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

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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

f_s or f	System frequency
P	Active power
Q	Reactive power
H	Power system inertia
S_n	Total apparent power of system
L	Line inductance
L_f	Inductance of DG
L_g	Inductance of grid
R	Line resistance
R_f	Resistance of DG
R_g	Resistance of grid
G	Line Conductance
C	Line Capacitance
Z_r	Resistance of receiver
Z_s	Resistance of sender
Z_C	Characteristic impedance of line
A^+	Backward moving wave of A
A^-	Forward moving wave of A
ρ_s	Reflection coefficient of sender
ρ_r	Reflection coefficient of receiver
I	Current
V	Voltage
LT	Line length
X	Distance
v (Nu)	Speed of traveling wave
t_z	zero time
T_V	voltage period
t_i	Time period of study

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1 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 case of fault in transmission line, the relay will separate line from supplier for a while to clear the fault, but in the presence of DG unit this fault has been fed and so the fault will remain. Yet, the most important problem of power system with DGs, which is the scope of the current paper, is disconnection of micro-grid from the main network. Losing the main (LOM) or islanding mostly will not be easily detected due to existence of interior suppliers (DGs). LOM leads to a decrease in network inertia and consequently significant frequency variations in case of load changes. Additionally, because DG units are not capable of voltage regulating, micro-grid will suffer from the voltage variation. Undoubtedly, both voltage and frequency variations which are made due to LOM of micro-grid will cause damages to electrical equipment [4]. To reduce or even prevent these bad effects, it is useful to detect LOM in the very second (few cycles) of happening. This could be possible by using islanding detection methods, which are divided into two groups of remote and local [5, 6]. Remote method which uses communication between micro-grid and protection relays to detect LOM [7] is beyond the scope of this paper. Local method is divided into three subgroups of passive, active, and hybrid methods. Passive method uses onsite measurable parameters like voltage and frequency and calculating rate of change of frequency (ROCOF) or rate of change of voltage (ROCOV). These detection methods are applicable in both non-inverter or inverter based DGs. For instance, in [8] a new method is proposed based on ROCOV which benefits from zero non-detection zone. In [9], a new index based on ROCOV and rate of change of active power is proposed which guaranties fast detection. Also, a new method based on ROCOV is proposed in [10]. In [11] method is introduced to detect any abnormal change in a signal which can be useful for passive islanding detection methods. Contrary to passive methods, the active methods are able to detect islanding by injecting a signal or making a distortion in grid and analyzing the response. These methods are usually used in inverter based DGs and are faster than the passive approaches. To prevent continuous operation of active method which reduces voltage quality of grid, hybrid methods are proposed, which are a combination of passive and active methods.

The current study aims to propose a new active method for islanding detection which is based on the theory of traveling wave in transmission lines. To examine the active method, a comprehensive simulation is performed in both EMTP/rv and MATLAB/Simulink software. The results show more accuracy and faster response compared to other methods. Furthermore, it provides near to zero non-detection zone (NDZ). Moreover, in this paper a model of transmission line is purposed in Simulink which shows voltage reflections and traveling waves. The contents of the paper are presented in five sections. The following section analyzes the common active islanding methods. Then, 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]:

$$cf = \frac{t_z}{2T_V} \tag{1}$$

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_{hf}), 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_{nw} and Z_{DG} impedances are so small and Z_M has high value, the difference between $Z_{nw}||Z_M||Z_{DG}$ and $Z_{DG}||Z_{Load}$ is very small. As a result, its NDZ will be significant. In addition, due to U_{hf}, 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 1 Pros and cons of each active method.

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

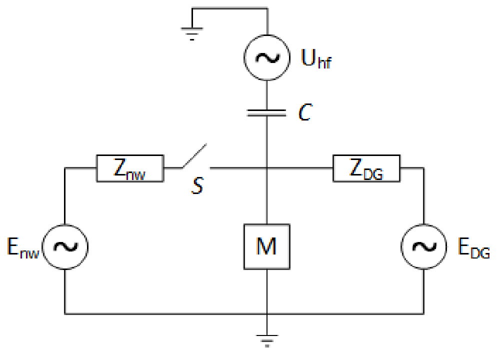

Fig. 1 Structure of system impedance monitoring method [15].

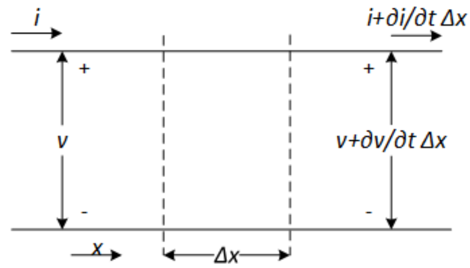

Fig. 2 Part of distributed transmission line.

current is measured. This method suffers from many issues. Firstly, islanding detector is applicable only in voltage zero crossing. Secondly, voltage shape is changed slightly in each operation; and third in case of unsynchronized switching, the fault current will be tremendous. In addition, this method has the same problem as the pervious method which is the difference in fault levels are not noticeable. The NDZ of this method is also significant.

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 shows that the voltage and current of the line are functions of both time and distance. Thereupon, partial derivation equations should be used. The voltage on Δx length of the line is given in the following equation.

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

Also, the current is calculated as:

$$\frac{\partial i}{\partial x}\Delta x = -\left(Gv + C\frac{\partial v}{\partial t}\right)\Delta x \tag{3}$$

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).

$$v = f_1(x - \mathrm{v}t) + f_2(x + \mathrm{v}t) \tag{7}$$

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

$$\mathrm{v} = \frac{1}{\sqrt{LC}} \tag{8}$$

Corresponding currents for forward and backward moving waves are defined as below using i = $-c$ dv/dt.

$$i^+ = \frac{1}{\sqrt{\frac{L}{C}}} f_1(x - \mathrm{v}t) \tag{9}$$

$$i^- = \frac{1}{\sqrt{\frac{L}{C}}} f_2(x + \mathrm{v}t) \tag{10}$$

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:

$$i_R^+ = \frac{V_R^+}{Z_c} \qquad i_R^- = -\frac{V_R^-}{Z_c} \tag{12}$$

Z_c is known as impedance characteristic of transmission line. Substituting (12) into (11) yields the voltage as a function of impedances.

$$v_R^- = \frac{Z_R - Z_c}{Z_R + Z_c} v_R^+ \tag{13}$$

The ratio of forward wave to backward wave v_R^-/v_R^+ is defined as reflection coefficient (ρ).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:

$$T_L = \frac{LT}{v} \times 2 \tag{16}$$

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 (ρ_R = 1). It means the transmitted wave will return without any change. And finally under normal conditions both ρ_R and ρ_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

Fig. 3 General structure of microgrid connection to main grid along with protection relays.

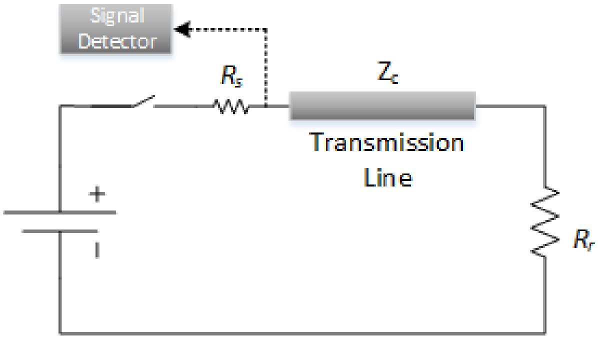

Fig. 4 Simple structure of proposed active method.

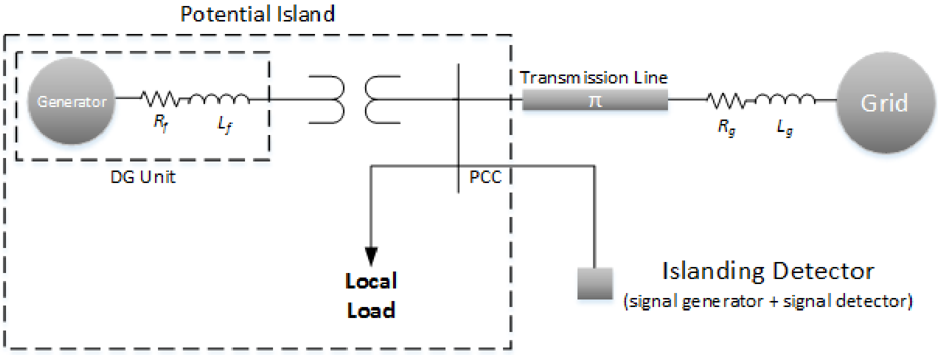

Fig. 5 The standard structure.

(a) (b)

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

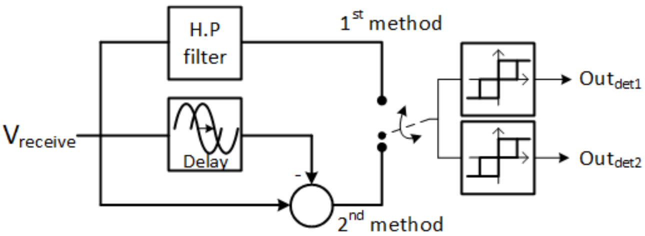

Fig. 7 Two proposed method for extracting traveling wave from voltage wave.

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 π 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.

Delay time (T_L) and reflection coefficients of send/receive side (ρ_S/ρ_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.

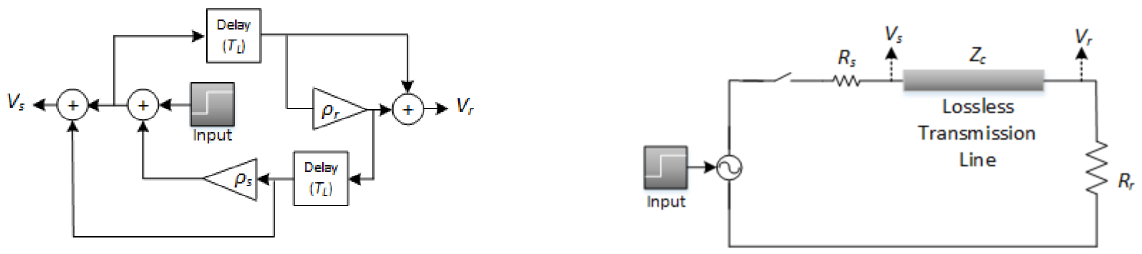

Fig. 8 Simulation of transmission line with traveling wave a) theoretical schematic and b) electrical schematic.

Table 2 Parameters values for simulation.

Parameter	Value
R_s (Ω)	0
R_r (Ω)	18.372
Line Capacitance (F/Km)	8×10^{-7}
Line Inductance (H/Km)	3×10^{-5}
Line Length (Km)	5
Z_c (Ω)	6.124
T_L (sec)	2.44×10^{-5}
ρ_s	-1
ρ_r	0.5
Step input (v)	120

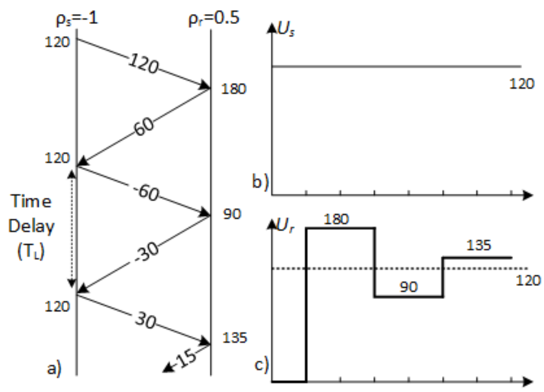

Fig. 9 Numerical analysis of traveling wave using lattice diagram a) the lattice diagram with both side of receive and send, b) the input step voltage and c) the voltage value in receive side.

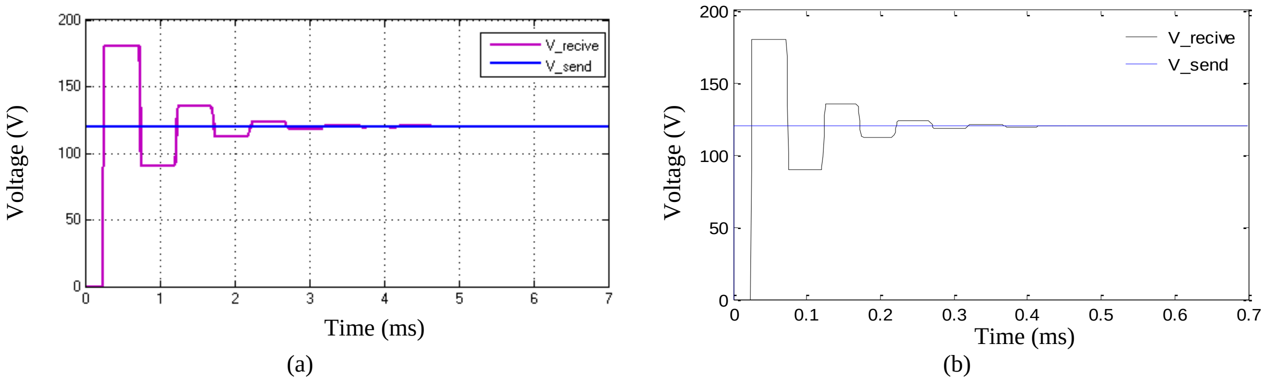

Fig. 10 Result of line simulation in a) MATLAB/Simulink and b) EMTP/rv.

Table 3 Parameters values for power system simulation.

Parameter	Value
Generator type	Synchronous
Output power (kW)	100
L-L RMS voltage (V)	$440\times\sqrt{3}$
Local Load (kW)	60
Grid frequency (Hz)	50

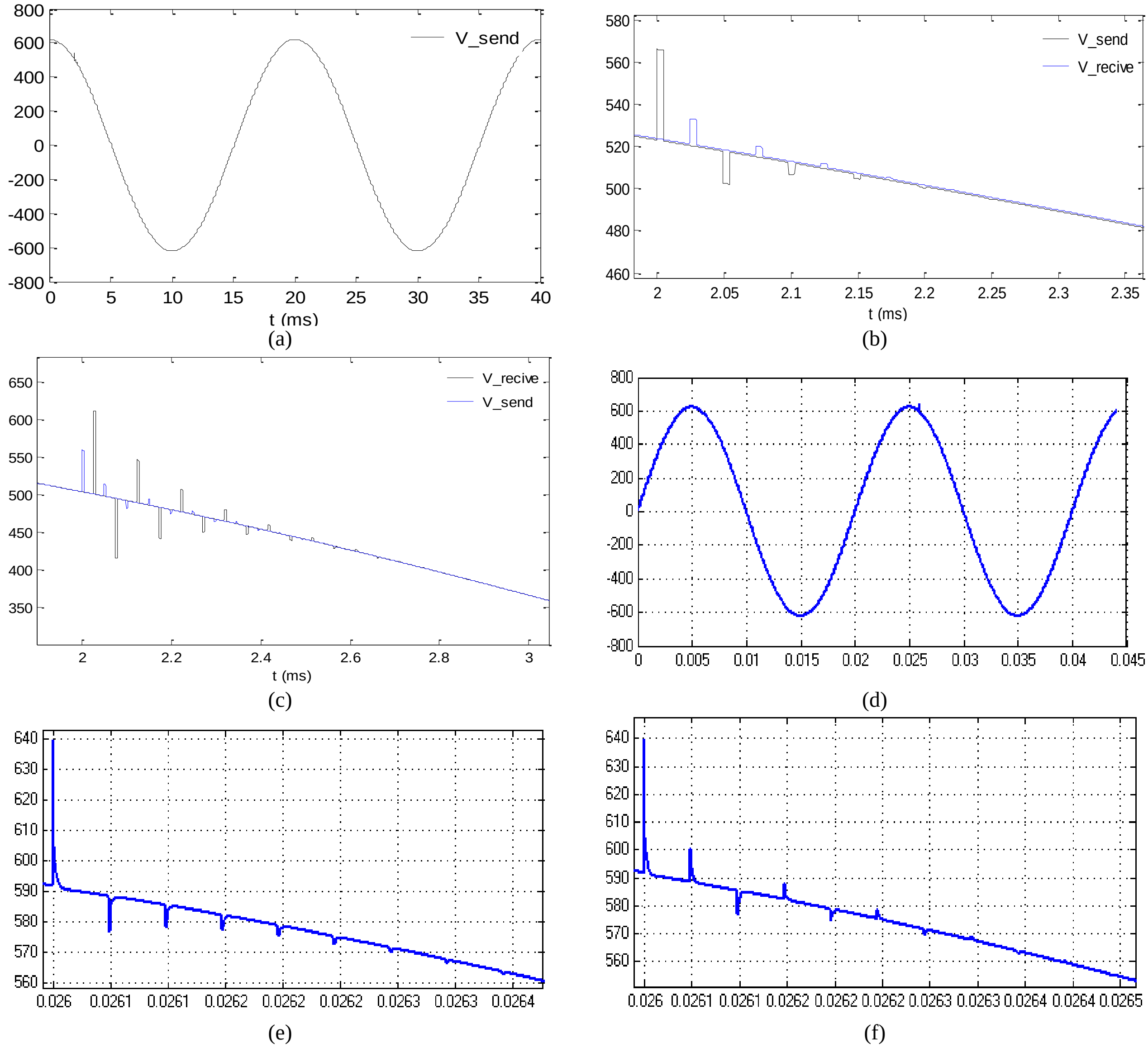

Fig. 11 Simulation results in EMTP/rv a) system voltage wave form with injected pulse, b) traveling wave in receiver and transmitter side under normal conditions, c) traveling wave in receiver and transmitter side under islanding conditions-simulation results in MATLAB/Simulink, d) system voltage wave form with injected pulse, e) traveling wave in transmitter side conditions and f) traveling wave in transmitter side conditions.

4.2.1 Results of Proposed Active Method

First, simulation is carried out for EMTP/rv 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 caries 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 ρs has always negative value. When the microgrid is islanded by the main grid relay, the terminate resistance is infinite and consequently ρr 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 ρ_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 $Z_c = \sqrt{L/C}$ 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.

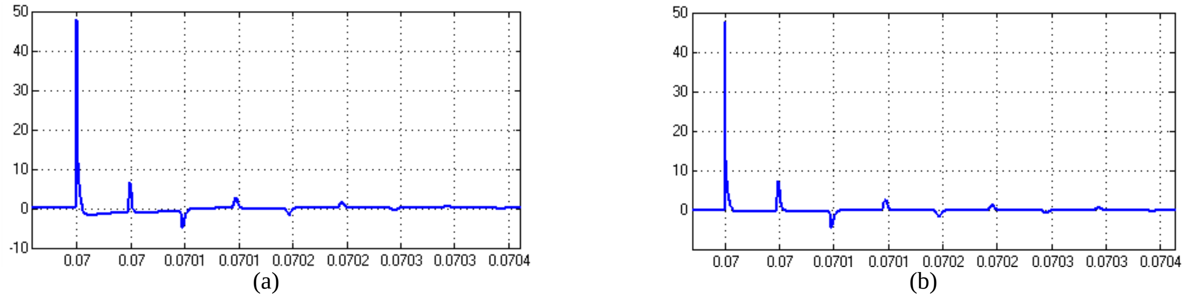

Fig. 12 Extracted traveling wave from system voltage wave form using a) high pass filter and b) comparison of two signal periods.

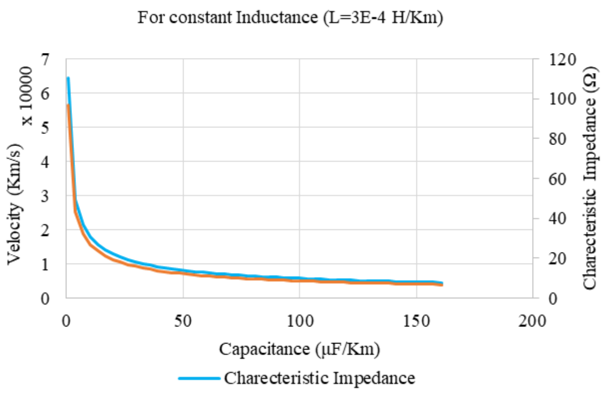

Fig. 13 Traveling speed and characteristic impedance curves for different capacitance values.

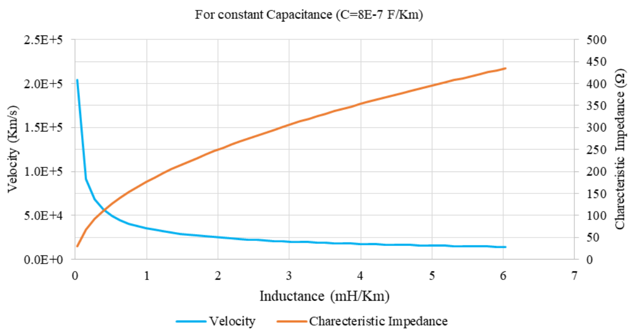

Fig. 14 Traveling speed and characteristic impedance curves for different inductance values.

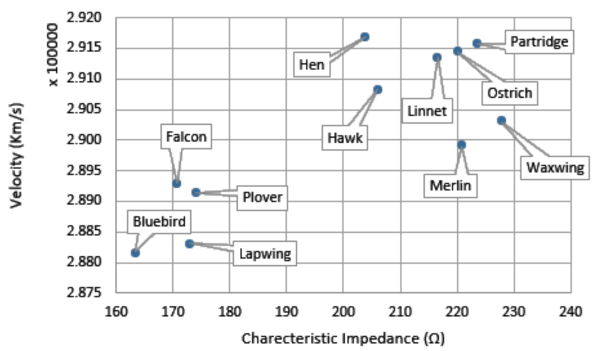

Fig. 15 Speed of traveling wave in 11 types of popular transmission line.

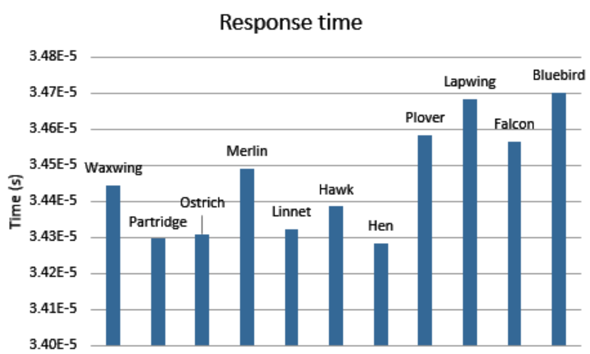

Fig. 16 Responding time of proposed method for 11 types of popular transmission line for 5 km length line.

Table 4 Properties of 11 studied types of transmission line with their characteristic impedance and traveling speed.

Line type	60 Hz		Capacitance (F/KM)	Inductance (H/KM)	Characteristic Impedance (Ω)	Velocity (Km/s)	Time(s)
	X_c (MΩ/mil)	X_L (Ω/mil)					
Waxwing	0.109	0.476	1.51E-08	0.000785	227.7806	2.90E+05	3.44E-05
Partridge	0.1074	0.465	1.53E-08	0.000766	223.4748	291577.89	3.43E-05
Ostrich	0.1057	0.458	1.56E-08	0.000755	220.0241	291463.167	3.43E-05
Merlin	0.1055	0.462	1.56E-08	0.000761	220.7736	289923.999	3.45E-05
Linnet	0.104	0.451	1.58E-08	0.000743	216.5733	291344.835	3.43E-05
Hawk	0.0988	0.43	1.67E-08	0.000709	206.1165	290819.263	3.44E-05
Hen	0.098	0.424	1.68E-08	0.000699	203.8431	291681.6	3.43E-05
Plover	0.0829	0.365	1.99E-08	0.000602	173.9497	289141.052	3.46E-05
Lapwing	0.0822	0.364	2.01E-08	0.0006	172.9763	288312.944	3.47E-05
Falcon	0.0814	0.358	2.02E-08	0.00059	170.7079	289300.786	3.46E-05
Bluebird	0.0776	0.344	2.12E-08	0.000567	163.3842	288157.922	3.47E-05

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 pervious 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.

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