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RESEARCH ARTICLE

Improved Differential Based Protection Scheme for Renewable Energy Based Microgrids With Low Communication Burden

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ABSTRACT Due to prevalence of distributed energy resources, especially inverter interfaced ones, conventional protection systems meet substantial challenges for fault detection. Differential protection is the most reliable protection method for current networks; however, the conventional method leads to high communication burden. We propose a new differential protection based on disturbance detection and positive phase angle differences. The disturbance detection method is proposed based on Mathematical Morphology which has high speed and accuracy. Instead of transmitting the instantaneous values or the phasor of the currents which impose high communication burden on the network, the phase angle of the current is the only data which is transmitted when a sudden change is detected. The proposed method reduces the communication burden significantly and increases the resiliency of the protection scheme. The effectiveness of the proposed method is verified in modified IEEE 9 bus 3 machine network with three distributed energy resources. PSCAD is used to simulate the microgrid and the proposed method is implemented in MATLAB. It is proved that this method works properly in both islanded and grid connected modes and despite significant changes in the grid. The robustness of method in presence of noise and its high reliability and dependability is verified through various simulation case studies.

INDEX TERMS Differential protection, microgrid, disturbance detection, mathematical morphology.

NOMENCLATURE

Indices/sets

A	Fundamental frequency amplitude.
B	DC offset amplitude.
$\boldsymbol{\theta}$	Current phase angle.
τ	Time constant.
ω	Fundamental frequency.
I	Phase current.
k	Center sample.
n	Sample number.
b_m	Structuring element.
SE	Structuring Element.
$\oplus$	Dilation operator.
$\ominus$	Erosion operator.
$\boldsymbol{\phi}$	Phase angle step based on sampling frequency.
m	Number of SEs.
D_n	Summation of dilation and Erosion.
ΔD	Disturbance detection criteria.
C	Counter.
M	Detection criteria threshold.
a	$-120^{\ominus}$
0, 1, 2	The sequence component values.
$\boldsymbol{V_m}, \boldsymbol{V_n}$	Voltages measured at both ends of the line.
$\boldsymbol{I_m}, \boldsymbol{I_n}$	Current measured at both ends of the line.
PAD	Phase angle difference.
$\boldsymbol{Z_m}, \boldsymbol{Z_n}$	Internal impedance of source at m and m.
$\boldsymbol{Z_l}$	Line impedance.
x	Per unit distance of line from source m.
$\boldsymbol{Z_f}$	Fault Impedance.
$\boldsymbol{I_f}$	Fault current.
$\boldsymbol{Z_{Tm}}, \boldsymbol{Z_{Tn}}$	Impedance seen by source m and n.
$\boldsymbol{\lambda}$	Determinant of the matrix.

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I. INTRODUCTION

Decarbonization motivates more utilization of renewable energies in power systems. Although, this transition will result in various environmental benefits, interconnection of these clean resources raises serious challenges for power systems. One of the salient challenges which has attracted lots of attentions is malfunction of power system classical protection system.

The majority of renewable energy resources are connected by inverters to distribution systems [1], [2], [3]. These new resources undermines some of the main premises of classical distribution systems, mainly the assumption of single source of energy and universal short circuit characteristics. In active distribution systems with high penetration of inverter-based resources (IBRs), the distribution grid is fed by multiple resources and these resources shows different current characteristics during faults [4]. In microgrids the protection challenges usually exacerbate since the short circuit current in grid-connected mode is much larger than islanded mode [5], [6]. Fault currents supplied by IBRs are limited to 1.2 to 2 p.u. which is low for overcurrent protection and the fault current's angle depends on the control strategy of the converter [7], [8]. In fact, one of the main challenges of microgrids is fault detection.

Various methods have been presented for fault detection in microgrids. High frequency feature extraction is used in [9] and [10]. In [11], [12], and [13], the proposed methods are based on sudden change detection algorithm. These methods are prone to failure in noisy conditions and normal switching events, if the threshold is not set properly. Some researchers proposed using active detection methods. An active detection method based on higher frequency injection by distributed energy resources (DERs) during faults is presented in [14]. In [15], harmonic injected by DERs is used for fault detection. Another active method which is based on differential protection is proposed in [16]. In this paper, inter-harmonics injected by IBRs are utilized as detection criteria. In [17], another active method based on harmonic injection is proposed. Intentional injection of disturbance to the network is the major challenge of active methods. Another algorithm is proposed in [18] which uses the rate of change of direct axis current for detection. Superimposed value based methods also attracted attentions in recent papers [19], [20], and [21]. In [19], the superimposed positive sequence power is used for detection and in [20] superimposed value of the reactive power is utilized. An overcurrent-based method and coordination strategy is presented in [21]. This method assumes that overcurrent directional overcurrent has accurate operation in microgrid which is not always a correct assumption in IBR based microgrids [1]. To find the correct direction of fault in microgrids, [22] proposes to use amplitude and angle of the negative sequence impedance.

Another type of methods which are of interest in IBR based microgrids are pilot protection methods. One of these methods presented in [23] uses the energy polarity for detection. This paper considers the increased range of the phase angle due to IBRs. In [24] a high frequency fault analysis based pilot algorithm is proposed for protection. Another method of this kind which uses the second order harmonic of the q axis current to separate internal faults from external one is presented in [25]. In [26], an impedance based pilot protection is proposed that considers the impact of IBRs. The current polarity comparison is another idea which is presented in [27] and [28].

Among all of the presented methods, differential based protection schemes are the most reliable ones. The principle of differential protection in microgrid is presented in [29]. The concerns about timing error of this method are addressed in [30] and [31]. Methods based on phase angle difference of superimposed complex power [32] and superimposed current difference [33] are proposed for fault detection. Another method that uses difference of impedance angle for detection is proposed in [34]. The deep neural network based method which is of interest these days is added to conventional differential protection to improve its accuracy in [35]. A novel method based on feature extraction by Mathematical Morphology and comparison of these features based on differential protection is presented in [36]. The main problem of these differential based methods is their communication burden and high costs.

In this paper, we propose an algorithm to decrease the communication burden of differential protection. In this method, the relays initiate to communicate after disturbance detection. The main advantage of this method is that it drops the communication burden of the network in normal conditions. Differential method based on instantaneous current presented in this paper is accurate and very fast in detection. The main contribution of this paper are as follows:

- Proposing a new differential protection based on sudden change detection and positive phase angle difference which reduces the communication burden significantly;
- Thorough examination of the proposed method in both islanded and grid-connected modes;
- Examining the performance of the method in response to high impedance faults, non-fault disturbances, and in presence of noise.;

Rest of the paper is organized as follows. In section II, the proposed protection scheme is presented which consisted of two subsections, disturbance detection and differential based protection. Simulation results are provided in section III. The performance of the proposed method in comparison to other famous microgrid protection schemes is discussed in section IV. And in last section, the conclusion is presented.

II. DIFFERENTIAL BASED PROTECTION ALGORITHM

A. DISTURBANCE DETECTION

It is widely accepted that a fault current is composed of sinusoidal waveform and decaying DC offset, ignoring harmonics. Then a fault current can be formulated as follows:

$$i(t) = A\cos(\omega t + \theta) + Be^{\lambda t} \tag{1}$$

where A and B are the amplitudes of fundamental frequency and DC offset and λ is time constant of the faulty line. In Equation (2), the discrete form of (1) is presented, where Δt is sampling time interval and k is sample number. The first order approximation of Taylor series for the DC component is presented in (3).

$$I(k) = A\cos(\omega.k\Delta t + \theta) + Be^{\lambda k\Delta t} \tag{2}$$

$$I(k) = A\cos(\omega.k\Delta t + \theta) + B(1 + \lambda k\Delta t) \tag{3}$$

If k-th sample is considered as the center sample, then we have:

$$I(k+n) = A\cos(\omega.(k+n)\Delta t + \theta) + B(1 + \lambda(k+n)\Delta t) \tag{4}$$

$$I(k-n) = A\cos(\omega.(k-n)\Delta t + \theta) + B(1 + \lambda(k-n)\Delta t) \tag{5}$$

$$I(k+n) + I(k-n) = 2I(k)\cos(\omega.n\Delta t) + 2B(1 + \lambda k\Delta t).(1 - \cos(\omega.n\Delta t)) \tag{6}$$

Due to high sampling frequency, Eq. (4) can be approximated as follows:

$$I(k+n) + I(k-n) \approx 2I(k)\cos(\omega.n\Delta t) \tag{7}$$

Immediately after fault occurrence, the current of faulty feeder meet a sudden change. Which means $I(k+n)$ will not be the same as $I(k-n)$. For fast detection of this change, Mathematical Morphology (MM) based method is utilized in this paper [37]. MM was previously proposed to be used in distance protection relays [38], [39] but it has never been used for sudden change detection of differential protection relays. Dilation and Erosion are the basic operators of MM presented in equation (8).

$$(I \oplus b)(k) = \max_{s}\{I(k-s)/b(s)\}$$
$$(I \ominus b)(k) = \min_{s}\{I(k+s)/b(s)\} \tag{8}$$

where $I(k)$ is the signal under process and b(s) is the Structuring Element (SE). A group of SEs is used for this work which is sinusoidal (9), as shown at the bottom of the next page.

where $*$ shows that sample is not involved in process which means, for instance, in b_1 and b_2 there are just 2 and 4 samples in the data window; m is the number of SEs and m-th SE has the length of (2m+1). The intermediate function, $D_n(k)$, is defined as (10).

Where I_m and I_n are the phasors of currents, measured at buses m and n respectively, and φ is the phase angle of the current.

$$D_n(k) = \frac{1}{2}(I \oplus b_n + I \ominus b_n) \tag{10}$$

The difference between $I(k)$ and $D_n(k)$ is estimated as follows:

$$\Delta I(k) = I(k) - \frac{D_1(k) + D_2(k)}{2} \tag{11}$$

$\Delta D(k)$, introduced in (12), is used to define Disturbance Detection (DD) criteria. If $\Delta D(k)$ is larger than a threshold value, M, for three consecutive samples, i.e. C defined in (13) is equal to 3, a disturbance is detected.

$$\Delta D(k) = |\Delta I(k+1) - \Delta I(k)| \tag{12}$$

$$C := \begin{cases} C+1 : \Delta D(k+1) > M \\ C-1 : \Delta D(k+1) \le M \text{ and } C \ge 1 \end{cases} \tag{13}$$

B. POSITIVE SEQUENCE PHASE ANGLE DIFFERENCE

In a line with no feeder taps, if a fault occurs inside the line, typically the phase angle of the positive sequence current calculated by only one of the relays of the line located at both ends will meet an almost 180' change. Consequently the phase angle difference PAD between those two relays will increase significantly [40]. Therefore, in this paper, phase angle difference of the positive sequence current is used for detection.

At first, the phasor of the currents, I_a, I_b and I_c, are captured by relays. The method used for phasor estimation is discrete Fourier transform (DFT) [41]. Then, the sequence analysis is done to extract the positive sequence current as formulated by Eq. (14).

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 1 & a & a^2 \\ 1 & a^2 & a \end{bmatrix}\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} \tag{14}$$

For this part, a two bus network is utilized with no feeder taps, shown in Figure 1. During the normal condition of the network when there is no fault in the line, currents measured on buses m and n are equal (15).

$$V_m - V_n = (Z_m + Z_n + Z_l)\, I_m$$
$$I_m = I_n = \frac{V_m - V_n}{Z_T}$$
$$\overset{Then}{\Longrightarrow} PAD = \varphi_m - \varphi_n = 0 \tag{15}$$

If a short circuit fault occurs inside the line which is the protection zone of the proposed relay, shown in figure 2, the current measured at bus n will meet a significant change in its phase angle, which is almost 180'. This fact is explained in the following.

As the fault current, I_f, is composed of I_m and I_n, the voltage measured at buses m and n will depend on the both end currents. The voltage of bus m can be calculated as follows:

$$V_f = Z_f I_f \;\&\; I_f = I_m - I_n$$

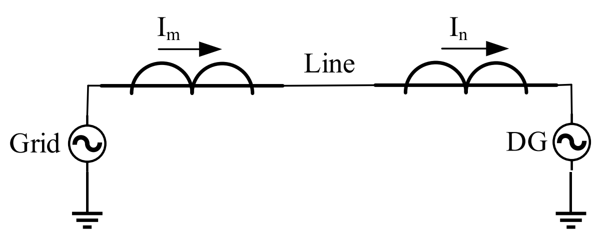

FIGURE 1. Single line diagram of the two bus network.

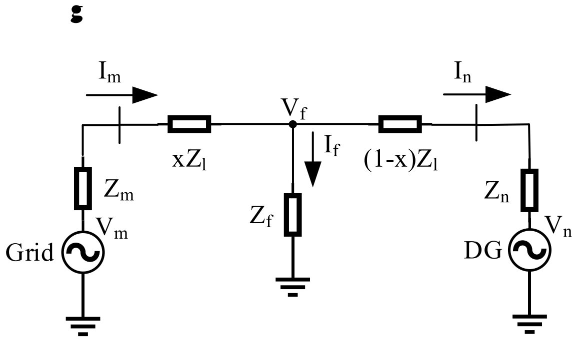

FIGURE 2. Diagram of the two bus network with a fault inside of the protection zone.

$$V_m = Z_m I_m + xZ_l I_m + V_f \quad (16)$$

$$\rightarrow V_m = Z_m I_m + xZ_l I_m + Z_f\,(I_m - I_n)$$
$$\rightarrow V_m = \left(Z_m + xZ_l + Z_f\right) I_m - Z_f I_n \quad (17)$$

where Z_f is the fault impedance and x is the fault distance from m. The same procedure is done for V_n:

$$\begin{cases} V_m = \left(Z_{Tm} + Z_f\right) I_m - Z_f I_n \\ V_n = +Z_f I_m - \left(Z_{Tn} + Z_f\right) I_n \end{cases}$$
$$Z_{Tm} = Z_m + xZ_l$$
$$Z_{Tn} = Z_n + (1-x)Z_l \quad (18)$$

Now we can use these equations to find I_m and I_n. To this aim, Cramer's rule can be used to find currents at both ends. λ is defined in (19) and the currents are extracted in (21).

$$\lambda = \left|\begin{bmatrix} Z_{Tm} + Z_f & -Z_f \\ +Z_f & -(Z_{Tn} + Z_f) \end{bmatrix}\right| \quad (19)$$

$$\begin{cases} I_m = \frac{1}{\lambda}\left[-\left(Z_{Tn} + Z_f\right) V_m + Z_f V_n\right] \\ I_n = \frac{1}{\lambda}\left[-Z_f V_m + \left(Z_{Tm} + Z_f\right) V_n\right] \end{cases} \quad (20)$$

$$\begin{cases} I_{m_1} = -\frac{1}{\lambda}\left(Z_{Tn} + Z_f\right) V_m,\ I_{n_1} = +\frac{1}{\lambda}(Z_f V_n) \\ I_{m_2} = -\frac{1}{\lambda}(Z_f V_m),\ I_{n_2} = +\frac{1}{\lambda}\left(Z_{Tm} + Z_f\right) V_n \end{cases} \quad (21)$$

Based on the derived equations which show the relations between currents and the voltages, the phasor diagrams of the currents can be drawn. As it can be seen in Eq. (21), I_m and I_n are composed of two components, each based on one sources at buses m and n. It is shown in Figure 3 that in internal faults PAD is roughly 180'.

When a short circuit fault out of the protection zone occurs, the amplitude of the currents will increase, but the difference of their phase angles will stay unchanged. This fault is represented in Figure 4. Using the Kirchhoff's voltage law for

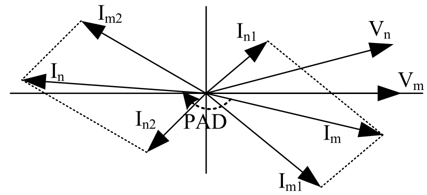

FIGURE 3. Phasor diagram of the currents for internal fault.

this fault too, the currents equations represented in (23) can be derived. Clearly, in an external fault, $I_n = I_m$. Then PAD for this type of fault is zero which is significantly smaller than an internal fault. Even If the fault happens behind bus m, the phase angle of both current will change 180, then the phase angle difference is still zero.

$$V_f = Z_f I_f \ \&\ I_f = I_m + I_{n'}$$
$$V_m = Z_m I_m + Z_l I_m + Z_{lf}(I_m + I_{n'}) + V_f \quad (22)$$
$$\rightarrow V_m = Z_m I_m + Z_l I_m + Z_{lf}\,(I_m + I_{n'}) + Z_f(I_m + I_{n'})$$
$$\rightarrow V_m = \left(Z_m + Z_l + Z_{lf} + Z_f\right) I_m + (Z_{lf} + Z_f) I_{n'} \quad (23)$$

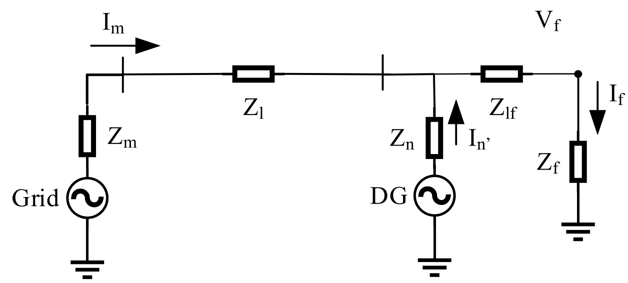

FIGURE 4. Diagram of the two bus network with a fault outside of the protection zone.

C. PROPOSED ALGORITHM

The flowchart of the proposed algorithm is represented in figure 5. The proposed protection scheme is combination of sudden change detection and positive sequence phase angle difference. The proposed protection algorithm is based on the line current measured at each end of the line. DFT is used to derive the phase estimation of measured current signal. The positive sequence current is extracted by the sequence analysis. Then, the relay at each end uses the proposed disturbance detection mechanism. The method described in Section II-A will be used to calculate C, the disturbance indicator. If C is greater than 3, i.e. the disturbance detection criterion is met for three consecutive samples, then a disturbance is detected. If disturbance is detected, the relays which have detected the disturbance start to send positive sequence angle to each

$$\begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_m \end{bmatrix} = \begin{bmatrix} * & \ldots & * & \cos\phi & \ldots & \cos\phi & * & \ldots & * \\ * & \ldots & \cos 2\phi & \cos\phi & \ldots & \cos\phi & \cos 2\phi & & * \\ & & & & \vdots & & & & \\ \cos m\phi & \ldots & \cos 2\phi & \cos\phi & * & \cos\phi & \cos 2\phi & \ldots & \cos m\phi \end{bmatrix} \quad (9)$$

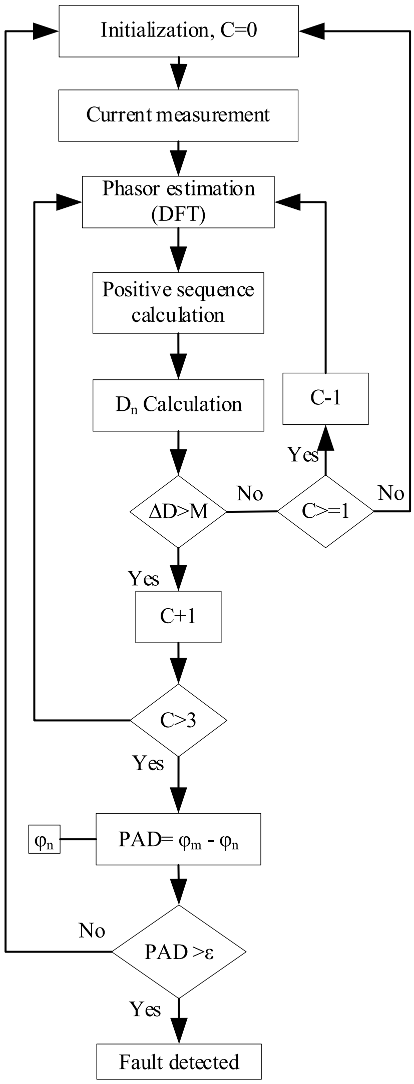

FIGURE 5. The flowchart of the proposed algorithm.

other. Disturbance detection in one of the relays is enough to enable both the relays to pass to the next stage. In the next stage, the relay uses the received positive phase angle from the other side and its own calculated value to find PAD and decides if the disturbance is internal or not.

The main advantage of the proposed method to classical differential relays is reduced communication. In classical differential relays, the instantaneous values or the phasor of the currents are sent continuously to the other relay which impose high communication burden to the network. In the proposed method, the measurements from one side of the line are sent to the other side only when a disturbance is detected. Restriction of the communication to the disturbance detection does not only decrease the communication burden, but adds complexity to the communication and hinders the cyberattacks. Disturbance detection only utilizes local measurement which reduces the surface for the cyberattack. In addition, the proposed protection scheme needs both local measurement (sudden detection) and communication (phase angle differential) to issue trip. The proposed protection mechanism can detect anomalies in the received phase angle from the other side using its local sudden detection function to avoid a false data injection attack.

Another strength of the proposed method is using phase angle measurement. In other words, the sent measurement over the communication channel is the phase angle of the positive sequence current, instead of instantaneous values of three phase current. It is shown that phase angle based differential relays provide a high reliability and selectivity as the major features of protection [29].

III. SIMULATION RESULTS

To investigate the performance of the proposed algorithm, a medium voltage microgrid system with a loop configuration, as shown in Fig. 6, is used as the system under the study. The parameters of the simulated microgrid is provided in Table 1. The studied microgrid provides an opportunity

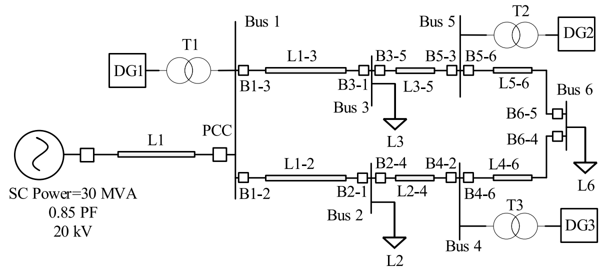

FIGURE 6. Modified IEEE 9 bus three machine network.

TABLE 1. Parameters of the simulated microgrid.

DG Parameters			
	DG1	DG2	DG3
Rated power (kW)	1000	1000	1000
Rated voltage (V)	260	260	260
Fundamental Frequency (Hz)	60	60	60
Step-up Transformer Parameters			
Rated power (kW)	1200	1200	1200
Rated Primary voltage (kV)	0.260	0.260	0.260
Rated secondary voltage (kV)	20	20	20
Winding configuration	D1Yg	D1Yg	D1Yg
Line Parameters			
Line Type	Overhead		
Positive sequence Parameters	Resistance (Ω/km)	Reactance (Ω/km)	Susceptance (µS/km)
	0.51	0.37	3.17
Zero sequence Parameters	Resistance (Ω/km)	Reactance (Ω/km)	Susceptance (µS/km)
	0.66	1.61	1.28
L1 = 2 km	L1-2 = 1 km	L2-4 = 0.6 km	L3-5 = 0.6 km
L4-6 = 0.4 km	L5-6 = 0.4 km		
Load Parameters			
	Active Power	Reactive Power	
Load 2 (kW)	700	100	
Load 3 (kW)	1300	400	
Load 6 (kW)	400	80	

to examine different aspects of proposed method via various scenarios. Nevertheless, the proposed technique can also be applied to any radial grids with numerous laterals as well.

Simulation results are presented in two subsections. The results for the proposed disturbance detection is reported in subsection A. In subsection B, the performance of the overall proposed algorithm is evaluated. Various cases are simulated to prove the accuracy of the proposed method.

A. DISTURBANCE DETECTION EVALUATION

Disturbance detection part of the algorithm must be very fast and sensitive. It must detect all types of the faults in the network including internal faults and external ones. Differential part of the algorithm for fault detection will not operate before disturbance detection. So, it is critical to have a very sensitive disturbance detection method. The sudden detection threshold is tuned for the worst-case scenario to ensure all faults are detected. The worst-case scenario occurs in the presence of a high-impedance fault and noisy conditions. By evaluating these worst-case conditions, including high-impedance faults and the lowest Signal-to-Noise Ratio (SNR) of 35dB, it was found that a threshold of 0.04 provides a good safety margin. Additionally, it is essential for the detection method to have correct performance for both islanding and grid connected modes of the microgrid. The results of different scenarios are presented in the following.

1) ISLANDED MODE

Islanded mode is the case when the microgrid is isolated from the utility by the PCC breaker, shown in Fig. 6.

As the first case study in islanded mode, a symmetrical three-phase fault (ABC) in L1-3 with 10 Ohm impedance is incepted at 1sec. The current and $\Delta D(k)$ during this fault seen by B1 is presented in Fig. 7. The detection criteria ($\Delta D(k)$) starts to rise immediately after fault inception and it crosses the threshold in 0.62 ms. So, three samples after fault are enough for C to detect the fault. It means that the disturbance is detected in 1.86 msec. This shows the ultra-high speed of

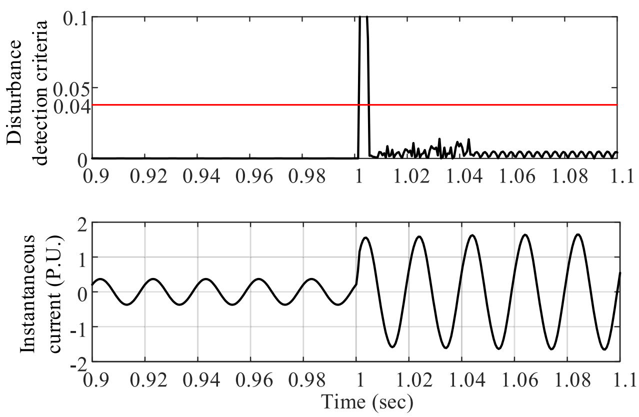

FIGURE 7. Fault current and disturbance detection criteria for 10 Ohm three phase fault on line 2A.

the method. It is worth to mention that the frequency of the network is 60 Hz and the sampling frequency is 1.2 kHz.

As the proposed disturbance detection method activates the relays for in-zone fault detection, the disturbance detection echanis must detect all of the types of the faults including high impedance ones. So, it is needed to increase its sensitivity which increases the risk of false activation on heavy load switching. However, these false activations will not result in any problem because the trip commend will be only issued after differential part of the algorithm detect an in-zone fault. Meanwhile, this high sensitivity ensures that all types of the high impedance faults will be detected. To evaluate the performance of the proposed method in such cases, a heavy load switching is incepted on Bus3. The switched load constitutes 40% of the total load connected to the same bus. As depicted in Fig. 8, detection criteria crosses the threshold in 0.62 ms, and activates the phase difference detection algorithm to decide whether it is fault. Another load switching constitutes 30% of the total load connected at the same bus is incepted to show that the method ignores the small switching and decreases the communication burden. It is shown in Fig. 9 that the criteria does not cross the threshold.

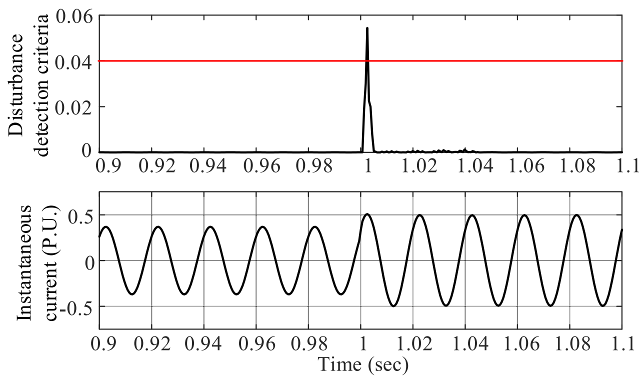

FIGURE 8. Current and disturbance detection criteria for 40% load switching on Bus A.

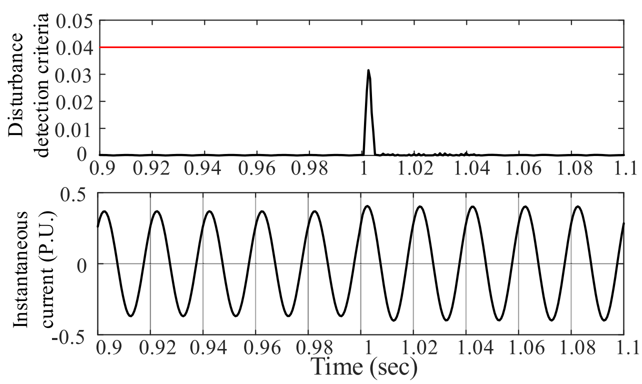

FIGURE 9. Current and disturbance detection criteria for 30% load switching on Bus A.

One of the issues with sudden change detection methods is related to the noise [9, 13, and 32]. However, in the proposed method, as there is no need for high sampling frequency, then the low sampling frequency which is 1.2 kHz serves as a low pass filter. Moreover, disturbances lead to high value of disturbance detection criteria and provides an acceptable margin between disturbance and noisy condition. To investigate the impact of noises further, a white noise signal is added to the current measurement of a single-phase-to-ground fault (AG) so that SNR becomes 40db. This fault is occurred in L1-3 by 50 Ohm impedance. This case can be considered as the worst case in the islanded mode of microgrid operation, because of a high impedance fault occurs in presence of noise. The results that prove the capability of the method is presented in Fig. 10. The proposed method correctly detects the disturbance in 2.5 ms. Although, the detection time is slightly increased compared to a similar but noise-less case, the proposed methods remains accurate and sufficiently fast.

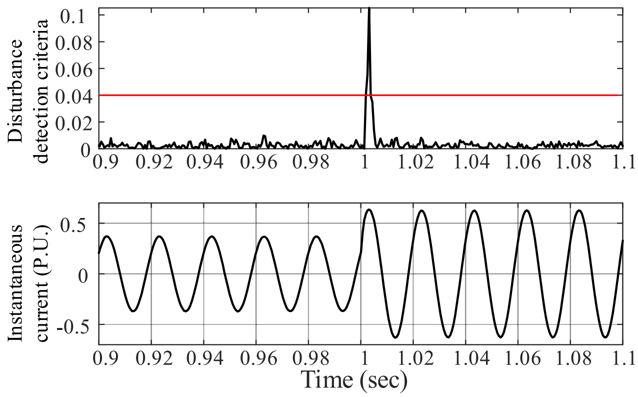

FIGURE 10. Disturbance detection criteria for 50 Ohm phase to ground fault disturbed by 40db noise on line 2A.

Another non-fault case which needs further investigation is generator disconnection. This case study is even more challenging when microgrid is operating in islanded mode and the relays are working in noisy conditions. To evaluate the performance of the proposed method for this case, it is designed that DG2 trips at t = 1 sec. It is shown in Fig. 11 that the current measured by relays at B1-3 and B3-1 is increased. It is due to the fact that DG1 will provide almost all of the power of the loads previously fed by DG2. Despite the high SNR ratio which is 35db, disturbance detection method successfully detects it and the phase-angle differential function correctly distinguish this case from a fault within its zone.

Various cases has been simulated to prove the correct performance of the method in presence of noises. Some of these cases are reported in Table 2. In this table, three different types of faults consisting of ABC, ABG and AG are presented with different fault impedances. Presence of noise and different fault inception times are considered in our studies.

TABLE 2. Simulation results for disturbance detection of various faults.

Disturbance Type	Inception Time (sec)	Fault Impedance (Ω)	Noise (45 dB)	Detection Time (sec)
AG	1	10	No	1.0018
AG	1	10	Yes	1.0024
AG	1.004	40	No	1.0058
AG	1.004	40	Yes	1.0058
ABG	1	10	No	1.0018
ABG	1	10	Yes	1.0018
ABG	1.004	40	No	1.0058
ABG	1.004	40	Yes	1.0058
ABC	1	10	No	1.0018
ABC	1	10	Yes	1.0018
ABC	1.004	40	No	1.0052
ABC	1.004	40	Yes	1.0052

2) GRID CONNECTED MODE

In this mode, simulated microgrid is connected to the grid through PCC breaker. In this mode, short circuit current ratio is high, consequently the conventional protection methods do not have problem in detection. In this sub-section it is shown that the presented method operate properly in this mode of microgrid as well.

High impedance faults are usually challenging to be detected since they cause a much smaller change in the current. However, the proposed method is capable of detecting that kind of fault as a disturbance. The presented method has a fast and accurate performance in such cases too. As can be seen in figure 12, a three phase fault with 100 impedance

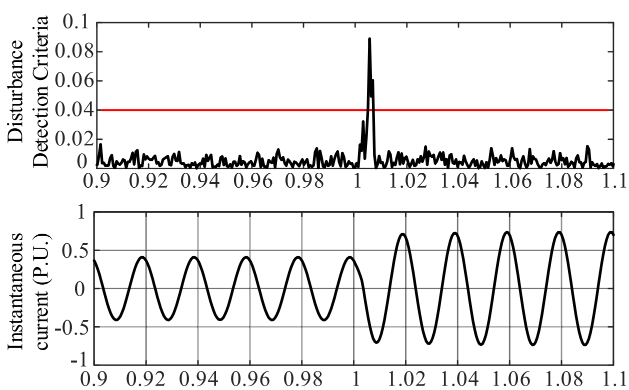

FIGURE 11. Disturbance detection criteria for DG2 disconnection by 35db noise measured at B1-3 and B3-1.

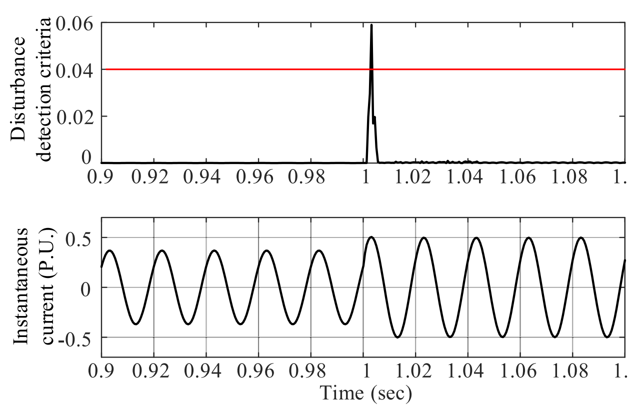

FIGURE 12. Fault current and disturbance detection criteria for 100 Ohm three phase fault on line 2A.

is detected 0.24 ms by the proposed method. The results for other cases including high impedance faults in noisy condition is presented in Table 3.

TABLE 3. Simulation results for disturbance detection of various faults.

Disturbance Type	Inception Time (sec)	Fault Impedance (Ω)	Noise (45 dB)	Detection Time (sec)
AG	1	10	No	1.0018
AG	1	10	Yes	1.0024
AG	1.004	50	No	1.0058
AG	1.004	50	Yes	1.0058
ABG	1	10	No	1.0018
ABG	1	10	Yes	1.0018
ABG	1.004	50	No	1.0058
ABG	1.004	50	Yes	1.0058
ABC	1	10	No	1.0018
ABC	1	10	Yes	1.0018
ABC	1.004	50	No	1.0052
ABC	1.004	50	Yes	1.0052
AG	1	100	Yes	1.0024
ABG	1	100	Yes	1.0024
ABC	1	100	Yes	1.0024
AG	1	100	Yes	1.0024

B. FAULT DETECTION BY PHASE ANGLE DIFFERENCE

Prior to disturbance detection, positive sequence phase angle are calculated locally. Immediately after disturbance detection, relays start to publish the calculated positive sequence phase angle together. During the internal fault, PAD will be a high value. But for external faults or other disturbances like, load switching or generator disconnection, PAD will not meet a significant increase. The proposed method can successfully detect the faulty conditions which cover the reliability feature of the method. The utilized method ignores the external faults and switching conditions that shows the selectivity of the method The threshold for distinguishing the faults within the protection zone and other disturbances is tuned to be 90° as the previous studies showed this threshold provides a very high security and dependability for the protective relay even in high-impedance faults or presence of noise or poor data synchronization [29]. In Table 4, results of the proposed algorithm for different cases are reported.

The phase-angle based differential protection also praised for their robustness against communication delays and data synchronization issues. A feeder in a distribution network is often no more than 15 km long. It is reasonable to ignore the electromagnetic wave's travel time along such short lines. Therefore, each terminal's fault instant (also known as the fault inception time) could be considered to be the same instant when a fault occurs on a feeder [29].

In this section, it is proved that the proposed protection algorithm has proper operation for all types of the fault in different operation modes of the microgrid. High impedance faults in islanded mode and noisy conditions as one the most challenging cases tested by this method, and shown that the method is sensitive, fast, selective and secure in these cases.

TABLE 4. Simulation results for fault detection using the proposed algorithm.

Disturbance Type	Inception Time (sec)	Fault Impedance (Ω)	Noise (45 dB)	Detection Time (sec)
AG	1	10	No	1.0024
AG	1	10	Yes	1.0024
AG	1.004	40	No	1.0024
AG	1.004	40	Yes	1.003
ABG	1	10	No	1.0024
ABG	1	10	Yes	1.0024
ABG	1.004	40	No	1.0024
ABG	1.004	40	Yes	1.0024
ABC	1	10	No	1.0024
ABC	1	10	Yes	1.003
ABC	1.004	40	No	1.003
ABC	1.004	40	Yes	1.003
Load Switching	1	Non Faulty	No	Not Detected
Load Switching	1.004	Non Faulty	No	Not Detected
Load Switching	1	Non Faulty	Yes	Not Detected
DG2 Disconnection	1	Non Faulty	No	Not Detected
DG2 Disconnection	1	Non Faulty	Yes	Not Detected

IV. DISCUSSION: COMPARISON WITH ESTABLISHED MICROGRID PROTECTION SCHEMES

The proposed differential protection scheme with a MM-based sudden change detection is still a differential relay and owns the main features and advantages of differential relays including fast detection, high accuracy, independence of grid topology and operation mode (islanding vs. grid-connected), accurate performance in presence of inverter-based resources, and robustness against noises. However, the proposed differential protection scheme provides some of the benefits which are not usual for classical differential relays, particularly the low communication burden. This is the key advantage of this method in comparison to the well-known differential methods like [11], [12], [13], [14], [15], [29], [30], [31], [32], [33], [34] and [35].

The proposed method shows superiority to active protection methods from power quality and cost perspectives. Active protection methods have high accuracy for microgrid protection [14], [15]. They also have high speed as they are also based on differential method. Yet, they need to inject intentional disturbances which decreases the power quality of the network and their price is much more than classical differential ones. Our proposed method shows similarly high level of accuracy and high speed, as it was shown in the previous section, but it does not actively perturb the power system. In addition, its lower communication burden reduces its cost even in comparison to classical differential relays.

The proposed method outperforms overcurrent based methods, another popular type of protection for microgrids. As the pickup current of these methods must be low, due to the restricted short circuit contribution of the inverter-based generation, the overcurrent-based protections are famously prone to mal-operation if a considerable generation disconnection occurs. The situation may exacerbate in a noisy condition. In Fig 10 and Fig 11, it is shown that the current increment is almost same for a high-impedance fault of 50 Ω and the non-fault disturbance of DG2 disconnection. The overcurrent-based methods including [18], [19], [20], and [21] cannot distinguish such a DG disconnection as a non-faulty condition from a high impedance fault. However, as shown in the previous section, our proposed method can correctly and accurately perform in such scenarios.

V. CONCLUSION

A new differential protection based scheme is proposed in this paper which can effectively work in presence of inverter interfaced distributed energies while reduces the burden on communication channels significantly. In this method communication link in line differential relays are activated after disturbance detection which decreases communication burden significantly. Several simulation cases on IEEE 9-bus 3-machine network in islanded mode and grid connected mode are used to prove the efficacy of the proposed method. It was shown that the proposed method can work properly even in noisy conditions or high-impedance faults.

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