A New Active Method for Islanding Detection Based on Traveling Wave Theory

S. Dolatabadi*, S. Tohidi* (C.A.) and S. Ghasemzadeh*

Abstract: In this paper, a new active method based on traveling wave theory for islanding detection is presented. A standard power grid that combines a distributed generation source and local loads is used to test the proposed method. Simulations are carried out in MATLAB/Simulink and EMTP/rv which demonstrate fast response and zero non-detection zone (NDZ) of the method along with low perturbation.

Keywords: Islanding Detection, Microgrid, Traveling Wave Theory, Distributed Generation.

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>( f )</td>
<td>System frequency</td>
</tr>
<tr>
<td>( P )</td>
<td>Active power</td>
</tr>
<tr>
<td>( Q )</td>
<td>Reactive power</td>
</tr>
<tr>
<td>( H )</td>
<td>Power system inertia</td>
</tr>
<tr>
<td>( S_n )</td>
<td>Total apparent power of system</td>
</tr>
<tr>
<td>( L )</td>
<td>Line inductance</td>
</tr>
<tr>
<td>( L_f )</td>
<td>Inductance of DG</td>
</tr>
<tr>
<td>( L_g )</td>
<td>Inductance of grid</td>
</tr>
<tr>
<td>( R )</td>
<td>Line resistance</td>
</tr>
<tr>
<td>( R_f )</td>
<td>Resistance of DG</td>
</tr>
<tr>
<td>( R_g )</td>
<td>Resistance of grid</td>
</tr>
<tr>
<td>( G )</td>
<td>Line Conductance</td>
</tr>
<tr>
<td>( C )</td>
<td>Line Capacitance</td>
</tr>
<tr>
<td>( Z_r )</td>
<td>Resistance of receiver</td>
</tr>
<tr>
<td>( Z_s )</td>
<td>Resistance of sender</td>
</tr>
<tr>
<td>( Z_C )</td>
<td>Characteristic impedance of line</td>
</tr>
<tr>
<td>( A^+ )</td>
<td>Backward moving wave of A</td>
</tr>
<tr>
<td>( A^- )</td>
<td>Forward moving wave of A</td>
</tr>
<tr>
<td>( \rho_s )</td>
<td>Reflection coefficient of sender</td>
</tr>
<tr>
<td>( \rho_r )</td>
<td>Reflection coefficient of receiver</td>
</tr>
<tr>
<td>( I )</td>
<td>Current</td>
</tr>
<tr>
<td>( V )</td>
<td>Voltage</td>
</tr>
<tr>
<td>( LT )</td>
<td>Line length</td>
</tr>
</tbody>
</table>

Introduction

NOWADAYS, the increasingly widespread use of distribution generator (DG) units in power systems causes some worries for system operators. A comprehensive understanding of such effects requires a definition of DG, which has been fully discussed in [1-3]. In brief, the current study refers to DG as a generator with limited output power compared to centralized generation, which is connected to low voltage (LV) or medium voltage (MV) side of distribution network. Here, two factors of size and placement are considered. The DG units have various types such as solar panels, wind turbines and gas turbines [3]. On one hand, using DG in power system leads to lower power loss in transmission lines, reliability improvement in most cases, improved voltage profile, and environmental benefits [3]. On the other hand, these types of resources make some difficulties for maintaining, repairing, and protecting systems. This is mainly because the direction for power flow is unknown when the DG units are involved, unlike power system with centralized generation which has a defined direction for power flow. This issue leads to many problems and side effects. For instance, in repairing the transmission line, the operator should disconnect two sides of the line. Besides, in auto reclosing relays, in the
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In the third section the proposed active method is discussed in two sub-sections. Section four presents the simulation and results. Finally, Section five consists of a brief conclusion of the study.

2 Active Islanding Detection Methods

Currently, there are lots of active methods available in papers. Due to their fast response and low NDZ, they have been subjected for many research topics. In this section, it is tried to briefly introduce some methods which are more common and then explain their drawbacks. Finally, Table 1 will provide a summarization of the advantages and disadvantages of such active methods.

2.1 Frequency Shift Method

Frequency shift method [12,13] is only used in inverter based DGs. In this method, the frequency of inverter current is changed which is slightly different from the main grid frequency. This frequency change is done by changing the power factor in one cycle and resynchronization in the next cycle. If the microgrid is connected to the main grid, no sign of frequency deviation will be observed. Otherwise, the islanding will be detected. As mentioned before, at least two cycles are necessary for detection. Also, this method cannot be used for non-inverter based DGs which is a big challenge for this method. The NDZ of this method is related to chopping fraction \( cf \) which is calculated by [14]:

\[
    cf = \frac{f_v}{2T_v}
\]

2.2 System Impedance Monitoring

In this method [15,16], a high frequency voltage source along with a series capacitor are connected to the point of common coupling (PCC) (Fig. 1). By measuring the current of voltage source \( U_{im} \), the system impedance is calculated. The islanding situation is detectable by the difference between impedances of the islanded and the normal grid. There is a major drawback in this method. Although the system impedance will be different in the islanded grid, this change will not be sensible. Since both \( Z_{sw} \) and \( Z_{DG} \) impedances are so small and \( Z_M \) has high value, the difference between \( Z_{sw} || Z_M || Z_{DG} \) and \( Z_{sw} || Z_{Load} \) is very small. As a result, its NDZ will be significant. In addition, due to \( U_{im} \), a tangible voltage ripple will affect the local load after islanding.

2.3 Fault Level Monitoring

In this method [15,17], the fault level, which is calculated in each half cycle, is used for islanding detection. While the sinusoidal voltage is near to zero, a switch will connect to a grounded inductor and then the


<table>
<thead>
<tr>
<th>Method</th>
<th>Advantage(s)</th>
<th>Disadvantage(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency shift method</td>
<td>• accuracy</td>
<td>• Only applicable to inverter based DGs</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Need to Two cycles for detection needed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Complexity</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Small NDZ</td>
</tr>
<tr>
<td>System impedance monitoring</td>
<td>-</td>
<td>• Voltage ripple on local load</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Need to sensible measurements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Low accuracy</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Significant NDZ</td>
</tr>
<tr>
<td>Fault level monitoring</td>
<td>-</td>
<td>• Limited to voltage zero crossing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Change in voltage shape</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Possibility of wrong operation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Significant NDZ</td>
</tr>
<tr>
<td>Voltage pulse perturbation</td>
<td>• Applicable to both inverter and non-inverter based DGs</td>
<td>• Negative effect on local loads</td>
</tr>
<tr>
<td></td>
<td>• simplicity</td>
<td></td>
</tr>
</tbody>
</table>

Table 1 Pros and cons of each active method.

2.4 Voltage Pulse Perturbation

This method uses an external voltage source or DG itself to make perturbations in the PCC [12], [18-20]. If the microgrid is islanded, the voltage pulse will be observable. It is a very simple method, but has bad effects on the local loads and increases voltage total harmonic distortion (THD) significantly.

In the following section, the proposed active method for islanding detection is presented, in which it is tried to eliminate the difficulties of aforementioned methods. This method can be used for both the inverter and non-inverter based DG units. Besides, it has a very low effect on local loads due to small value of voltage perturbation. In addition, it is very accurate and without NDZ. By adding additional signal processing steps, this method is also able to determine the fault location in the transmission lines.

3 Proposed Active Method Based on Voltage Reflection

This novel method is based on traveling wave theory [21, 22]. In this section, the traveling wave theory is discussed in detail and then the proposed method and its structure for the microgrid islanding detection are introduced.

3.1 Voltage Reflection in Transmission Lines

This calculation is mostly used in overvoltage conditions due to lightening or switching. For explanation, a distributed line model is assumed (Fig. 2) [21].

Fig. 2 Part of distributed transmission line.

In the following section, the proposed active method for islanding detection is presented, in which it is tried to eliminate the difficulties of aforementioned methods. This method can be used for both the inverter and non-inverter based DG units. Besides, it has a very low effect on local loads due to small value of voltage perturbation. In addition, it is very accurate and without NDZ. By adding additional signal processing steps, this method is also able to determine the fault location in the transmission lines.

\[
\frac{\partial v}{\partial x} \Delta x = - \left( Ri + L \frac{\partial i}{\partial t} \right) \Delta x \quad (2)
\]

Also, the current is calculated as:
The transmission line resistance is neglected due to its small effect in this study. According to [23], line resistance is defined as an exponential coefficient. This coefficient is directly related to the frequency, so this coefficient undermines front of pulse wave where frequency value is high. Assuming that the line is lossless \((G, R = 0)\), Eqs. (2) and (3) could be expressed as (4) and (5), respectively.

\[
\frac{\partial v}{\partial x} = -L \frac{\partial i}{\partial t} \tag{4}
\]

\[
\frac{\partial i}{\partial x} = -C \frac{\partial v}{\partial t} \tag{5}
\]

By partial derivation of (4) and (5) with respect to \(x\) and \(t\), respectively, the current value is eliminated:

\[
\frac{1}{LC} \frac{\partial^2 v}{\partial x^2} = \frac{\partial^2 v}{\partial t^2} \tag{6}
\]

Eq. (6) is known as traveling wave equation. A complete solution of this differential equation is given in Eq. (7).

\[
v = f_1(x - \nu t) + f_2(x + \nu t) \tag{7}
\]

Note that \(v\) stands for voltage wave and \(\nu\) (Nu) represents wave speed. Considering Eq. (7), both waves \(f_1\) and \(f_2\) have the same speed \((\nu)\) but in opposite directions. Substituting \(v = f(x-\nu t)\) in Eq. (6) yields the speed of travelling wave in a lossless transmission line.

\[
\nu = \frac{1}{\sqrt{LC}} \tag{8}
\]

Corresponding currents for forward and backward moving waves are defined as below using \(i = -c \frac{\partial v}{\partial t}\).

\[
i^+ = \frac{1}{\sqrt{C}} f_1(x - \nu t) \tag{9}
\]

\[
i^- = \frac{1}{\sqrt{C}} f_2(x + \nu t) \tag{10}
\]

The proportion of voltage at the end of line \((v_R)\) to the current at the end of line \((i_R)\) is equal to the terminating impedance. The \(v_R\) and \(i_R\) could be written according to their forward and backward waves (Eq. (11)).

\[
\frac{v_R}{i_R} = \frac{v_R^+ + v_R^-}{i_R^+ + i_R^-} = Z_R \tag{11}
\]

Using \(Z_c = \sqrt{L/C}\) the currents equations could be rearranged as:

\[
i_R^+ = \frac{V_R^+}{Z_c} \tag{12}
\]

\[
i_R^- = \frac{V_R^-}{Z_c} \tag{13}
\]

The ratio of forward wave to backward wave \(v_R^+/v_R^-\) is defined as reflection coefficient \((\rho)\). This coefficient for both the receiving and sending sides are calculated by using (14) and (15).

\[
\rho_R = \frac{Z_R - Z_c}{Z_R + Z_c} \tag{14}
\]

\[
\rho_S = \frac{Z_S - Z_c}{Z_S + Z_c} \tag{15}
\]

Moreover, duration of wave sweep in transmission line is obtained as:

\[
T_c = \frac{LT}{\nu} \times 2 \tag{16}
\]

### 3.2 The Proposed Method for Islanding Detection

This active method is based on traveling wave theory which comprehensively was explained in Section 3.1. As aforementioned, islanding occurs due to disconnection of the microgrid and main grid. Hence two conditions are considerable, first a fault in the main grid triggers grid side relay, or second a fault is occurred in transmission line which triggers both relays on two sides (Fig. 3).

Considering both mentioned conditions and also normal operation of network, three responses from the proposed method is expected. First, if the line is disconnected from microgrid side, the line will not be available for traveling wave and therefore, no response is observed. Second, if the main grid side relay is triggered, \(Z_R\) will be infinite and reflection coefficient in receiving side will be equal to 1 \((\rho_R = 1)\). It means the transmitted wave will return without any change. And finally under normal conditions both \(\rho_R\) and \(\rho_S\) have negative values and hence change of returned wave to transmitter is significant \((Z_c > Z_R & Z_S)\).

To perceive the proposed method, following simple structure is considered.

UL1741 standard is used to test the proposed novel
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Fig. 3 General structure of microgrid connection to main grid along with protection relays.

Fig. 4 Simple structure of proposed active method.

Fig. 5 The standard structure.

Fig. 6 Proposed electrical schematic of non-inverter based DG a) voltage injection to one phase and b) voltage injection to two phases.

Fig. 7 Two proposed method for extracting traveling wave from voltage wave.

method (Fig. 5) [24].

Two different ways for pulse generator connection can be considered as depicted in Fig. 6.

Although both structures are useful, structure of Fig. 6(a) is preferred in this study again for its generality.

The proposed method sends voltage pulse into transmission line and the islanding will be detected by performing signal processing on the returned signal. Therefore, it is important to analyze returned signal correctly, and for this purpose two methods are applicable (Fig. 7). First method uses a high pass (H.P) filter and second one compares each period of signal with previous period. The output of both approaches are given in Section 4.

4 Simulation

This section is divided into two parts. At first, a computer-based model of transmission line is presented which shows traveling wave and voltage reflection. The model of transmission line is created in
MATLAB/Simulink and to verify the model, its results are compared with the EMTP built-in model of transmission line. It is noteworthy that EMTP is a computer software for simulating the transitions of power system. As it will be shown, the Simulink model of transmission line completely matches with the EMTP transmission line model. Then using the model of transmission line, simulation of the proposed active islanding detection method is carried out in Matlab/Simulink.

4.1 Modeling of Transmission Line

Simulink library only has simple model of $\pi$ transmission line which does not show traveling waves. Using equations of Section 3.1, this ability is added to line model in this study. Fig. 8 shows both theoretical and electrical schematics.

![Fig. 8 Simulation of transmission line with traveling wave a) theoretical schematic and b) electrical schematic.](image)

### Table 2 Parameters values for simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_s$ (Ω)</td>
<td>0</td>
</tr>
<tr>
<td>$R_r$ (Ω)</td>
<td>18.372</td>
</tr>
<tr>
<td>Line Capacitance (F/Km)</td>
<td>$8\times10^{-7}$</td>
</tr>
<tr>
<td>Line Inductance (H/Km)</td>
<td>$3\times10^{-5}$</td>
</tr>
<tr>
<td>Line Length (Km)</td>
<td>5</td>
</tr>
<tr>
<td>$Z_c$ (Ω)</td>
<td>6.124</td>
</tr>
<tr>
<td>$T_L$ (sec)</td>
<td>$2.44\times10^{-5}$</td>
</tr>
<tr>
<td>$\rho_s$</td>
<td>-1</td>
</tr>
<tr>
<td>$\rho_r$</td>
<td>0.5</td>
</tr>
<tr>
<td>Step input (V)</td>
<td>120</td>
</tr>
</tbody>
</table>

Delay time ($T_L$) and reflection coefficients of send/receive side ($\rho_s/\rho_r$) are determined from (16), (14) and (15), respectively. Besides of EMTP/rv software, the numerical method also is applied which is known as lattice diagram [21]. Both simulations and the numeric methods use the parameters that are given in Table 2.

For a step input, the lattice diagram and voltage plots of send and receive sides are shown in Fig. 9.

Results of both softwares are depicted in Fig. 10 which shows proposed model in Simulink works correctly.

4.2 Simulation of Active Method

The results of active method from both EMTP and Simulink are shown in this subsection. For simulation, the structure of Fig. 6(a) is used. Simulation parameters for power system are defined in Table 3.

![Fig. 9 Numerical analysis of traveling wave using lattice diagram a) the lattice diagram with both side of receive and send, b) the input step voltage and c) the voltage value in receive side.](image)

![Fig. 10 Result of line simulation in a) MATLAB/Simulink and b) EMTP/rv.](image)
Table 3 Parameters values for power system simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator type</td>
<td>Synchronous</td>
</tr>
<tr>
<td>Output power (kW)</td>
<td>100</td>
</tr>
<tr>
<td>L-L RMS voltage (V)</td>
<td>$440\sqrt{3}$</td>
</tr>
<tr>
<td>Local Load (kW)</td>
<td>60</td>
</tr>
<tr>
<td>Grid frequency (Hz)</td>
<td>50</td>
</tr>
</tbody>
</table>

4.2.1 Results of Proposed Active Method

First, simulation is carried out for EMTPrv where a 120V DC voltage source is used for sending the pulse into transmission line. As shown in Fig. 11, the effect of this traveling wave is hardly observable and hence voltage perturbation is very low in the proposed method (Fig. 11(a)-(b)). Similar simulation is done in MATLAB/Simulink with the same parameters. The islanding situation is identified according to returned voltage pulse, due to the fact that this pulse carries reflection coefficient of receiver side (main grid side). By knowing the fact that the resistance of send side is always constant and lower than $Z_C$, the $\rho_s$ has always negative value. When the microgrid is islanded by the main grid relay, the terminate resistance is
infinite and consequently $\rho_r$ becomes equal to 1 (Fig. 11(c)-(f)). Thus the first reflected voltage has a negative value. Under normal conditions, the main grid impedance is too small ($Z_R$) and consequently $\rho_R$ has a value near to -1. Hence the first reflection will have a positive value (Fig. 11(b)-(e)).

As mentioned before, two methods could be used for extracting traveling wave. Fig. 12(a) shows output of these two methods. The result of high pass filter has some distortion but it is satisfying for islanding detection. Although the second method (Fig. 12(b)) has better response, it is only applicable when THD of voltage is very low.

The response time in proposed active method is related to line inductance and capacitance. In this study, the method detects islanding 48.8 microsecond after occurrence (for a 5 km length line). However, the proposed method is faster than any other active methods.

Fig. 13 shows effect of line capacitance on traveling wave velocity and $Z_c$. This plot is obtained from $Z_c = \sqrt{\frac{L}{C}}$ and (8). Thus, as line capacitance gets higher, the response time of proposed method is increased.

Fig. 14 depicts both velocity and $Z_c$ for constant capacitance in different inductances. Although inductance has the same influence on velocity, contrary to capacitance it increases $Z_c$.

In practice, there are limited number of traditional transmission lines and their capacitance and inductance are similar and in a specific range. In Figs. 15 and 16, 11 common types of transmission lines are presented (Table 4). Fig. 15 shows velocity and $Z_c$ for each of 11 transmission lines and in Fig. 16, the response time of each line is shown for a 5 km line.

![Image](https://example.com/image1)

**Fig. 12** Extracted traveling wave from system voltage wave form using a) high pass filter and b) comparison of two signal periods.

For constant Inductance ($L=3E+4$ H/Km)

![Image](https://example.com/image2)

**Fig. 13** Traveling speed and characteristic impedance curves for different capacitance values.

![Image](https://example.com/image3)

**Fig. 14** Traveling speed and characteristic impedance curves for different inductance values.

![Image](https://example.com/image4)

**Fig. 15** Speed of traveling wave in 11 types of popular transmission line.

![Image](https://example.com/image5)

**Fig. 16** Responding time of proposed method for 11 types of popular transmission line for 5 km length line.
Table 4 Properties of 11 studied types of transmission line with their characteristic impedance and traveling speed.

<table>
<thead>
<tr>
<th>Line type</th>
<th>60 Hz $X_0$ (Ω/Km)</th>
<th>Capacitance ($F/Km$)</th>
<th>Inductance ($H/Km$)</th>
<th>Characteristic Impedance ($Ω$)</th>
<th>Velocity ($Km/s$)</th>
<th>Time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waxwing</td>
<td>0.109</td>
<td>0.476</td>
<td>1.51E-08</td>
<td>0.000785</td>
<td>227.7806</td>
<td>2.910E-05</td>
</tr>
<tr>
<td>Partridge</td>
<td>0.1074</td>
<td>0.465</td>
<td>1.53E-08</td>
<td>0.000766</td>
<td>223.4748</td>
<td>2.915779</td>
</tr>
<tr>
<td>Ostrich</td>
<td>0.1057</td>
<td>0.458</td>
<td>1.56E-08</td>
<td>0.000755</td>
<td>220.0241</td>
<td>2.9146317</td>
</tr>
<tr>
<td>Merlin</td>
<td>0.1055</td>
<td>0.462</td>
<td>1.56E-08</td>
<td>0.000761</td>
<td>220.7736</td>
<td>2.8992399</td>
</tr>
<tr>
<td>Linnet</td>
<td>0.104</td>
<td>0.451</td>
<td>1.58E-08</td>
<td>0.000743</td>
<td>216.5733</td>
<td>2.9134483</td>
</tr>
<tr>
<td>Hawk</td>
<td>0.0988</td>
<td>0.43</td>
<td>1.67E-08</td>
<td>0.000709</td>
<td>206.1165</td>
<td>2.9081926</td>
</tr>
<tr>
<td>Hen</td>
<td>0.0918</td>
<td>0.424</td>
<td>1.68E-08</td>
<td>0.000699</td>
<td>203.8431</td>
<td>2.916816</td>
</tr>
<tr>
<td>Plover</td>
<td>0.0829</td>
<td>0.365</td>
<td>1.95E-08</td>
<td>0.000602</td>
<td>173.9497</td>
<td>2.8914102</td>
</tr>
<tr>
<td>Lapwing</td>
<td>0.0822</td>
<td>0.364</td>
<td>2.01E-08</td>
<td>0.000606</td>
<td>172.9763</td>
<td>2.8831294</td>
</tr>
<tr>
<td>Falcon</td>
<td>0.0814</td>
<td>0.358</td>
<td>2.02E-08</td>
<td>0.000559</td>
<td>170.7079</td>
<td>2.89300786</td>
</tr>
<tr>
<td>Bluebird</td>
<td>0.0776</td>
<td>0.344</td>
<td>2.12E-08</td>
<td>0.000567</td>
<td>163.3842</td>
<td>2.88157922</td>
</tr>
</tbody>
</table>

5 Conclusion

In this paper a novel active method is introduced. The proposed active method uses traveling wave theory in transmission line which enables detecting of microgrid islanding more accurate and faster than previous methods. The zero non-detective zone plus quick response with low perturbation of this method make it outstanding from other methods. To verify proposed method in this study, comprehensive simulations in both EMTP/rv and MATLAB/Simulink are carried out.

References


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