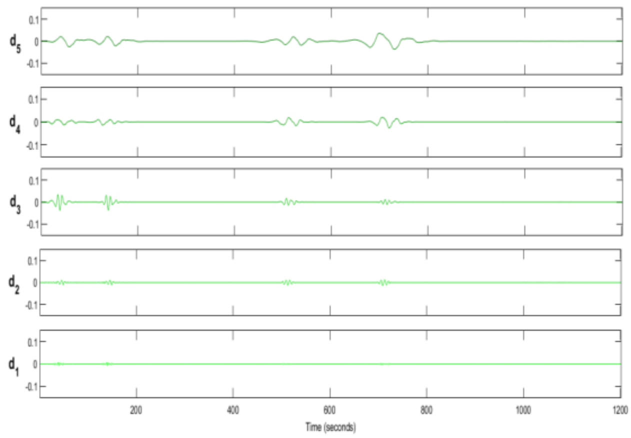

Fig.21: Details of Wavelet Transform at L-G fault

Table 3: Feature Vector for ANN Training of L-G Fault

Feature Vector					Label
Loading (MW)	SD3	SD4	E3	E4	
0.875	0.00494453	0.01195818	0.05639256	0.09861007	3
1.015	0.00494597	0.01196308	0.05641079	0.09865040	3
1.295	0.00495142	0.01204052	0.05647472	0.09928896	3
1.505	0.00496716	0.01207443	0.05665421	0.09956846	3
1.75	0.00495896	0.01213379	0.05656272	0.10005795	3

L-L Fault

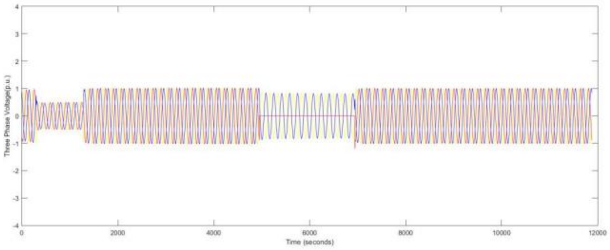

Fig.22: Three Phase Voltage at PCC at L-L Fault

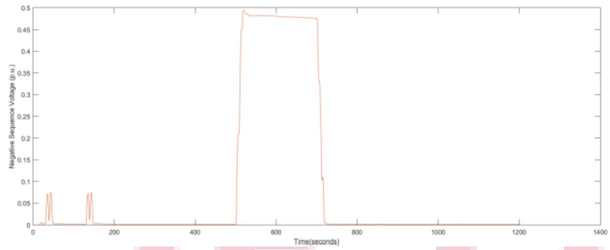

Fig. 23: Negative Voltage at PCC at L-L fault

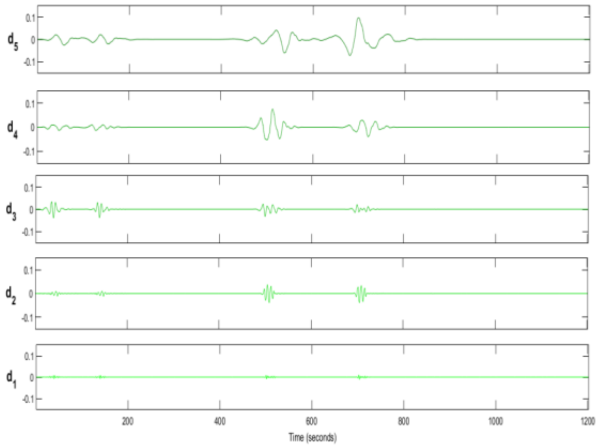

Fig.24: Details of Wavelet Transform at L-L fault

Table 4: Feature Vector for ANN Training of L-L Fault

Feature Vector					Label
Loading (MW)	SD3	SD4	E3	E4	
0.875	0.00911728	0.02928778	0.10401861	0.24154712	4
1.015	0.00911516	0.02921008	0.10399256	0.24090679	4
1.295	0.00911595	0.02910395	0.10399785	0.24003145	4
1.505	0.00911367	0.02904593	0.10397254	0.23955288	4
1.75	0.00912749	0.02892913	0.10413084	0.23858983	4

Non Linear Load Switch

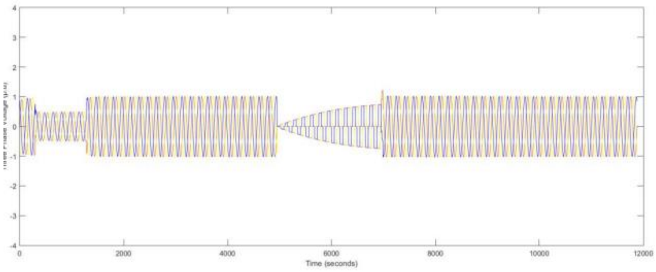

Fig.25: Three Phase Voltage at PCC during Non- Linear Load Switch

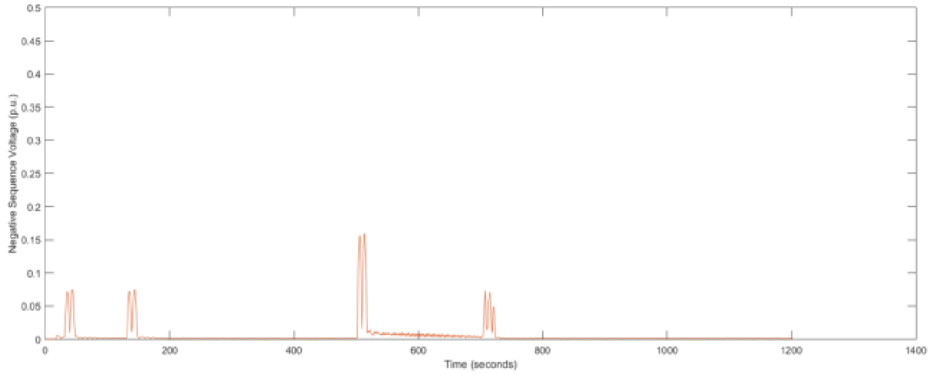

Fig.26: Negative Sequence Voltage at PCC during Non- Linear Load Switch

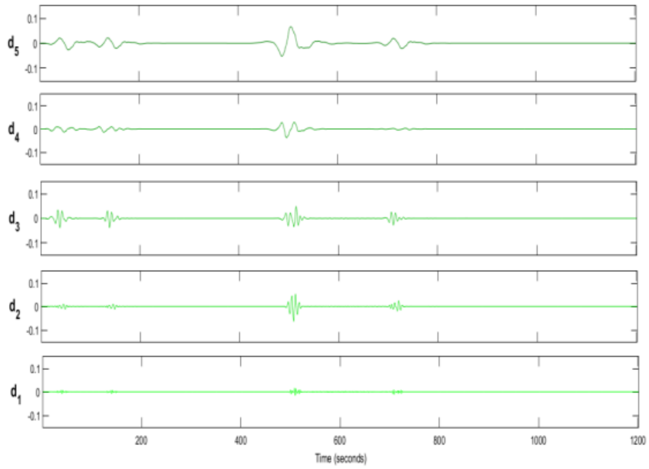

Fig.27: Details of Wavelet Transform during Non Linear Load Switch

Table 5: Feature Vector for ANN Training of Non-Linear Load Switch

Feature Vector					Label
Loading (MW)	SD3	SD4	E3	E4	
0.875	0.01280362	0.02509573	0.14671166	0.20694654	5
1.015	0.01280433	0.02509539	0.14673016	0.20694387	5
1.295	0.01279189	0.02506549	0.14659020	0.20669716	5
1.505	0.01278282	0.02503957	0.14650191	0.20648373	5
1.75	0.01277151	0.02500862	0.14638457	0.20622875	5

VI. CONCLUSION

Many schemes have been proposed to detect islanding such as passive, active and communication based techniques. Passive techniques work well when there is power imbalance between the power generated from the DG and the power consumed form the load. On the other hand, active methods affect the power quality and do not perform well in the presence of multiple DGs. WT-ANN based islanding technique was successfully implemented for hybrid distribution system. Wavelet transform is capable of decomposing the voltage signals into different frequency bands. It can be utilized in extracting discriminative features from the acquired negative sequence voltage signals. Implementing WT-ANN based anti-islanding technique using Microsoft Azure Machine Learning Studio brings feasibility for application of Machine Learning in power industry in an easy and user friendly manner. Deploying the trained model as a Web Service will help to access the model from multiple devices and from multiple places at same time. Continuous monitoring of the system is effectively possible with greater accuracy. The implementation cost is less and can be considered as a robust prospect to power system control and detection in future. Future work though the proposed method resulted in very good accuracy rate, the technique has been validated using relatively small testing set. Increasing the testing data set will result in more general and accurate recognition rate. The proposed technique was implemented on one system configuration. To increase confidence in these results, similar simulations could be performed using different system models. Another direction for future work is to implement and verify the proposed approach with practical and real time implementation. The poor performance of WT in voltage swell events also needs further study.

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