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Detection of Islanding and Fault Disturbances in Microgrid using Wavelet Packet Transform

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ABSTRACT

Fast detection of islanding is very important for effective operation and control in distributed generation (DG) penetrated distribution networks. The islanding detection techniques such as passive, active, communication and hybrid have their own merits and demerits. This paper proposed wavelet transform (WT) and wavelet packet transform (WPT) based techniques for detection of islanding and fault disturbances in a microgrid consisting of resources like wind turbine generator, fuel cell and micro-turbine. Voltage signal is extracted at the point of common coupling (PCC) and is passed through these detection techniques to obtain the time-frequency multi-resolution analysis. Further, to validate the graphical study, performance indices (PIs) like standard deviation and entropy are calculated for the disturbance detection using suitable selection of threshold. A comparative analysis using wavelet and wavelet packet transform is presented in the form of graphical simulation as well as in terms of PIs to analyze their effectiveness and robustness under different operating conditions. It is observed that WPT shows better detection capability in comparison to WT even under 20 dB noisy scenarios.

Keywords: Distributed generation (DG), fault and islanding, microgrid, wavelet transform, wavelet packet transform.

1. INTRODUCTION

The continuous increase in power demand, environmental pollution and unavailability of fossil fuels are the reason for motivation towards power generation from renewable or distributed generation (DG) systems. The DG system includes small-scale generation resources like wind turbine, solar energy, fuel cells, micro-turbine, diesel generators etc. There are many advantage of distributed generation such as less requirements of new transmission lines, lower transmission losses, pollution and higher reliability in supply of electricity to consumers [1]. However, many problems are being encountered due to the integration of DGs into the utility network like their impacts on voltage, frequency, phase etc. creating instability, power quality and protection issues. The major effect is because of the intermittency characteristics of renewable energy resources. Disconnection of the main supply in the event of some intentional or unintentional condition leads to a peculiar phenomenon called islanding disturbance which plays an important role in power system operation, control and stability [2]. The reason of intentional islanding is for constructing a power “island” that will be feeding power to local loads during disturbances occurring in grid side. But, the disconnection/island is done by the active part of the distribution system from the main grid which physically isolates the distributed generation sources from the utility grid. This type of disturbances must be detected as quick as possible in order to protect the electrical system with all supporting equipments and load. The prime focus of all the

power systems is to provide a high level of quality of service (QoS) under abnormal operating conditions, may it be fault or islanding so that the line outages in the system can be reduced and power blackout can be minimized in the system. Of course, it may not be possible to completely clear all the consequences of natural disturbances/events, physical accidents, apparatus malfunction which leads to islanding, power interruptions, voltage dips/swells, harmonics and transients in the power system [3]. Rather, optimum efforts have to be provided to protect the whole power system and equipments from such type of disturbances.

As a consequence of such disturbances, large variations in some of the system parameters may happen and this may lead to instability in the power system. Therefore, to maintain the continuity of power supply, these disturbances are required to be detected and cleared very fast. Recently, protective relays have achieved much progress to sense faults very fast due to the advances in digital relaying and signal processing techniques [4]. It is used to examine precisely the signals measurement and estimation online with a merit of change in some signal features necessary for possible detection of islanding or faults occurring in the system [5]. Fourier analysis and Kalman filtering methods are the most popular tools in signal processing for fault detection [6]-[8]. The Fourier transform has the proficiency to accurately analyze and present the signal with non-periodic features [5]. To deal with non-stationary signals, time-frequency techniques like Fast Fourier Transform (FFT) and Short Time Fourier Transform

(STFT) have been proposed [9]. But, the main demerit of STFT is due to design of a constant window for obtaining time-frequency resolution [5]. Hence, to attain a variable time and frequency resolution, the wavelet transform (WT) and wavelet packet transform (WPT) has been introduced. Moreover, WPT does not necessarily require stationary characteristics of signals and suitable for processing of signals with sudden variation in frequency components. The tracking of distorted signals using wavelet is addressed to identify faults in a high voltage direct current (HVDC) line [10]. Line faults, commutation failures in the converter and single phase short circuits at the AC side are designed and shown to create time varying transients. For these applications, isolation of faults is very essential because the safety procedures are very different depending on the type of fault. Though, many works are available in literature for fault monitoring and islanding detection including wavelet and wavelet packet, few research is being carried out dealing with detection of both faults as well as islanding events. Again, it is indispensable to discriminate islanding from the common faults in DG based microgrid to apply suitable mitigation techniques to protect the power system under both the operating conditions. Again, because of the presence of synchronously rotating DG and inverter based DG in the microgrid, its very important to study their impact on the detection techniques. This is a part of the present study, to analyze the effect of disturbances on the voltage signal at PCC due to above two DG technologies.

Therefore, in this paper wavelet transform and wavelet packet transform is proposed for extracting time-frequency information to detect and identify the islanding and fault disturbances when different DGs like wind, fuel cell and micro-turbine are integrated to form a micro grid. Wavelet packet introduces a new approach to characterize islanding/fault disturbances at multiple scales where both approximate and detail coefficients are being decomposed with the help of a series of low pass and high pass filters. Its performances are measured in terms of sensitivity and selectivity for the classification of different type of faults. It is superior to FT, STFT and WT in detecting the disturbances even in the presence of noise because of the detailed analysis of lower as well as higher frequency contents.

The following Section 2 presents mathematical background and descriptions of wavelet and wavelet packet transforms followed by system modeling in Section 3. Section 4 explains the simulation results followed by conclusion in Section 5.

2. WAVELET AND WAVELET PACKET TRANSFORM

2.1 Wavelet Transform (WT)

Wavelet Transform (WT) is an efficient signal processing tool for analyzing disturbances in power system based on time-frequency multi-resolution analysis. It uses an adaptive window whose size decreases with high frequencies and comparatively increases for lower frequencies. A set of basis functions are designed in the form of mother wavelets that are used to decompose the signal into different frequency ranges based on continuous dilation and translation processes [11].

The Discrete Wavelet Transform (DWT) [12]-[13] of a discrete function $x(k)$ can be expressed as:

$$DWT(m, k) = \frac{1}{\sqrt{a_0^m}} \sum_n X(n) \phi\left(k - na_0^m / a_0^m\right) \quad (1)$$

where m and n are two positive integers used to define scaling and the translating parameters and used to design the selected mother wavelet ϕ . For lower decomposition level, the response time for the islanding or fault detection will be shorter [14] and thus, 4th decomposition levels of Daubechies mother wavelet have been selected in the current disturbances analysis. Choice of a suitable mother wavelet is an important factor in wavelet analysis. Fig. 1 shows the filter decomposition tree using WT and its mother wavelet.

Figure 1: Filter representation of Wavelet Transform and mother wavelet.

Each decomposition level is processed through high pass filter (HPF) which produces the detail coefficient, and low pass filter (LPF) that generates the approximate coefficient. Down sampling of outputs of HPF and LPF is done to avoid redundancy of information to obtain detail coefficient $d(k)$ and approximate coefficient $a(k)$ [15]. These coefficients depend on the selected mother wavelet ϕ and logarithmic resolution for obtaining the frequency bands and this is possible because of dyadic down sampling process. Using the scaling function, the voltage signal can be expressed as [15]:

$$v(t) = \sum_{k=-\infty}^{\infty} a_{j_0}(k) 2^{j_0/2} \phi(2^{j_0}t - k) + \sum_{k=-\infty}^{\infty} \sum_{j=j_0}^{\infty} d_j(k) 2^{j/2} \phi(2^j t - k) \quad (2)$$

Where j_0 represents the coarsest scale. The approximate and detail wavelet coefficients of the signal can be determined using the following equations:

$$a_j(k) = \sum_{m=-\infty}^{\infty} c_{j+1}(m) h(m - 2k) \quad (3)$$

$$d_j(k) = \sum_{m=-\infty}^{\infty} c_{j+1}(m) h_1(m - 2k) \quad (4)$$

Equations (3) and (4) show that the coefficients at different frequency levels that can be attained by passing the coefficients through their respective filter followed by a down sampling. Implementation of DWT is achieved through

application of successive pairs of high pass and low pass filters for each scaling stages of wavelet transform.

2.2 Wavelet Packet Transform (WPT)

Wavelet packet is a transform where the signal is processed through more filters than the DWT and are distinct linear combination of the wavelets. The coefficients in the linear combinations are figured out by a recursive algorithm, making each newly computed wavelet packet coefficient array the root of its own analysis tree. In the wavelet transform, each level is determined by passing the approximate coefficient through a high and low pass filter. However, in WPT, both detail and approximation coefficients are decomposed using the filters as shown in Figure 2.

Figure 2: Wavelet Packet Transform Decomposition Trees.

The multi-resolution analysis using wavelets was suggested for disturbance detection in hybrid power system [14]. After the advancement in analysis, wavelet transform gained more attention and have found various applications in fields of power system and others [12]-[15]. Wavelet packets [16] were introduced as a generalized family of multi resolution orthogonal or bi-orthogonal basis, unlike wavelet transforms which is realized only by a low-pass filter bank. Wavelet packet transform is implemented by a basic two-channel filter bank, which can be repeated over either the low-pass or the high pass branch. Therefore, with the wavelet packet transform the data in high frequencies as well as that at low frequencies can be analyzed very effectively. The array of functions is defined by:

$$W2n(x) = \sqrt{2} \sum_{k=0}^{2N-1} h(k) W_n(2x-k) \quad (5)$$

$$W2n+1(x) = \sqrt{2} \sum_{k=0}^{2N-1} g(k) W_n(2x-k) \quad (6)$$

Here the length of the two filters is $2N$, where $h(n)$ and $g(n)$ corresponding to the wavelets, here $W_0(x) = \phi(x)$ is the

scaling function and $W_1(x) = \psi(x)$ is the wavelet function. For example, in the Daubechies wavelet we have taken $N = 1, h(0) = h(1) = 1/\sqrt{2}$ and $g(0) = -g(1) = 1/\sqrt{2}$. Then the equations become :

$$W2n(x) = Wn(2x) + Wn(2x-1) \quad (7)$$

$$W2n+1(x) = Wn(2x) - Wn(2x-1) \quad (8)$$

Here $W0(x) = \phi(x)$ is the Daubechies scaling function and $W1(x) = \psi(x)$ is the Daubechies wavelet, both supported in the range of $[0, 1]$. From here $W2n$ can be obtained by adding two $1/2$ -scaled versions of Wn with distinct supports $[0, 1/2]$ and $[1/2, 1]$ for getting $W2n+1$ by subtracting the same versions of Wn . Wavelet packet has developed an enormous interest in both applied and theoretical applications. Wavelet packet analysis [17] is a powerful and prominent tool for the study of non-stationary signals. This transforms detach signal variability both in time t , and also in “scale” s , by rescaling and relocating the wavelets. Therefore, influenced by the characteristics of these transforms, the monitoring of disturbances can be further explored for improving the performance of power system with the penetration of renewable energy resources.

3. SYSTEM MODELING

The system under study is a microgrid which is a combination of distributed energy resources like wind, fuel cell and micro-turbine. The intermittent characteristic of the wind energy system may affect the reliability of power supply. Therefore, alternative energy resources like the fuel cell and micro-turbine are being integrated with wind system to compensate the uncertainty in power output. The hybrid combination of these resources formulates a small microgrid which can be operated either in stand-alone or grid-connected mode. This microgrid is simulated in MATLAB/Simulink for the detection of disturbance study. The disturbance due to islanding is simulated by three-phase breakers through which the DG is connected to grid. Solid oxide fuel cell, is connected to grid through buck/boost converter. Along with the DFIG configuration, a wind turbine is connected to the point of common coupling along with a capacitor bank for reactive power compensation required for voltage stability in steady operating conditions. A synchronously rotating machine based DG in the form of the micro turbine is connected to grid through back-to-back converters. The three-phase voltage is extracted at PCC for detection using the proposed transforms. The wavelet or wavelet packet transform is employed to extract certain features of the transformed voltage signal to distinguish between normal, islanding and different fault conditions.

The types of disturbances include islanding LG, LLG, LLL and LLLG faults under different operating configurations. Wavelet and wavelet packets are utilized to diagnose the signals at PCC, decompose them by a set of low-pass and high-pass filters to extract the frequency components which helps further to detect the disturbances based on time-frequency multi resolution analysis. In this paper, islanding and the different types of faults are discriminated based

comparing the calculated standard deviation and entropy values with the selected threshold value.

Figure 3: Microgrid structure with wind, fuel cell and micro-turbine.

Figure 4: Microgrid connected to the utility grid.

3.1 Wind turbine model

Wind turbine (WT) converts kinetic energy contained in the wind in atmosphere into mechanical energy and then transformed to electrical energy by the help of wind generator. The wind generator can be modeled as an induction or synchronous machine depending upon the application and situation. Here, doubly fed induction generator (DFIG) is used for the design of wind energy conversion system. The DFIG is connected through a back to back convertor. The relationship between wind speed and mechanical power extracted from the wind can be given by [2]:

$$P_m = \frac{\rho}{2} A_{wt} C_p(\lambda, \beta) V_w^3 \quad (9)$$

where, P_m is the power extracted from the wind in watts; ρ is the air density (kg/m^3); C_p is the performance coefficient or power coefficient; λ is the tip-speed ratio (V_t/V_w), V_t (m/s) is blade tip speed, and V_w (m/s) is wind speed at hub height upstream of the rotor; $A_{wt} = \pi R^2$ is the area covered by the wind turbine rotor (m^2), R is the radius of the rotor; and β is the blade pitch angle (in degrees). The tip-speed ratio (TSR) is defined as:

$$TSR = \frac{R\omega_e}{V_w} \quad (10)$$

where, $\omega_e = p\omega_m$ is the electrical speed (elec. rad/s); p is the number of pole pairs of the machine; and ω_m is the mechanical speed of the rotor (mech. rad/s). The doubly-fed induction generator (DFIG) model used as a part of the WECS

is taken from [2]-[3] and described briefly in the following sub-sections.

3.2 Solid oxide fuel cell model:

The fuel cell is static device which converts chemical energy into electrical energy without combustion process. It has the merits like low pollutions, can be reused with cogeneration as heat, better efficiency, power back-up, reducing the capacity of grid during peak load, etc. Though, it was previously being used for space application, but, its technologies is advancing day-by-day to be utilized as power supplying resource [2]. The hydrogen inputs to FC interact with oxygen in the presence of an electrolyte leading to a chemical reaction producing electrical energy. As the power output is DC in nature, it is converted to AC power using DC/DC and DC/AC power electronic interfacing converters. The chemical reaction also produces heat as cogeneration to be used for some applications. The model of a solid oxide fuel cell (SOFC) is taken in the study for islanding and fault detection problem which is realized in MATLAB/ Simulink. The voltage equation of the FC stack is given by

$$V_{fc} = N_0 \left(E_0 + \frac{RT}{2F} \ln \left(\left(\frac{P_{H_2} P_{O_2}}{P_{H_2O}} \right)^{0.5} \right) \right) - r I_{fc} \quad (11)$$

with P_{H_2} , P_{H_2O} , P_{O_2} are the hydrogen, water and oxygen pressure input in the fuel cell given by the following expressions [14]:

$$P_{H_2} = -\frac{1}{t_{H_2}} \left(P_{H_2} + \frac{1}{K_{H_2}} (q_{H_2}^{in} - 2K_r I_{fc}) \right) \quad (12)$$

$$P_{H_2O} = -\frac{1}{t_{P_{H_2O}}} \left(P_{H_2O} + \frac{2}{K_{H_2O}} K_r I_{fc} \right) \quad (13)$$

$$P_{O_2} = -\frac{1}{t_{O_2}} \left(P_{O_2} + \frac{1}{K_{O_2}} (q_{O_2}^{in} - 2K_r I_{fc}) \right) \quad (14)$$

where N_0 is the number of series FCs in the stack; E_0 is the standard no-load voltage (V); R is the universal gas constant ($\text{kPa}/(\text{kmol} \cdot \text{K})$); T is the absolute temperature ($^\circ\text{K}$); I_{fc} is the current of the FC stack (A); F is Faraday's constant (C/kmol); K_{H_2} , K_{H_2O} and K_{O_2} are the molar constants ($\text{kmol}/\text{kPa} \cdot \text{s}$) of the hydrogen, water, and oxygen respectively; P_{H_2} , P_{H_2O} and P_{O_2} are the partial pressure (kPa) of hydrogen, water and oxygen, respectively; $q_{H_2}^{in}$ is the hydrogen input flow (kmol/s) $q_{O_2}^{in}$ is the oxygen input flow (kmol/s); r is the FC internal resistance (Ω); t_{H_2} , t_{O_2} and $t_{P_{H_2O}}$ are the hydrogen, oxygen and water time constants (s), respectively.

3.3 Micro-turbine model

Micro turbine is usually utilized in transportation sectors, but, now-a-days thought of supplying electrical energy to different loads and applications. In the coming years, it is

expected to be one of the promising technologies for alternative power generation due to its merits like growing research and developments, less moving parts, less maintenance, its flexibility in the way it can be connected to load; stand-alone or grid-connected mode, back-up power, minimizing the stress on the grid during peak load demand etc. The power capacity may range from 25 kW to 500 kW with a variable speed ranges depending upon the type of application. The main components of micro turbine are compressor, recuperator, combustion chamber and turbine, similar to that of a gas turbine but are comparatively smaller in size. The compressor increases the air and pushes it into the combustion chamber. There, it is mixed with the input fuel to be burned in the combustion chamber. The hot gas with increased pressure is converted to mechanical energy by the turbines and fed to generator for converting it into electrical energy [17]-[18]. The mechanical power of micro turbine, $P_m(t)$, is given by the difference of mechanical power generated by the turbine $P_{turbine}(t)$ and mechanical power taken the compressor $P_{comp}(t)$

$$P_m(t) = P_{turbine}(t) - P_{comp}(t) \quad (15)$$

This is the shaft power generated by the micro-turbine to be transmitted to the high-speed permanent magnet synchronous generator (PMSG). The power generated by the micro-turbine, $P_{gen}(t)$ is expressed by [17]:

$$P_{gen}(t) = P_m(t) \eta_{mech} \eta_{pmsg} \eta_{elect} \quad (16)$$

Where, η_{mech} is the mechanical efficiency; η_{PMSG} is the PMSG efficiency and η_{elect} is the electrical efficiency of the interfacing converters. The power output of the MT is fed into the conventional grid through back-to-back converters as shown in Figure 5 for fulfilling the power requirements by the loads.

Figure 5: Microturbine system with back-to-back AC/DC-DC/AC converters.

3.4 Different interfacing converter topology

3.4.1 Modeling of DFIG

DFIG principle is commonly used for converting power from the wind by wind energy conversion system (WECS) to supply power into electric grid. The stator, of the wound rotor induction machine, is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back PWM voltage-source inverters (VSIs) with a common DC link as shown in Figure 6. The flow of power between the DC bus and the AC side is controlled by grid side converter with the help of sub-synchronous and super-synchronous speed operation of the machine [2]. Whereas, rotor side converter provides rotor excitation, active and reactive power control on stator and rotor sides respectively by using vector control technique. The mathematical modeling of DFIG is described

by the following equations [2]-[3].

Figure 6: Wind system with DFIG topology.

Stator voltage is given by:

$$v_{ds} = i_{ds} R_s - \omega_s \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (17)$$

$$v_{qs} = i_{qs} R_s + \omega_s \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (18)$$

Rotor voltage is given by:

$$v_{dr} = i_{dr} R_r - s \omega_s \psi_{qr} + \frac{d\psi_{dr}}{dt} \quad (19)$$

$$v_{qr} = i_{qr} R_r + s \omega_s \psi_{dr} + \frac{d\psi_{qr}}{dt} \quad (20)$$

Flux linkage is given by:

$$\psi_{ds} = L_m i_{dr} - L_s i_{ds} \quad (21)$$

$$\psi_{qs} = L_m i_{qr} - L_s i_{qs} \quad (22)$$

$$\psi_{dr} = -L_m i_{ds} - L_r i_{dr} \quad (23)$$

$$\psi_{qr} = L_m i_{qs} - L_r i_{qr} \quad (24)$$

Electro-magnetic torque is given by:

$$T_{el} = \psi_{qr} i_{dr} - \psi_{dr} i_{qr} \quad (25)$$

where, v_s , i_s and ψ_s are stator voltage, current and flux respectively; v_r , i_r and ψ_r are rotor voltage, current and flux respectively; ω_s is the angular velocity of the chosen frame of reference; d and q represent direct and quadrature axes respectively. L_m is the mutual inductance; L_s and L_r are the stator and rotor leakage inductances, respectively.

3.4.2 Grid Interface system

Usually small scale generations in the form of fuel cell, microturbine, photovoltaic etc. are connected to the utility grid at the distribution level through interfacing DC/DC or DC/AC converters. Since, the power electronics converters affect power quality of the system, they must be suitably designed and controlled in order to avoid any mal-operation in protective relaying system.

3.4.2.1 DC/DC boost converter

Because of the drooping characteristic, the unregulated terminal voltage cannot be directly interfaced to the DC bus or by using DC/AC inverters for grid applications. Therefore, a PWM DC/DC boost converter operating in closed loop

continuous conduction mode can be used as shown in Figure 7. The suitable design of boost inductor and capacitor of filter helps to reduce the harmonics. However, if the inductance becomes large, the start-up time increases, whereas, small inductance value will cause high current in the coil before the switch turn off [1], [19].

Figure 7: Equivalent circuit of a DC/DC boost converter.

The inductor current, i_L during turn on and turn off period of the converter, in steady state condition, can be expressed as:

$$i_L(t) = \frac{1}{L} V_{in} t + i_L(0) \quad \text{for } 0 \leq t \leq dT \quad (26)$$

$$i_L(t) = \frac{1}{L} (V_{in} - V_0)(t - dT) + i_L(0) \quad \text{for } dT \leq t \leq T \quad (27)$$

where, V_{in} is the input voltage, V_0 is the output voltage, $i_L(0)$ is the initial current through the inductor and dT is the time instant which discriminate the on and off periods of the converter. Then, applying the initial conditions and simplifying the above equations, we can express the ratio of output and input voltage as :

$$\frac{V_0}{V_{in}} = \frac{T_{sw}}{t_{off}} = \frac{1}{1-D} \quad (28)$$

where,

$T_{sw} = t_{on} + t_{off}$, is the switching time period, t_{on} is switch on time, t_{off} is the switch off time and D is the duty cycle of the converter. The size of the reactive elements of boost converter can be determined from the rated voltage, current ripple, voltage ripple and switching frequency of the converter.

3.4.2.2 DC/AC converter

Three-phase DC/AC converter are connected between DC/DC converter and the grid for proper interfacing of renewable resources. The equivalent circuit representation of a three-phase DC/AC converter is shown in Figure 8 where filters are connected between the converter and the grid to minimize the harmonics. Filters are represented by the series combination of R_s and L_s . The three-phase AC output voltage of the inverter are v_{ia} , v_{ib} and v_{ic} and the output currents are i_a , i_b and i_c for phase-a, phase-b and phase-c respectively. The bus voltages of the grid are represented as v_a , v_b and v_c . The brief dynamics of the three-phase voltage source

converter (VSC) [1], [18] is described below:

$$\frac{di_k}{dt} = \frac{R_s}{L_s} i_k + \frac{1}{L_s} (v_{ik} - v_k) \quad (29)$$

where $k = \{a, b, c\}$

In Park's d-q frame that rotates synchronously with the grid angular speed ω , current dynamics can be reasonably represented by the following equations:

$$v_{iq} = R_s i_q + L_s \frac{di_q}{dt} + L_s \omega i_q + v_q \quad (30)$$

$$v_{id} = R_s i_d + L_s \frac{di_d}{dt} + L_s \omega i_q + v_d \quad (31)$$

Where,

v_{id} , v_{iq} , i_d , i_q are the d-axis and q-axis inverter's voltages and currents and v_d , v_q are the d-axis and q-axis components of the supply voltage at the PCC.

Figure 8: DC/AC voltage source inverter

The injected active and reactive power components, P, Q can be represented in terms of the d-axis and q-axis components of the supply voltage at the PCC and the injected currents as follows:

$$P = \frac{3}{2} (v_d i_d + v_q i_q) \quad (32)$$

$$Q = \frac{3}{2} (v_q i_d - v_d i_q) \quad (33)$$

In addition, the magnitude of the voltage at the PCC v_s is given by:

$$\|v_s\| = \sqrt{v_d^2 + v_q^2} \quad (34)$$

4. SIMULATION RESULTS AND ANALYSIS

The simulated graphical results followed by quantitative results based on performance indices; standard deviation and entropy, for detection of islanding and different fault disturbances are presented in this section using the proposed wavelet and wavelet packet transforms. The microgrid with integration of distributed generation resources like wind, fuel cell and micro turbine is connected to the utility grid and simulated in MATLAB/Simulink environment under different operating conditions.

The procedural steps for detection of fault and islanding disturbances are described in the flowchart shown in Figure 9. At the point of common coupling (PCC), the voltage signals are monitored and extracted to being processed through the

wavelet and wavelet packet transform, to observe the change in pattern during faults and islanding events. The disturbance instants are being detected and analyzed using Daubechies (dB4) as the mother wavelet and designed for four level of decomposition of the voltage signal to obtain different ranges of frequencies. Then, quantitative analysis in terms of the performance indices (PIs), standard deviation and entropy, are also presented to support the graphical study. Based on suitable selection of the threshold values, SD and entropy are compared to detect the fault and islanding disturbances under different operating conditions. This study help in identifying the disturbance condition as well as normal operating condition based on the variation/non-variation in system parameters such as voltage profile at PCC of the microgrid system. The details of the parameters used for wind, fuel cell and micro-turbine and converters is presented in Table 1 A and Table 2 A, in the Appendix section [2], [23]-[24]. The simulation results are described for different conditions in the following sub-sections.

Figure 9: Flowchart for WP based Fault Detection.

4.1 Detection of fault disturbances in microgrid

In this subsection, ten different fault disturbances such as AG, BG, CG, AB, BC, CA, ABG, BCG, CAG, ABCG are created in the microgrid where A, B, C designates the three phases and G is ground of the system. The faults taken into study are a mixture of both symmetrical and unsymmetrical faults, which provides a variety in the disturbances so that the robustness of the proposed technique can be tested. Also, different configurations of microgrid are formulated by integrating different combination of resources to study the impact of both synchronously rotating and inverter based DG. The faults are created in the microgrid using a fault simulator in sim power system of MATLAB/Simulink. After the fault being created, the voltage signal is extracted from PCC and is passed through wavelet transform or wavelet packet

transform. For a first case, an AG fault is created with wind and fuel cell combination connected to grid, i.e., micro-turbine is absent and the voltage signal is shown in Figure 10. It is observed that at nearly 605 sec, the voltage magnitude falls miserably and finally regains its rated value at 850 sec after the fault is cleared. This voltage signal is passed through wavelet and wavelet packet transform and the simulated results are shown in the same figure. It is clearly observed that both WT and WPT are detecting the fault instants effectively and correctly. As noticed from the contours, color code in both the transform is changing during the fault, thereby helps in detecting the disturbance in the voltage signal. This is also observed that the color during fault is different from that of normal operating period.

Figure 10: Detection of AG fault when wind-fuel cell system is connected to grid

Figure 11: Detection of AG fault when wind-fuel cell system is connected to grid with 20-dB noise.

Then, to test the efficiency of the proposed techniques, 20-dB random noise is added synthetically to the voltage signal and the corresponding detection results are shown in Figure 11. This voltage signal with noise is passed through WT and WPT. It is observed that, wavelet transform fails to detect the changes in voltage magnitude during fault period, showing no noticeable changes in color in the contour. Whereas, in case of wavelet packet, the contour clearly shows the changes during fault, thereby proving its effectiveness in detecting the disturbances in the voltage signals under noisy condition. This is because of the fact that WPT do detail time-frequency analysis of its detail as well as approximate coefficients in each level of decomposition, whereas the WT do the synthesis

for only approximate coefficient using low pass filters. The added advantage of WPT over WT in fault detection is reflected in the simulated result.

Figure 12: Detection of BG fault when micro-turbine and the fuel cell is connected to Grid.

Figure 13: Detection of BG fault when micro-turbine and fuel cell is connected to grid with 20-dB noise.

Figure 14: Detection of ABG fault when wind-fuel cell and micro turbine are connected to grid.

Again, a BG fault is created in micro-turbine and the fuel cell combination connected to grid in the absence of wind energy system. The voltage signal, WT contour and WPT contour is shown in Figure 12, clearly showing the changes during the fault condition. The oscillation due to inertia of the rotating machine based microturbine is clearly reflected as oscillations in the voltage profile during fault period. Similarly, the simulation results with addition of 20-dB random noise are shown in Figure 13 reflecting the effective detection of fault period using WPT. Further, an ABG fault is simulated in microgrid in the presence of all the resources

followed by incorporation of no-noise and 20-dB random noise in the voltage signal. The corresponding detection results are shown in Figure 14 and 15 respectively. Of course, the simulation study is being carried out for all the ten faults, but the results are not presented being similar in analysis. Finally, it is being concluded that, detection using WT is degraded to large extent in the presence of increased noise in the system or the voltage signal, whereas WPT detect the disturbances nicely in the absence as well as presence of 20-dB noise. Definitely, the voltage waveform is affected by the inertia of the rotating machine based DG as well as inverter based DG. However, the disturbances could nicely be observed by the transforms under no-noise conditions. But, with increased noise level of 20 dB, WPT could detect the disturbances present in the signal because of its detailed decomposition as compared to WT, showing a failure in the later case.

Figure 15: Detection of ABG fault when wind-fuel cell and micro turbine are connected to grid with 20-dB noise.

4.2 Detection of islanding disturbances in microgrid

This subsection represents the detection analysis of islanding disturbances, under different operating conditions. Here, different configurations are taken into consideration by changing the combination of energy resources like wind turbine connected to grid, wind-fuel cell, wind-micro-turbine, wind-fuel cell-micro-turbine etc. connected to grid. This is done so in order to study the impact of inverter based as rotating machine based DGs. Here, it is obvious that wind energy system and microturbine have inertia of rotating mass. Similarly, design of the interfacing converter plays a important role in controlling the system parameters like voltage and current. So, the intention of taking different configurations of DGs is to test the effectiveness of the proposed techniques to take care of the inertia of rotating machines as well as the disturbances injected by the interfacing converters. In this regard, a sudden intentional islanding disturbance is created in the system by isolating the utility grid using three-phase circuit breaker simulation block in MATLAB. This creates islanding disturbance in microgrid, thereby changing the magnitude in the voltage profile abruptly. The extracted voltage signal is then passed through WT and WPT to test the detection capability both under no-noise and noisy conditions. For an example, islanding disturbance is created in a micro grid consisting of all the three resources being connected to

the utility grid. The voltage signal is presented in Figure 16 showing the changes in magnitude of voltage at PCC. Then, the contours using WT and WPT are also shown in the same figure, clearly detecting the islanding instants displayed with changed pattern. Further, 20-dB noise is added to voltage signal and is processed through both the transforms and the corresponding results are shown in Figure 17. It is noticed that WPT able to detect the islanding instant correctly and effectively, whereas, WT fails completely in the presence of 20-dB noise as well as under the impact of rotating machine and inverter based DG.

Figure 16: Detection of islanding event for grid-connected wind-fuel cell system.

Figure 17: Detection of islanding event for grid-connected wind-fuel cell system with 20-dB noise.

4.3 Detection of fault and islanding disturbances using performance indices

In this subsection, all the ten faults along with islanding are considered as disturbances. After creation of fault/islanding disturbance in the microgrid, the voltage signal is passed through WT and WPT. Then, from the transformed detailed co-efficient profile, the standard deviation and entropy are calculated for different faults and islanding conditions and presented in Table 1. It shows a comparative analysis between WT and WPT, based on which the PIs are calculated and compared with a threshold value in order to whether disturbance is an islanding event or fault disturbance. It is observed from the comparison that the PI values are varying from one configuration to the other because of the impact of different combination of rotating and inverter based DG. Similarly, the SD and entropy for 20-dB noise conditions is presented in Figure 18. Then, based on observation of these

values for different configurations, threshold values are selected. If for a particular configuration, if the SD and entropy are greater than the selected threshold value, then islanding is detected. Otherwise, if the PIs are less than the threshold value, then any of the ten fault disturbance is detected. This quantitative analysis based on the performance indices (PIs) and suitable selections of threshold values detect the fault and islanding disturbances effectively. The only difficulty being observed here is the selection of suitable threshold as it will change with the different configuration of the microgrid structure.

Further to support the analysis, a graphical results using entropy for a microgrid consisting of wind-fuel cell as resources is shown in Figure 19 using WPT. It is observed from this result that if the threshold selection is proper, the islanding and ABC three-phase fault disturbance can be identified effectively without any ambiguity. Of course, the index for other types can be calculated and be presented in the comparison. But, only three-phase fault is considered for comparison with islanding because its being treated as the most severe fault in power system. Again, by the proposed study and analysis, an important discrimination of the islanding and fault disturbances becoming possible based on the threshold selection. Clearly from the graphical threshold or numerical selection of threshold value, the islanding disturbances can easily be separated from the fault disturbances. This helps us to classify islanding from the other fault disturbances so that proper protection and mitigation technique can be applied to enhance the voltage profile of the microgrid system and thereby improves the stability and reliability.

5. CONCLUSION

The objective of this paper is to detect the islanding and fault disturbances using WT and WPT. The proposed methods take advantage of time and frequency localization of the wavelet and wavelet packet transform applied to the high-frequency components introduced by the rotating machine and inverter based DGs at the point of common coupling. A complete analysis is done for different distributed generators such as wind, fuel cell and micro turbine in an isolated or grid-connected mode using simulation in MATLAB/Simulink. The wavelet and wavelet packet transform could characterize and identify islanding and fault disturbances based on the variation of contours and the statistical parameters; standard deviation and entropy. It is observed from the various case studies presented in section 4 that wavelet packet transform is a delicate tool for the detection analysis of different types of fault and islanding disturbances under different operating scenarios like no-noise, 20-dB noise, with effect of rotating machine and inverter based DGs. Though, wavelet and wavelet packet could able to extract the statistical features for detection of the disturbances under no-noise conditions, fails when the noise level in voltage signal increases to 20-dB. Therefore, it is being concluded that WPT is more effective and robust to detect the disturbances under varying operating scenarios as mentioned above.

Table 1: A comparative analysis of SD and entropy for different islanding and fault scenario using (a) WT (b) WPT
(a) WT

Type of Disturbance	Wind Connected to grid		Micro-Turbine Connected to grid		Wind and Micro-Turbine Connected to grid	
Scenario	SD	Entropy	SD	Entropy	SD	Entropy
Islanding	183.7	221.2	178.6	236.2	257.8	282.6
Fault in Phase-AG	141.8	173.6	151.5	170.8	198.4	224.6
Fault in Phase-BG	141.3	178.4	144.4	182.2	201.4	218.3
Fault in Phase- CG	142.6	177.5	146.8	181.7	210.2	222.6
Fault in Phase -AB	154.5	183.6	157.8	188.7	206.4	234.2
Fault in Phase-BC	152.5	178.3	158.8	180.6	211.4	244.6
Fault in Phase-CA	156.4	177.5	160.3	181.8	204.5	239.6
Fault in Phase-ABG	156.9	182.7	166.5	192.2	212.4	243.7
Fault in Phase-BCG	157.6	172.9	161.8	179.1	210.6	253.8
Fault in Phase-CAG	158.7	171.0	167.5	180.8	211.6	251.4
Fault in Phase-ABCG	167.8	198.5	170.3	209.6	237.1	278.9

(b) WPT

Type of Disturbance	Wind Connected to grid		Micro-Turbine Connected to grid		Wind and Micro-Turbine Connected to grid	
Scenario	SD	Entropy	SD	Entropy	SD	Entropy
Islanding	198.8	236.6	197.2	241.5	264.3	312.4
Fault in Phase-AG	155.3	186.3	157.7	185.8	210.1	248.7
Fault in Phase-BG	157.0	194.9	159.5	192.6	217.7	237.5
Fault in Phase- CG	155.2	183.7	157.6	188.2	218.5	238.8
Fault in Phase -AB	165.2	191.5	168.1	189.3	225.6	267.7
Fault in Phase-BC	162.1	184.2	164.8	188.7	225.8	265.2
Fault in Phase-CA	162.8	182.6	165.4	186.5	226.4	266.5
Fault in Phase-ABG	169.8	184.7	165.5	187.2	227.1	267.8
Fault in Phase-BCG	167.6	187.3	167.4	187.8	219.8	265.2
Fault in Phase-CAG	166.2	176.9	167.3	189.1	219.3	267.6
Fault in Phase-ABCG	178.6	207.8	186.6	218.5	240.7	290.3

Figure 18: Standard deviation and entropy for islanding and faults with 20-dB noise

Figure 19: Detection of islanding and fault based on entropy as performance index.

Appendix

Table 1 A: Parameters of the fuel cell

Power rating	50 kW
N (No. Of Cell)	60
Open Circuit Voltage	48V
H_2 Value Molar constants	$8.4 \times 10^{-5} (\text{kmol/s.atm})$
O_2 Value Molar constants	$2.51 \times 10^{-5} (\text{kmol/s.atm})$
H_2O Value Molar constants	$2.8 \times 10^{-6} (\text{kmol/s.atm})$
H_2 time constant	1.25s
H_2O time constant	7.83s
O_2 Value time constant	2.91s
m(constant)	0.05
n(constant)	0.011
i_l (Limiting Current)	110A
R_{ohm} (Ohmic Resistance)	0.0185(Ohms)
F(Faradays Constant)	96480(C)

Table 2 A: Parameters of wind turbine/microturbine

Wind turbine generator: 5 MW	
Turbine Rated Power	5 MW
Generator Rated Power	5.5 MVA
Generator Speed (rpm)	1000 – 3000
Inertia constant	8.04 s
AC Nominal Voltage	380 V
DC Link Voltage	1200 V
DC Link Capacitor	0.01 F
Microturbine: 100 kW	
R_s (Stator Resistance)	2.875ohm
No. of Poles	4
$L_d L_q$	8.5mH
Rated Voltage	380Vrms
Frequency	50Hz

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