A Novel Algorithm of Directional Overcurrent Protection Relay Based on Adaptive Linear Neural Network

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***Abstract*—In the coming years, the flexibility of distribution network will be required more due to the implementation of distributed generation of renewable energy sources such as wind, solar, biomass, etc. The distributed generations are connected to the power grid in order to contribute to supplying energy for the loads. Thus the power flow direction and fault direction at the relays will be also changed. Therefore, using directional overcurrent protection relay is necessary to isolate the fault quickly and exactly. This paper proposes a novel method based on linear adaptive neural network which is used in directional overcurrent protection relay. The proposed method has the advantages compared with the fast Fourier transform method in signal processing. It can estimate the amplitude and phase angle of voltage and current signals accuracy after each updated sample. In addition, the proposed method is verified on the distribution network with/without distributed generation which is modeled on Matlab/Simulink software. The simulation results show that the proposed method accurately detect the direction at the relay when the fault occurs at different locations on the network.**

***Index Terms*—ADALINE, directional protection relay, distributed generator, smart grid**

I. INTRODUCTION

A reliable protection scheme is essential for both the consumers and producers in any distribution network. This will be especially true in the coming years when the power flow will change over the course of a day with the application of Distributed Generation (DG) and changing loads, like charging of electric cars and the demand response strategy towards end-users. The distribution network will evolve towards a so-called smart grid which applies a communication infrastructure next to the existing electrical infrastructure to increase the reliability of the system [1]-[4]. This communication infrastructure allows the use of substation automation systems and data exchange between the intelligent electronic device systems inside the protection scheme which could be used in advantage of the distribution system operation.

The DG units that are currently being installed inside the distribution network are preferably connected directly to the main-station via relatively long feeders. The protection scheme for these feeders is simple and straightforward with the help of overcurrent relays with additional directional relays [5], [6]. An overcurrent relay in a looped or networked system needs a directional element to determine fault direction and supervise the overcurrent element to provide more performance that is precise [5]. The directional overcurrent protection relays are used to protect interconnected power systems and looped distribution systems. The fault direction may be forward (between relay and grid), or reverse (between relay and source), the normal power flow being from source to the grid. Known directional overcurrent relays rely on a reference voltage phasor for estimating direction of the fault, requiring both current and voltage sensors [7].

There are many approaches being designed to determine the direction of the fault current flow in the system, among all the techniques Fast Fourier Transform (FFT) is the most common technique implemented [7]. FFT technique bases on digital sampling and uses phase estimation between the voltage and current for the forward or reverse flow direction of the fault current. However, FFT technique also has some drawback in determining the direction of the fault current, such as during the fault occurrence in the network, both voltage and current signal are badly distorted and the signal may contain harmonics as well as decaying of dc component, which cause the phase measurement error [7]. Moreover, FFT technique requires stored data accomplished by buffering the data which adds latency on delay in detection of the fault.

An adaptive linear neural network (ADALINE) is an adaptive filter which is used for extracting signals from noisy environments, in model identification, and in nonlinear linearization problems [8], [9]. So this paper proposes a novel algorithm of directional overcurrent protection relay based on ADALINE. The ADALINE is used to estimate phasor of the voltage and current. Then the phasor is used to determinate the fault direction when a fault occurs in the distribution network. The sections of this paper are arranged as follows: In Section II, a novel algorithm of directional overcurrent protection relay based on ADALINE is presented. Two case studies of a distribution network with/without DG are researched in Section III. The distribution networks in both cases are

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modeled in Matlab/Simulink. Finally, Section IV presents the conclusion in this paper.

II. Directional Overcurrent Protection Relay Based on ADALINE

A. Background of ADALINE

We assume that the discrete-time signal *y(k),* which represents the voltage and current signals at the relays in the distribution network only includes the fundamental frequency component as follows:

$$\begin{aligned} y(k) &= A\sin(2\pi fkT_s + \varphi) \\ &= A\cos\varphi\sin(2\pi fkT_s) + A\sin\varphi\cos(2\pi fkT_s) \end{aligned} \quad (1)$$

where A and φ are magnitude and phase angle of the fundamental frequency, k is sampling index, T_s is sampling interval.

ADALINE is an adaptive filter which is used for extracting signals from noisy environments, in model identification, and in nonlinear linearization problems [8]. It is a two-layered feed-forward neural network. There are N input units and a single output unit. The ADALINE is described as a combination circuit that accepts several inputs and produces one output. Its output is a linear combination of these inputs and its characteristics are: *on-line training based on the changing inputs and the target response, self-adaptive algorithm can be applied to weights training, simple structure makes it easily implemented on hardware.*

By using the ADALINE to extract the fundamental frequency component of voltage signal, (1) is arranged as follows:

$$y(k) = \mathbf{w}^T(k).\mathbf{x}(k) \quad (2)$$

with

$$\mathbf{w}(k) = \begin{bmatrix} A\cos\varphi \\ A\sin\varphi \end{bmatrix}, \quad \mathbf{x}(k) = \begin{bmatrix} \sin(2\pi fkT_s) \\ \cos(2\pi fkT_s) \end{bmatrix} \quad (3)$$

where ***w*** is weight vector and ***x*** is input signal vector.

The weight adaptation algorithm used to minimize error is Widrow-Hoff rule [8], [9], which has some advantages over other algorithms. This can be described as follows:

$$e(k) = y(k) - \mathbf{w}^T(k)\mathbf{x}(k) \quad (4)$$

$$\mathbf{w}(k+1) = \mathbf{w}(k) + 2\alpha e(k)\mathbf{x}(k) \quad (5)$$

where *e(k)* is the instantaneous error, α is the learning rate $(0<\alpha<1)$.

The magnitude and phase angle of the fundamental component can be readily calculated from the elements of the weight vector as follows:

$$A = \sqrt{\mathbf{w}(1)^2 + \mathbf{w}(2)^2} \quad (6)$$

$$\varphi = \tan^{-1}\left(\frac{\mathbf{w}(2)}{\mathbf{w}(1)}\right) \quad (7)$$

In this paper, the authors apply the ADALINE method which is described as above to estimate the magnitude and phase angle of the voltage and current signals at the relay. The estimation results are used for fault direction detection in the directional overcurrent protection relay. The ADALINE topology in this paper is shown in Fig. 1.

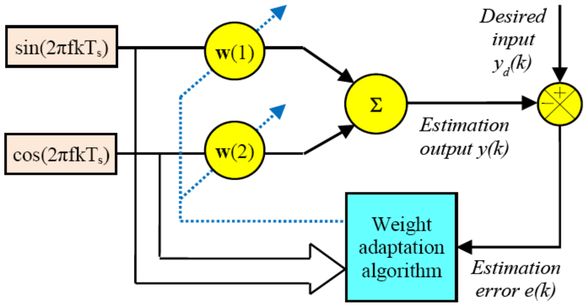


Figure 1. An adaptive linear neural network topology of the proposed method.

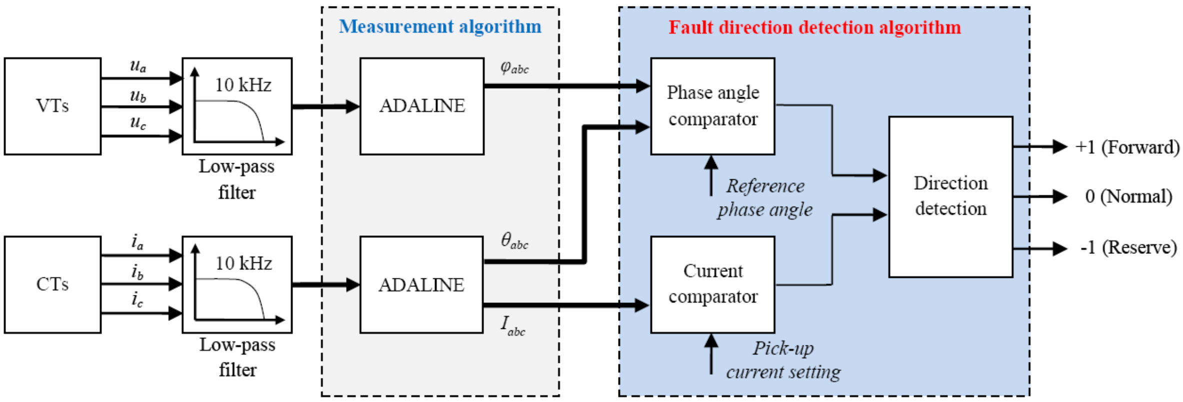


Figure 2. The proposed method of directional protection relay based on ADALINE.

B. The Proposed Method

The proposed method of directional overcurrent protection relay based on an adaptive linear neural network as shown in Fig. 2. The voltage and current signals from the Voltage Transformers (VTs) and Current Transformers (CTs) are passed through low-pass filters to eliminate higher frequency components unnecessary. Then, the voltage and current signals are passed through the linear adaptive neural network to estimate the magnitude and phase angle of each voltage and current signal of each phase. The results are considered as the input of the fault direction detection algorithm to determine the fault direction at the protection relay when a short circuit occurs in the distribution network. To do this, the algorithm detects the fault direction by using the comparators including current comparator and phase angle difference the current - voltage comparator to determine the exact direction at the relay. The proposed method has two major parts include the measurement part which is used the algorithm-based ADALINE method was described in Section II.A and the fault direction detection part which is used for detecting the fault direction at the relay as shown in Fig. 3.

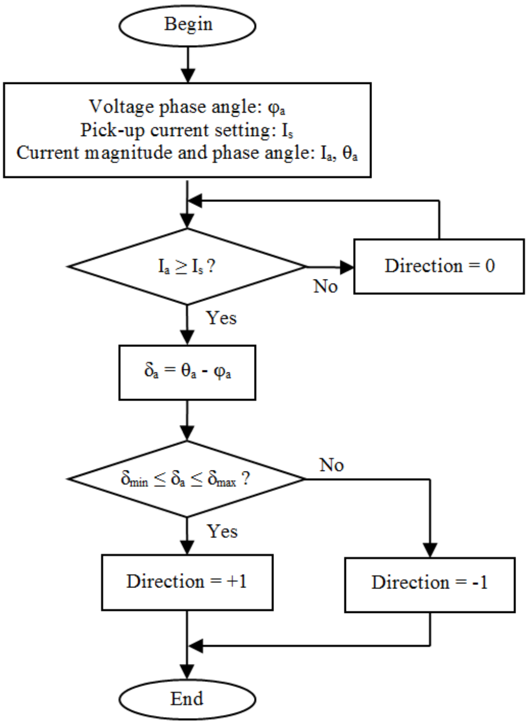


Figure 3. The algorithm of fault direction detection (only for phase a).

Fig. 3 shows the fault direction detection algorithm of the directional overcurrent protection relay based on the proposed method. The input of the algorithm include the pick-up current setting (I_s), the current amplitude (I_a), the current phase angle (θ_a) and voltage phase angle (φ_a) are estimated by ADALINE method. If the current magnitude (I_a) is smaller the pick-up current setting, there is no fault in the distribution network. So the fault direction is determined by 0 (*Direction*=0). If the current magnitude (I_a) is greater than the pick-up current setting, the algorithm will determine the deviation between current and voltage phase angle ($\delta_a=\theta_a-\varphi_a$) and compare the deviation angle (δ_a) with a range from δ_{min} to δ_{max}. If the angle is not in the range, the fault direction is determined to be the reserve direction (*Direction*=-1). Otherwise the direction are identified as forward direction (*Direction*=+1).

III. Case Studies

To evaluate the proposed method in Section II, this paper uses a distribution network diagram including a grid source and DG which supply for three loads through two feeders as shown in Fig. 4. The component parameters in the diagram are shown in Table I. The forward and reserve directions at the relays on the distribution network are shown in the solid and dash arrows, respectively. The network is simulated in Maltab/Simulink software. The sampling frequency of voltage and current signals at the relays is 128 samples per each cycle for the fundamental frequency 50Hz. Two case studies which are researched in this paper are presented in detail as follows:

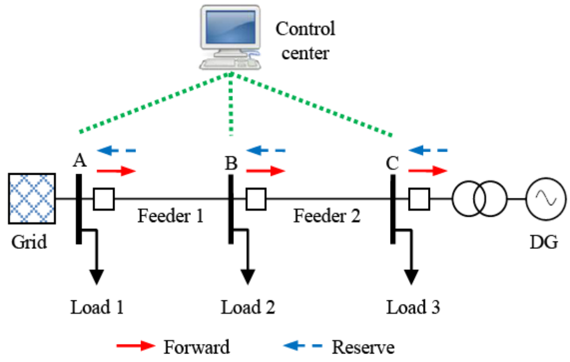


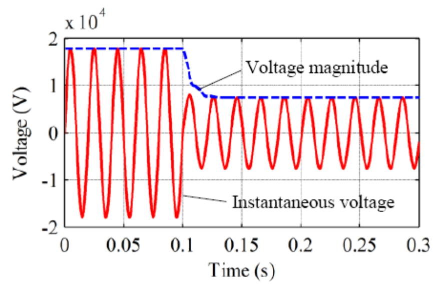
Figure 4. The one-line diagram of distribution network.

TABLE I. The Component Parameters in the Network

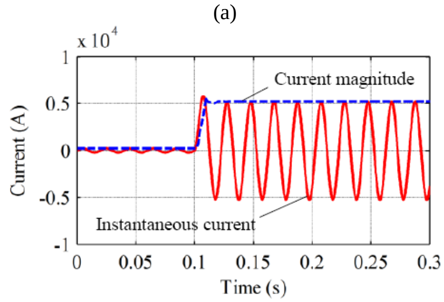
Component	Parameters
Grid	U_{Grid} = 22kV, f = 50Hz, X/R = 2 S_{Grid} = 250MVA (short-circuit power)
Feeder 1	AL XLPE 150: L = 12km r_0 = 0.205Ω/km, x_0 = 0.125Ω/km
Feeder 2	AL XLPE 150: L = 10km r_0 = 0.205Ω/km, x_0 = 0.125Ω/km
Loads	For each load: S = 2MVA, cosφ = 1
DG	S_{DG} = 2.7 MVA, X''_{DG} = 0.168 p.u R_{stator} = 0.0504 p.u, cosφ = 1

A. Case Study 1

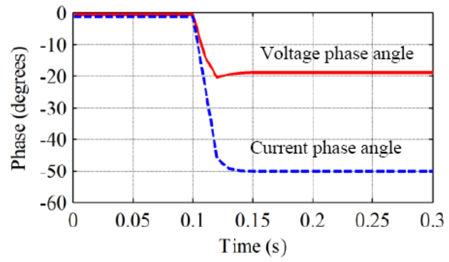
In this case, the distribution network is assumed that it is a radial network without DG. Therefore, the relays at location A, B, and C often use non-directional overcurrent protection relay to protect the network. However, in order to evaluate the proposed method and compare it to the distribution network with DG, the directional protection relays are applied at the relays A, B, and C to protect the network.



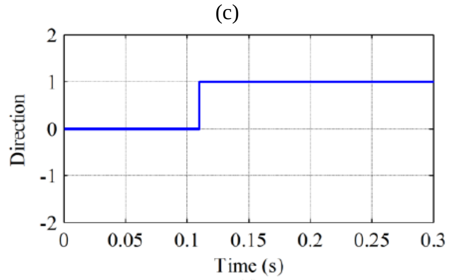
(a)



(b)



(c)

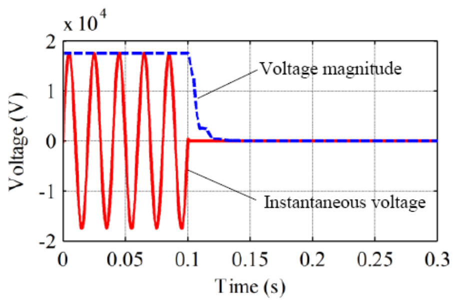


(d)

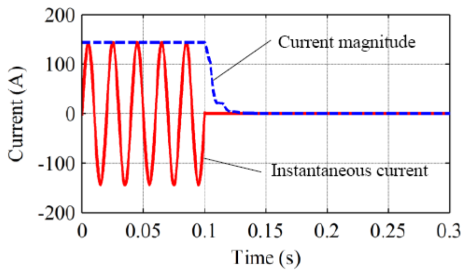
Figure 5. The simulation results at relay A when a fault occurs in feeder 1: (a) voltage signal and voltage magnitude estimation using ADALINE, (b) current signal and voltage magnitude estimation using ADALINE, (c) voltage and current phase angle using ADALINE, (d) fault direction.

Fig. 5 shows the analysis results of the voltage and current signals at the relay A by using the proposed method when a three-phase short circuit occurs in the feeder 1. Fig. 5(a) and Fig. 5(b) show the voltage and current signals at the relay A, respectively. The dash lines in the figures show voltage and current magnitude which are estimated by ADALINE. The results show that the voltage magnitude is decrease and the current magnitude is increase when the three-phase short circuit occurs in the feeder 1. Fig. 5(c) shows the phase angle of voltage and current which are estimated by ADALINE. The phase angles and the current magnitude shown in Fig. 5(b) are used to determine the fault direction at the relay A. The fault direction at the relay A is determined by the forward direction (+1) as shown in Fig. 5(d).

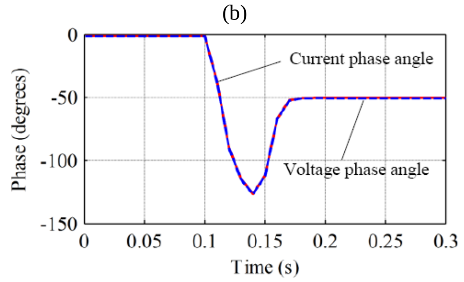
Whereas Fig. 6 shows the analysis results of the voltage and current signal at the relay B. Fig. 6(a) and Fig. 6(b) show the results of the phase a voltage and current signals at the relay B. Because the distribution network in this case is operated by the radial network method without DG, the three-phase short circuit occurs in the feeder 1, the voltage and current at the relay B and C reduced to zero value. The phase angles of the voltage and current in this case are almost similar as shown in Fig. 6(c). Finally the fault direction at the relay B is determined by the reserve direction as shown in Fig. 6(d).



(a)



(b)



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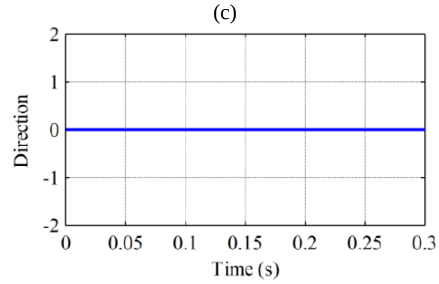

(d)

Figure 6. The simulation results at relay B when a fault occurs in feeder 1: (a) voltage signal and voltage magnitude estimation using ADALINE, (b) current signal and voltage magnitude estimation using ADALINE, (c) voltage and current phase angle using ADALINE, (d) fault direction.

The short circuit types including single-phase to ground, two-phase to ground, two-phase and three-phase short circuit in the feeders in the distribution network are also simulated in this paper. The fault direction results at the relay A, B, and C are determined by using the proposed method as shown in Table II. The results indicate that the fault direction information at the relays in the distribution network is necessary in the coordination between the protection relays in the network when a short circuit occurs.

TABLE II. THE RESULTS OF CASE STUDY 1

Event	**Relay A direction**	**Relay B direction**	**Relay C direction**
Normal	0	0	0
Fault in A-B	+1	0	0
Fault in B-C	+1	+1	0

B. Case Study 2

In this case, a DG is considered in the diagram as shown in Fig. 4. When DG is connected in the distribution network, it may change the power flow direction and the fault direction through the relays in the steady-state operation mode and the fault in the network. Assuming the three-phase short circuit occurs in the feeder 2, the simulation results for the proposed method at the relays B and C are shown as follows.

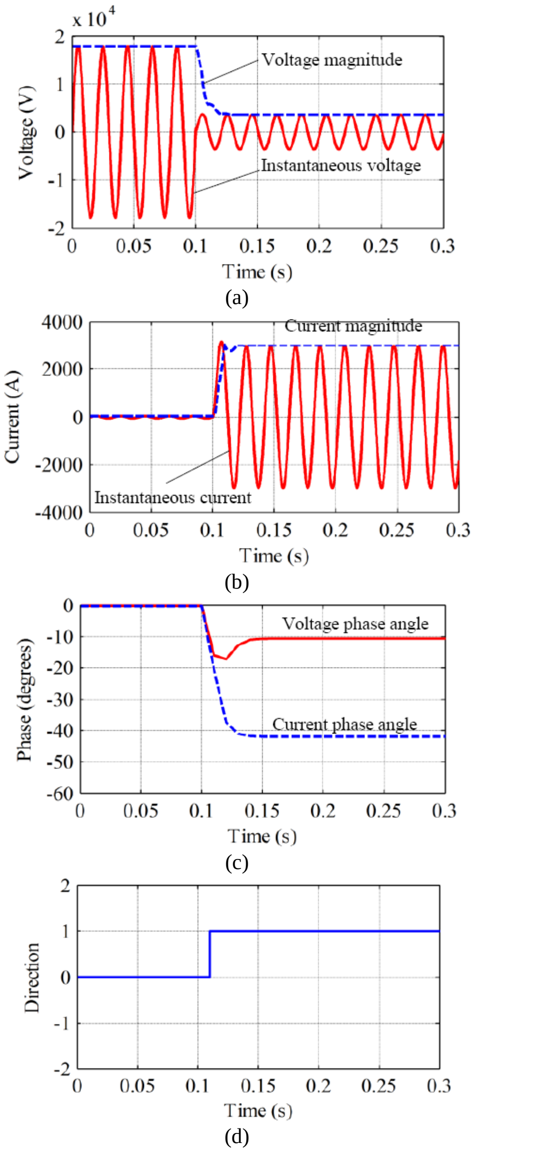

Figure 7. The simulation results at relay B when a fault occurs in feeder 2: (a) voltage signal and voltage magnitude estimation using ADALINE, (b) current signal and voltage magnitude estimation using ADALINE, (c) voltage and current phase angle using ADALINE, (d) fault direction.

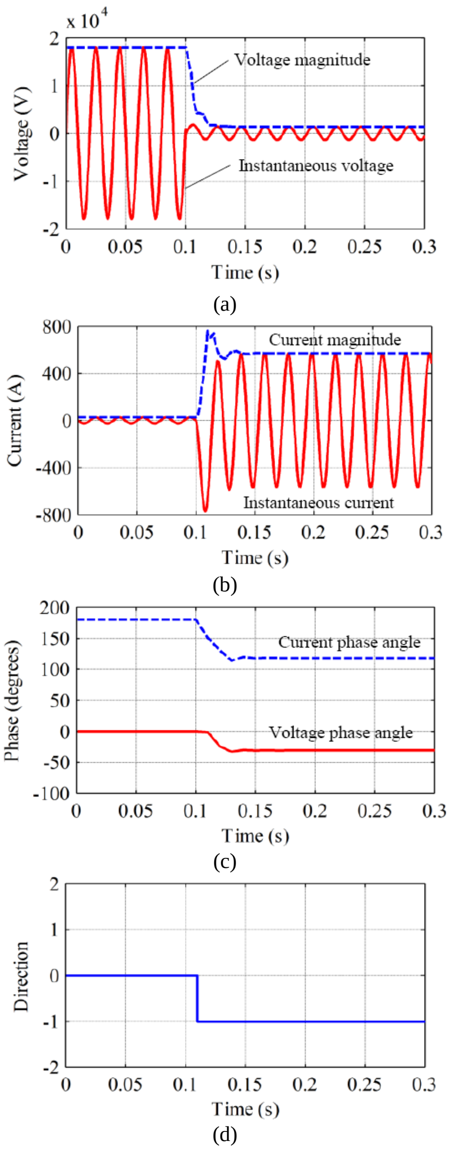

Figure 8. The simulation results at relay C when a fault occurs in feeder 2: (a) voltage signal and voltage magnitude estimation using ADALINE, (b) current signal and voltage magnitude estimation using ADALINE, (c) voltage and current phase angle using ADALINE, (d) fault direction.

Fig. 7 shows the analysis results of the phase a voltage and current signals at the relay B. Fig. 7(a) and Fig. 7(b) show the voltage and current signals at the relay B. The results show that the voltage magnitude is decreased and the current magnitude is increased. The phase angle of voltage and current at the relay B is changed as shown in Fig. 7(c). Finally the fault direction is determined by the forward direction (+1) as shown in Fig. 7(d).

In addition, the voltage and current signals at the relay C are analyzed in Fig. 8. Fig. 8(a) and Fig. 8(b) show the phase a voltage and current signals at the relay A. Since the DG is connected with the distribution network at the location C, the current flow through the relay C increases when the fault occurs in the feeder 2. This has made substantial changes to the phase angle of voltage and current as shown in Fig. 8(c). The phase angle deviation of the current - voltage and the current magnitude at the relay C, the fault direction is determined as the reverse direction (-1) as shown in Fig. 8(d).

Moreover, the short-circuit types in the feeder 1 and feeder 2 are simulated in this paper, the fault direction results at the relays on the network as shown in Table III. These results show that the proposed method for accurate results in detecting the fault direction.

TABLE III. THE RESULTS OF CASE STUDY 2

Event	Relay A direction	Relay B direction	Relay C direction
Normal	0	0	0
Fault in A-B	+1	-1	-1
Fault in B-C	+1	+1	-1

IV. CONCLUSION

This paper proposes a new algorithm of overcurrent directional protection relay in the distribution network with distributed generation based on ADALINE method. With the advantages of ADALINE, the magnitude and phase angle of voltage and current signals are evaluated after every updated sample. It has overcome the disadvantages of the FFT method which uses samples in a one cycle window to estimate the magnitude and phase angle of the voltage and current signals.

The research on the distribution network with/without DG which is modeled in Matlab/Simulink shows the effectiveness of the proposed method to detect the fault direction at the relay in the network. The fault direction information is necessary in the coordination between the protection relays on the distribution network especially the network with DG - smart grid trend in the near future.

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