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A novel passive approach for Islanding detection of wind turbines with mathematical morphology

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Abstract

This paper presents a novel passive approach for islanding detection of wind turbines. Islanding is such a condition which the DG get disconnected from the utility because of disturbances in the network. Islanding can create many problems in power systems and existing standards thus do not permit the DGs to be utilized in island mode. Some of the major problems that can happen in island mode are: disruption in the protection network, over load conditions of DG, out of phase connection of DG to the network, decrement of the customer's power quality, safety hazards for personnel, DG over loads and etc. The proposed method in this paper is based on the voltage signal that is measured in point of common coupling (PCC) and processing this voltage with mathematical morphology (MM). In comparison with other methods, this method is so fast. The simulations of this paper is based on Matlab/Simulink and the feasibility of the proposed technique is evaluated with that simulations. The results of the evaluation and comparison with other methods approves the feasible performance and higher speed of the proposed method.

Keywords: : passive method, islanding detection, mathematical morphology, wind turbine.

1. INTRODUCTION

Nowadays to have clean and renewable energy and the requirement of efficient power transmission to far consumers have caused an increasing interest in distributed generation. The distributed generators (DGs) that supply the local loads, in one hand improve the power quality and in the other hand increase the efficient of energy production. At the same time these DGs have some disadvantages like islanding phenomena [1]. Among the multiple technologies used in DGs, because of higher efficient and availability of power production in AC mode, Wind Turbines extensively get used. Islanding is such a condition which the DG get disconnected from the utility because of disturbances in the network. So the DG supplies local loads individually. Islanding can create many problems in power systems and existing standards thus do not permit the DGs to be utilized in island mode. Some of the major problems that can happen in island mode are: disruption in the protection network, over load conditions of DG, out of phase connection of DG to the network, decrement of the customer's power quality, safety hazards for personnel, DG over loads and etc. The major problem of this phenomena occurs when the power consumption of island is almost equal to the production in this site. In this condition, signals at the point of common coupling has somehow slow changes, so protection devises couldn't have ability to detect islanding occurrence instantaneously. In accordance to the standards that are used in this paper, DG shouldn't utilized in island mode and the occurrence of this condition should be detected in a shortest possible time and after that detection the DG gets out of service[3].

Many detection methods have been proposed for this phenomena in literature. These methods can be separated into three groups: remote detection methods, local detection method (Passive, Active and Hybrid) and signal processing based methods. Each of these methods have some especial advantages and disadvantages [4-6]. Remote detection methods are based on sending and receiving of signals to transmission lines. These methods because of high prices of them are less interested [4-6].

Local detection methods monitor the changes in the system different parameters. This group includes tow sub groups of passive and active. Passive methods are based on monitoring and processing of system parameters like frequency, voltage or harmonics at the point of common coupling or at the terminal of DG. Most of these methods use threshold value to detect islanding. Some of the parameters that have been used to this purpose are rate of change of power (ROCOF) [7], rate of change of frequency (ROCOF) [8,9], impedance sudden changes [10], over voltage or under voltage (O/U voltage), and over frequency or under frequency (O/U frequency) [11], harmonic disturbances (voltage or current) [11,12] and phase jump [13]. The advantages of these methods are their high speed, simple commissioning and low costs. However these methods are dependent on threshold values and they have more non detection zone [14]. The other subgroup is active methods. The base of these methods is sending a signal to the network and monitoring the changes on it. Some of the active methods are slip mode frequency shift method (SMS) [15,16] Active Frequency Drift (AFD) [17], frequency jump (FJ)[18], Active frequency drift with positive feedback (AFDPF) [19], sandia voltage shift (SVS) [20], variation of active and reactive power [21], negative sequence current injection [21,22]. It’s worth to mention that the disturbance caused by the sent signal in island mode is considerable. Reliability of these methods are more than last ones but they are more complicated and their detection time cost of commissioning is higher and also they disturb the power quality in island mode [23]. An addition to these methods, there are some other methods that include both mentioned methods that are said hybrid methods [24-28]. In these methods for avoiding of entrance of disturbance to network, at first passive methods get used, but whenever islanding didn’t detected the active methods come into use. In [24-28] some of these methods have been proposed and analyzed. Time of detection and cost of these methods are higher than others. In order to the methods that have proposed until today, high precious and speed and adoption with different technology of DGs aren’t reached by a single method. So the researchers are more interested in passive methods because of its potential abilities [29]. However these methods have their own problems. In this way they use signal processing methods to extract different features of signal and compare them with threshold values. Some of these proposed methods are furrier transform, Hilbert and Hong transform, wavelet transform. These methods can be used in different technologies of DGs. In [29] presented a brief review of the methods in this area. Some of the features of these methods have been compared in that paper. It can be said that signal processing methods in comparison with passive methods are more adaptive and fast and they have higher precious than others. In this paper wind turbine is selected DG technology for performed analyses. The method that is used to islanding detection is differential morphological filter. This algorithm in addition to its ability of island detection can determine the disturbances that are because of other conditions in the power systems. It’s worth to mention that the evaluation of this method is performed on the asynchronous machines. In section 2 mathematical morphology is introduced. Introduction of wind turbine is in section 3. Section 4 completely presents the proposed algorithm and performance of it. The evaluation of this method and simulation of islanding condition are in fifth section of this paper. Section 6 compares this method with some other ones and the last section is a brief conclusion of the paper.

2. Mathematical Morphology

Mathematical morphology was presented in 1964 by Matern and Serra. It's firs performance was on image processing. Nowadays this algorithm is promoted to different areas that a major one of them is power systems. In signal processing, MM analyses the signal in time domain, however most of the current methods like Fast Furrier Transform (FFT) performs in frequency domain [30]. Dilation and Erosion are two major operation in MM. Other compound operators like opening, closing, hit or miss, top-hat transform and etc are defined based on the major two operations. In power systems, signal are usually two dimensional. Dilation, Erosion, Opening and Closing are mostly used for these systems. The Definitions of these operators are presented below [31]: $f(n)$ and $g(m)$ is supposed to be input signal and SE (Structuring Element) respectively. These signals are defined in domains, $D_f = \{x_0, x_1, x_2, \dots\}$ and $D_g = \{y_0, y_1, y_2, \dots\}$ respectively with n>m, where n and m are integers. So the Dilation of $f(n)$ by $g(m)$ is defined with $(f \oplus g)$, where:

$$y(n) = (f \oplus g)(n)$$

$$= \max\left\{\begin{matrix} f(n-m) + g(m), \\ 0 \leq (n-m) \leq n, m \geq 0 \end{matrix}\right\} \quad (1)$$

And the Erosion of $f(n)$ by $g(m)$ is defined with $(f \ominus g)$, where:

$$y(n) = (f \ominus g)(n)$$

$$= \min\left\{\begin{matrix} f(n+m) - g(m), \\ 0 \leq (n+m) \leq n, m \geq 0 \end{matrix}\right\} \quad (2)$$

By the use of these basic operations that introduced above two following operators Opening and Closing are defined. Opening of $f(n)$ by $g(m)$ is defined by $(f \circ g)$, where:

$$y(n) = (f \circ g)(n) = ((f \ominus g) \oplus g)(n) \quad (3)$$

Similarly, the Closing of $f(n)$ by $g(m)$ is defined by $(f \cdot g)$, where:

$$y(n) = (f \cdot g)(n) = ((f \oplus g) \ominus g)(n) \quad (4)$$

In general SE moves along the signal and extracts the different features of it by considering which operator or filter is used. Many other operators or filters has been defined based on major operators. Morphological Median Filters (MMF), Open-Closing maximal and Close-Opening minimal (OCCO), Generalized Multi-resolution Morphological Gradient (GMMG), Multi-resolution Morphological Opening-Closing (MMOC), multi resolution morphological gradient (MMOC), series MMG and Close-Opening-Open-Closing morphological Gradient (COOCG) are some of these examples [31]. One of the performances of mathematical morphology is event detection. As an example by the use of this algorithm, sudden changes in signal that is caused by fault or other disturbances in power system can be detected. The major reason of proposing this algorithm for island detection is its high speed along with precious in detection process. The calculation process of this algorithm is very simple and this merit causes the high speed of proposed method.

3. The Case Study

Wind turbines get its input powers of transformation of wind force to input torque that is made by rotating turbine blades. Wind energy is directly related to wind density and velocity of turbine blades. This power is calculated by equations (5).

$$P_{Wind} = \frac{1}{2}.\rho.(\pi r^2).V_W^3 \tag{5}$$

Where:

ρ :Air density

r :The radius of the turbine blades

V_W :wind speed

According to Betz theory, the power can exchanged to electrical energy by equation (6).

$$P_{Extracted} = C_P \times P_{Wind} \tag{6}$$

Cp is turbine power factor, that shouldn't be exceeded of its theoretical bounds that is said the Betz limit. The coefficient is a function of λ and β.This function have different patterns, by considering aspects of the used turbine, model proposed in [32] have been used in this paper.

$$C_p(\lambda,\beta) = C_1\left({}^{C_2}/_{\lambda_i} - C_3\beta - C_4\right).e^{-C_s/\lambda_i} + C_6\lambda \tag{7}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{8}$$

The amounts of C_p in the paper are as follows: $C_1 = 0.5176$,$C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$,$C_5 = 21$,$C_6 = 0.0068$.

To simulation of a wind turbine induction generator models available in the SimPower Systems of Matlab / Simulink have been used [33]. The wind turbine is connected by a transmission line to utility and RL load. Wind turbine that is used in this simulation is the squirrel cage induction generator and this generator is connected directly to the grid, the pitch angle is controlled in order to limit the generator output power at its nominal value for winds exceeding the nominal speed. The wind turbine that is used in this simulation has 2 kVA and 400 V nominal power and voltage respectively at 50 Hz frequency and it is connected to the shunt RLC load. This island is connected to the utility by 20kV to 400V power transformer. The other aspects of this system is mentioned in [34]. Also, the schematic of simulated system can be seen in Figure 1.

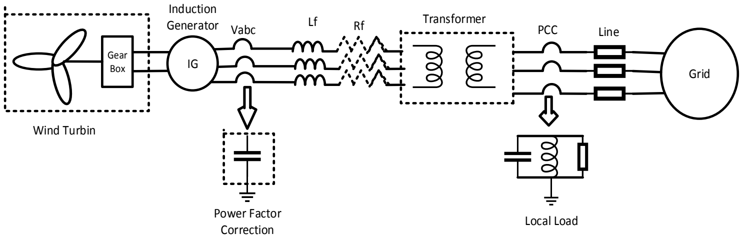


Fig.1. Studied network in this paper

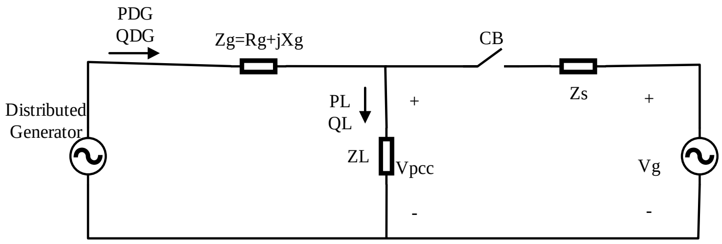


Fig. 1. the equivalent circuit of DG on islanding mode

The equivalent circuit on islanding mode has been shown in Figure 2. The power balance in network is based on Equ. 9,10.

$$P_{load} = P_{DG} + \Delta P \tag{9}$$

$$Q_{load} = Q_{DG} + \Delta Q \tag{10}$$

Where if $P_{load} = P_{DG}$ or $Q_{load} = Q_{DG}$, any power between island and network would be transferred. Also if the resonant frequency of RLC load is equal to the line frequency network, then linear load don't get any reactive power.

Reactive power is directly related to voltage. Also, after the network outage, active power of load get equal to reactive power of turbine. So:

$$V'_{pcc} = K.V_{pcc} \tag{11}$$

Where:

$$K = \sqrt{P_{DG}/P_{load}} \tag{12}$$

If $P_{Load} < P_{DG}$, The voltage domain increases and if $P_{Load} > P_{DG}$, the voltage domain decreases. Also, because of reactive power and voltage-frequency relation:

$$Q'_{load} = Q_{DG} = \left(\frac{1}{\omega'.L} - \omega'.C\right).V'^{2}_{pcc} \tag{13}$$

So in the islanding mode, the swing ω' calculated by the following equation:

$$\omega' = \frac{1}{2} \times -\frac{Q_{DG}}{C.V'^{2}_{pcc}} + \sqrt{\frac{Q_{DG}}{C.V'^{2}_{pcc}}^{2} + \frac{4}{L.C}} \tag{14}$$

So when changes in ΔP and ΔQ are higher, better and faster detection can be done. Because of the extent and success of passive methods, the main focus of this article is based on passive methods. Voltage unbalance is one of the methods in many networks that can show changes easily. According to the Figure 2 for the proposed method, voltage of point PCC have been expressed by the following expressions:

$$V_{pcc} = \frac{Z_L}{Z_L + Z_s} V_g + Z_L.I_L \quad \text{,When CB is on} \tag{15}$$

$$V_{pcc} = Z_L.I_L \quad \text{,When CB is off} \tag{16}$$

The impedance of each component are calculated according to the following equations:

$$Z_s = R_s + j\omega L_s \tag{17}$$

$$Z_g = R_g + j\omega L_g \tag{18}$$

$$Z_{islanding} = R_L \; || \; j\omega I_L \; || \frac{1}{j\omega C_L} || \left(R_g + j\omega L_g\right) \tag{19}$$

According to the new method, based on analysis of the voltage, if amount of voltage is greater than a contestant, the islanding detection.

4. Proposed Method

In this paper, Dilation-Erosion Differential Filter (DEDF) is implemented for islanding detection. In this process at first instantaneous voltage signal in point of common coupling is monitored. At the next step, output of this filter gets processed by Dilation and Erosion operators. By comparing of these operations sudden change of voltage signal that is caused by islanding can be determined. Structuring element that is used in this process is linear. This filter and SE signal are presented below:

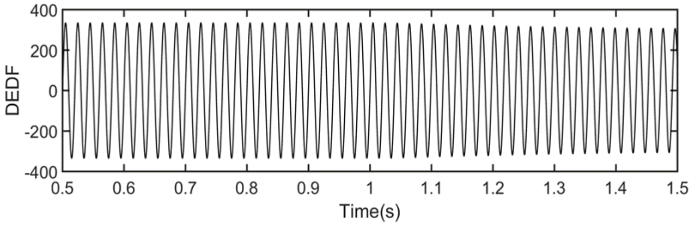
$$g(n) = [0.1,0.1,0.1,0.1,0.1] \tag{20}$$

$$y(n) = [(f \oplus g)(n) - (f \ominus g)(n)] \tag{21}$$

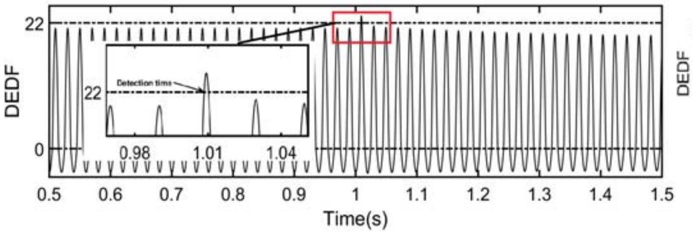
Threshold value for this system is 22. It's worth to mention that this algorithm is not adaptive and threshold values is depending on power system condition.

5. Results of Implementation

As shown in Figure 1, Vf shows the voltage across the load and both the circuit breakers is close in normal operation condition but instantly after islanding occurrence, circuit breaker 1 gets opened and the wind turbine feeds the island's loads alone. Voltage and frequency power system is so important for utility and customers. So they shouldn't exceed the bounds that is defined by respective standards. In grid connected mode, the utility controls these parameters, but when islanding occurs, these parameters exceeds from predefined bound but in some cases this change happens gradually. As an instance, when generation and load of island is balanced, islanding detection would be so difficult because of the slow change in voltage and other parameters. In this paper, by the use of one of the mathematical morphology filters that has been explained in related section. This algorithm is used for processing of voltage signal because of its availability.



(a)



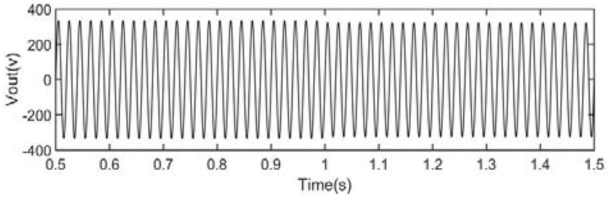
(b)

Fig. 3. A voltage across the load in Island condition, a) without algorithm, b) by applying the algorithm

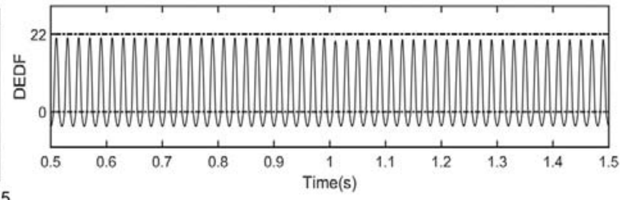
By considering that in power systems some other events like motor starting or capacitor switching can cause similar change in voltage signal, methods of island detection should have be able to determine these events from islanding. Accordance to simulations, proposed method can do it in a high speed. In this section, three events have been simulated to show the precious of this method. These simulations are islanding, capacitor switching and motor starting.

5.1. Islanding

In this case, as shown in Figure 1, the CB is closed and island is connected to the network. At t = 1s CB opens and electrical island gets separated from utility, so DG and load works in island mode. In this mode, DG lonely feeds the load and because of balance between generation and consumption, voltage of load terminal doesn't change. This condition can causes wrong islanding detection. Voltage of the load terminal, before and after applying the filter at Point of Common Coupling (PCC) shown in Figure 3. As shown in the figure 3a, applying the proposed algorithm to the voltage signal determines the islanding and sends trip signal in less than one cycle. Speed of this algorithm for this system is 10ms. Also, this algorithm can detect the islanding for any other systems in less than 1 cycle.



(a)



(b)

Fig. 4. Voltage across the load in the motor driving condition, a) no algorithm, b) by applying the algorithm

5.2. Motor Starting

Due to the dynamic characteristics of motors, in starting time it needs high current and so lowers the terminal voltage. Because this mode causes the voltage drop across the load on the transmission line, anti-islanding protection relays should have the ability to separate it from islanding. This algorithm can separate motor starting from the islanding with high precious. The results of the simulation prove the reliability of the proposed method. Figure 4 shows the voltage signal and result of algorithm at this moment.

5.3. Capacitor Switching Condition

When capacitor banks enters to the grid, the reactive power of grid changes. In this condition the grid voltage can have a similar motion to islanding. So islanding protection relay should have ability to distinguish it from the island and wouldn't send a wrong trip. According to fig 5b, it separates the islanding condition from capacitor switching. At the PCC, a large 2kVar capacitor bank at t=1s was switched. As shown in Figure 5, shows the result of algorithm on voltage signal at the load terminal.

Finally, with the focus on the results of the simulations, it was observed that in addition to high speed of islanding detection, the proposed algorithm have high accuracy. So that any change in the load or the grid power that causes the change in the voltage of load at PCC can be separated correctly and the relay don't send a wrong trip. This algorithm detection time is less than 1 cycle (10ms for this simulation), which is faster than other methods such as Wavelet transform and Fourier transform [29].

6. Results Comparison Table

Table 1, have compared the results of the proposed method with other ones. As seen in Table 1, many methods have to detect the island and have been used for various DG types. Each of them have advantages and disadvantages. The performance time is also very important in islanding protection, so this parameter is highlighted in this comparison. As can be seen in [34], by considering that the studied system is similar with the mentioned articles, the time of detection was 20ms; that in this paper, the proposed method achieved 10ms. In [34], the anti-islanding protection of the same system was done based on wavelet transform and can be seen that the time of detection is longer that proposed method in this paper.

Table 1. Comparison of different method of islanding detection

Approach	SP- Model	DG Technology	Detection Time	Pros And Cons
Fourier Transform	. DFT [35]	PV	Around 1ms	.Robust control against grid disturbance and .Fast harmonic computation
TT-Transform	.TT-Transform [40]	Hybrid (PV, Fuel cell, wind)	-----	Best in noisy environment
Wavelet Transform	. DWT [36] . DWT [37] .WSE [38]	. PV . Wind Farm (DFIG) .Three Wind Farm and a Diesel Generator	.0.05s .20ms .10ms	.low computational burden, high speed, Not worked in harmonic free environment .High efficiency .Effective .easily implemented on DSP but NDZ occurs if power mismatch is above 15%
S-Transform	.S-Transform [39]	Inverter based & rotating machine based i.e. PV, Fuel cell and wind	26-28ms	most efficient
Hilbert Huang transform	.HHT [41] (EMD + IMF)	Inverter based DG	Less than two cycle	.Simple and Accurate in noisy environment
Mathematical Morphological	.MM [30,31]	Wind Turbine	Less than two cycle	. Accurate Detection .Low computational burden .fast response .can be implemented in different DGs

This algorithm addition to reducing the detection time, due to the availability and ease of the algorithm and low computational burden in compared with other algorithms, can be used for the different DGs. According to Table 1 and analyzing it, performance of this method and high speed of it gets approved.

7. Conclusion

This paper presented a novel method for the islanding detection by using mathematical morphology to increase the ability to protect the grid. This method, in addition to system stability maintenance and no disturbance in power production, detects the islanding at 10ms that is higher in compared with other methods. The other advantage of this method in compared with other methods is its low computational burden. The results of the simulation and applying the proposed method on three different events and comparing it with other methods, approves the capabilities, advantages and higher speed of the proposed method in island detection. The next step for completing this method is making it adaptive.

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