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Fault detection and location in a microgrid using mathematical morphology and recursive least square methods

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ABSTRACT

The concept of microgrids has been proposed as an economical, reliable, and efficient way to integrate a large number of distributed energy resources (DERs) into distribution networks. To ensure the safe operation of a microgrid fast and accurate fault detection and location are crucial. This paper proposes fault detection and location in a microgrid using mathematical morphology (MM) and recursive least-square (RLS) methods. The proposed method first applies dilation and erosion median filter (DEMF) on a current signal to detect and classify the faults in microgrids. Then, the RLS method estimates the fault location using a differential equation derived from an equivalent model of the microgrid. The performance of the proposed method is evaluated on a medium voltage microgrid test system through simulations using MATLAB/SIMULINK. The simulation results depict that the proposed method provides faster fault detection and accurate fault location.

1. Introduction

The increased integration of distributed energy resources (DERs) into conventional distribution networks encourages the formation of microgrids. A microgrid is a sustainable small-scale electric distribution system that comprises several DERs, energy storage systems, and controllable loads [1,2]. The operation mode of a microgrid can either be grid-connected or islanded. A microgrid provides enhanced power quality, reliability, and stability of distribution networks [3,4]. Nevertheless, there are protection and control issues associated with the integration and operation of microgrids.

Fast and accurate fault detection and location together with a protection mechanism are required for a safe and secured microgrid operation. It is also required to shorten the time of line inspection, reduce the outage time and economic loss, and improve the reliability of distribution networks. However, microgrid causes a significant operational changes in power distribution networks, such as bidirectional power flow, reduced fault current level during islanded mode, and looped feeder, which has a direct impact on fault detection and location in microgrids [5–7].

Several methods have been proposed in the literature for fault detection and location in electric power distribution networks [8–11]. In [12], a combination of wavelet singular entropy and fuzzy logic were used for fault detection and classification in distribution lines in the presence of DERs. The method did not consider high-impedance faults and looped structure of microgrids. In [13], the statistical cross-alienation coefficients of measured current signals were used for fault detection and classification. The authors did not check the effectiveness of their method for islanding mode of operation and looped structure of microgrids. Fault location based on impedance method for distribution networks in the presence of DERs proposed in [14–18]. In [19], the concept of minimum fault reactance combined with the Fibonacci search method was used for fault location in distribution networks with multiple DERs. The method was sensitive to load data errors. A wide-area high-frequency impedance comparison based fault location method for systems with DERs proposed in [20]. The faulty section was identified by using only the high-frequency comparison of the IEDs impedance estimation results, which does not require the exact system parameters. In [21], the effect of DERs and external measurement errors on the performance of voltage sag based fault location was investigated. In [22], fault detection and location were achieved by phasor measurement unit (PMU)-based state estimation. Since this method was based on state estimation, the presence of DERs did not affect the accuracy of fault location. The authors of [23] propose a fault location method based on an iterative load flow algorithm by considering the synchronization angle as an unknown variable to be estimated. The method did not check the performance for islanding mode of operation and looped configuration of the microgrid.

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This paper proposes fault detection and location in a microgrid using mathematical morphology (MM) and recursive least-square (RLS) methods. MM is used to detect and classify the fault in a microgrid. The features of the fault current waveform captured by using MM operator and compare it with the threshold for fault detection and classification. Then fault location is estimated by applying the RLS method. The RLS method works directly on voltages and currents samples acquired at one-terminal of the medium voltage (MV) distribution line segment. Several simulations have been performed in MATLAB/SIMULINK for different types of shunt faults in radial and looped topologies of microgrids for both grid-connected and islanded modes. These simulation results show that the proposed method improves the fault detection and location process in a microgrid.

The remainder of the paper is structured as follows: Section 2 presents the background of MM; Section 3 discusses the proposed method; Section 4 is dedicated to simulation results; and finally, the paper is concluded in Section 5.

2. Overview of mathematical morphology

Mathematical morphology is a tool used for the analysis of spatial structures based on set theory, integral geometry, and lattice algebra [24]. It is based on the shape of a time-domain waveform rather than that of a frequency-domain waveform. MM has processed signals by using structuring element (SE). The SE is a signal processing function used for the extraction of relevant features in the signal.

Erosions and dilations are the most elementary operators in MM. The erosion and dilation of a signal *f(k)* by an SE *g(k)* are defined as follows [25]:

$$Y_{erode} = (f\Theta g)(k) = \min_s\left\{\frac{f(k+s)}{g(s)}\right\} \tag{1}$$

$$Y_{dilate} = (f\oplus g)(k) = \max_s\left\{\frac{f(k-s)}{g(s)}\right\} \tag{2}$$

From elementary operators, more operations can be designed, for example, opening, closing, and dilation and erosion median filter (*DEMF*). The opening operator is the dilation of erosion given by $(f\circ g)(k)$ and the closing operator is the erosion of dilation given by $(f\bullet g)(k)$.

$$Y_{open} = (f\circ g)(k) = Y_{erode}\oplus g(s) = (f\Theta g)(k)\oplus g(s) \tag{3}$$

$$Y_{close} = (f\bullet g)(k) = Y_{dilate}\Theta g(s) = (f\oplus g)(k)\Theta g(s) \tag{4}$$

The dilation and erosion median filter (*DEMF*) is the average of dilation and erosion. It can be used to extract the transient features of the signal defined as.

$$DEMF(k) = \frac{1}{2}(f\oplus g + f\Theta g)(k) \tag{5}$$

The major advantages of MM for fault detection and classification include faster fault detection, accurate fault classification, simple calculations, higher reliability and robust performance [26–28].

3. Proposed method for fault detection and location

The proposed method is applied to detect, classify, and locate faults in a microgrid by using the one-terminal voltage and current data, measured at each distribution line of the microgrid. The measured currents and voltages are first filtered by a low-pass Butterworth filter to remove higher order harmonics. Then, an analog-to-digital converter (ADC) with a sampling frequency of 3840 Hz is used to convert the analog signal to a digital signal. The subsequent subsections explain the proposed method in details.

3.1. Fault detection

The occurrence of a fault on an MV distribution line causes transient disturbances in the current and voltage waveforms. To detect the fault transients, the MM method uses morphological operators, which are developed according to the shape of the analyzed signal. Sinusoidal characteristics of voltage and current can be considered by using a group of SEs (g) as

$$g = \begin{bmatrix} * & \cdots & * & \cos\phi & * & \cos\phi & * & \cdots & * \\ * & \cdots & \cos2\phi & \cos\phi & * & \cos\phi & \cos2\phi & \cdots & * \\ & & & & \vdots & & & & \\ \cos m\phi & \cdots & \cos2\phi & \cos\phi & * & \cos\phi & \cos2\phi & \cdots & \cos m\phi \end{bmatrix} \tag{6}$$

where "$*$" means that the corresponding sample of the analyzed signal is not involved in MM operations, $\phi = 2\pi f\Delta t$, f is fundamental frequency, and Δt is the sampling time interval. The dilation and erosion operators for a fault current, with signal I_f and SE g_n are given by.

$$(I_f\oplus g_n)(k) = \max_s\left\{\frac{I_f(k-s)}{g_n(s)}\right\} \tag{7}$$

$$(I_f\Theta g_n)(k) = \min_s\left\{\frac{I_f(k+s)}{g_n(s)}\right\} \tag{8}$$

$1\leqslant n\leqslant m$

The dilation and erosion median filter, $DEMF_n$ *(k)*, and ΔI_f *(k)*, which is the difference between I_f *(k)* and $DEMF_n$ (n = 1, 2, …, m), are defined as

$$DEMF_n(k) = \frac{1}{2}(I_f\oplus g_n + I_f\Theta g_n) \tag{9}$$

$$\Delta I_f(k) = I_f(k) - \frac{DEMF_1(k) + DEMF_2(k) + \ldots + DEMF_m(k)}{m} \tag{10}$$

An MM fault detector ($\Delta DEMF_n$ *(k)*) is developed based on ΔI_f *(k)*, and it is defined as

$$\Delta DEMF_n(k) = |\Delta I_f(k+1) - \Delta I_f(k)| \tag{11}$$

An MM fault detector ($\Delta DEMF$ *(k)*) is compared for each sample with the fault detection threshold (*M*), which depends on the current flow through the distribution line. *M* is set to 125% of the pre-fault current. The *counter* is initialized and increased by 1for following samples if $\Delta DEMF(k) > M$. In contrast, if $\Delta DEMF\ (k+1) \leq M$ and *counter* ≥ 1, then the counter is reduced by 1. The *counter* is compared with a threshold C_{set} for any phase current to confirm the fault detection. C_{set} is given depending on the sampling frequency. This process is applied simultaneously for all phase currents.

3.2. Fault classification

For fast fault location in microgrid accurate fault classification is very important. Fault type and faulty phases are identified by using phase and zero-sequence currents. If the zero-sequence current MM fault detector ($\Delta DEMF_0$ *(k)*) exceeds the morphological fault detector threshold (*M*), then the fault is classified as grounded fault such as a single line to ground (SLG) or double line to ground (DLG) faults; otherwise, the fault is classified as a ungrounded fault, such as a line to line (LL) or three phase (LLL) faults. The phase currents are used to determine the type of fault and the faulty phases are determined by comparing each of the phase currents with the fault detector threshold (*M*).

The flowchart in Fig. 1 shows the fault detection and classification process. In the first step of the proposed scheme the counter is initialized for each phase. The phase currents are obtained from the terminal of the MV distribution line. Then the zero sequence current and the change of dilation and erosion median filter (*ΔDEMF*) are