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IMPROVED SYMMETRICAL FAULT DETECTION SCHEME DURING POWER SWING

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Summary

Relays may not perform as intended occasionally due to many complex reasons, which may result in relay misoperation. This paper provides a fast detection scheme for symmetrical fault during power swing based on travelling wave theory and wavelet transform. The implementation of the proposed method is discussed in detail, which covers implementation framework, data requirements, selection of mother wavelet, and fault detection criteria. The simulation cases are studied by using IEEE reference model implemented using Alternative Transient Program (ATP) and the test results are presented in this paper. This proposed method can be used for distance relay operation blocking or monitoring.

Keywords

Wavelet transform, fault detection, travelling wave, power swing, relay misoperation

1. Introduction

Power swing is a phenomenon resulting in large fluctuations of power between two areas of a power system. It is referred as the variation of power flow, which often occurs with the pole slipping in synchronous generators. There are many causes that may result in the power swing, such as transmission line faults, loss of generator units, or switching heavy loaded transmission lines. The occurrence of power swings is very difficult to predict [1]-[5]. When power swing takes place, the apparent impedance measured by a distance relay may move away from the normal load area and into one or more of the distance relay operating characteristics. This may cause unintended trips [6]-[8].

The traditional and popular method to solve the above problem is to block the distance relay operation during the power swing [9], which is based on timing the movement of the measured impedance through the operation zone of the distance protection. The impedance rate of change is slower under power swing conditions then under regular faults. If a fault occurs during the power swing, the distance relay should be able to detect the fault and operate correctly. In that case it is necessary to unblock the relay during power swing. The procedure is easy to implement for unsymmetrical faults, since the negative and zero sequence components do not exist during power swing, which can be used as fault detection criterion. However, it is much more difficult to identify symmetrical fault during stable power swing, which may delay the operation of the relay [10].

Many schemes using different methods have been proposed to solve this problem. Mechraoui and Thomas [3, 4] present the method to discriminate fault from power swing by monitoring the voltage phase angle at the relay location and considering the changing frequency in their formulation. They did not consider the symmetrical fault in their case studies. Benmouyal et al. [11] present a fault detector based on tracking the power swing center voltage (SCV) by comparing the rate of change of SCV with a threshold value.

Choosing the appropriate thresholds is still very difficult to implement, which may require offline system stability study to determine the rate of change of SCV. Brahma [12] introduced the use of wavelet transform (WT) to detect the symmetrical fault, which is proved to be quick and reliable. But it needs the sampling rate of 40.96 kHz to satisfy the cases studied.
Pang and Kezunovic [7, 8] introduced a fast detection scheme for symmetrical fault during power swing based on extracting the high frequency component energy of forward and backward travelling waves induced by faults. This paper extends this study by implementing the proposed method and proposed criteria functions.

2. Fault Detection based on Travelling Wave Theory and Wavelet Transform Analysis

A. Power Swing Behaviour

Power swing is a variation in power flow which occurs when generator rotor angles are advancing or retracting relative to each other. It is possible for one generator, or group of generators that terminal voltage angles (or phases) go past 180 degrees with respect to the rest of the connected power system, which is known as pole slipping. The power swing is considered stable if pole slipping does not happen and system remains stable and returns to a new equilibrium state. [13]. However, large power swings, no matter whether they are stable or unstable, will cause large fluctuations of voltages and currents, which may lead to relay misoperations.
The system frequency during power swing only varies over the range around the nominal frequency, which can be as high as 4-7 Hz [11]. The occurrence of fault, on the contrary, will generate transient signals in the waveforms of currents and voltages. The type and degree of existences of transient signals are largely determined by the fault location, fault duration, and system pre-fault conditions. Based on the difference in frequency behavior, it is feasible to detect the symmetrical fault during power swing by extracting the high frequency components from the voltage and current waveform. Thus a fast detection method for symmetrical faults is presented by using wavelet analysis to extract the high frequency components from the fault-induced voltage and current travelling waves propagating along transmission line. In this section, the fundamental theory is presented. The detailed definition and discusses can be found in [8].

B. Travelling Wave Theory during Fault

When a fault occurs in power system, the voltage and current signals could be decomposed into two parts: the pre-fault steady-state component and the fault injected component, or often called superimposed component. The superimposed component can be expressed in terms of travelling waves, including forward travelling wave and backward travelling wave, as shown in Figure 1. When fault occurs, the travelling wave will propagate along the line. The wave propagation can be recorded. The forward and backward travelling waves can be calculated easily and fast. The detailed discussion can be found in [8].

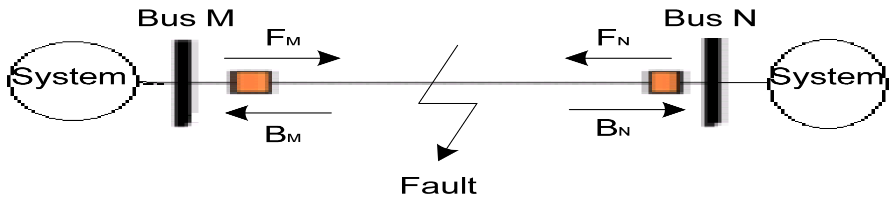

Fig. 1. Diagram for single phase transmission line

C. Wavelet Transform Analysis

Wavelet transform (WT) is a relatively new and efficient signal processing tool. The performance of Wavelet transform highly depends on the selection of the mother wavelet. The different mother wavelets will affect the performance of Wavelet-based methods.

Selecting the appropriate mother wavelet is very important to implement the wavelet analysis.
Power swing is mostly the phenomena of low frequency oscillation. The fault voltage or current contains high frequency transient signals. The multi-resolution analysis (MRA) is the best tool for decomposing the signal at the expected levels, by which the fault-derived signals can be represented in terms of wavelets and scaling functions. Thus, we can easily extract the desired information from the input signals into different frequency bands related to the same time period. Figure 2 shows the procedure of two-scale decomposition using the MRA.

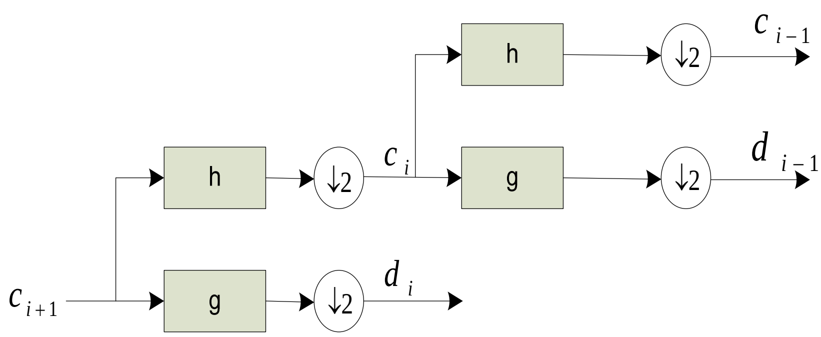

Fig. 2. Diagram of MRA decomposition into two scales

3. Implementation of the Detection Method

A. Implementation Framework

The diagram of proposed symmetrical fault detection method based on travelling wave technique and wavelet transform is conceptually shown in Figure 3.

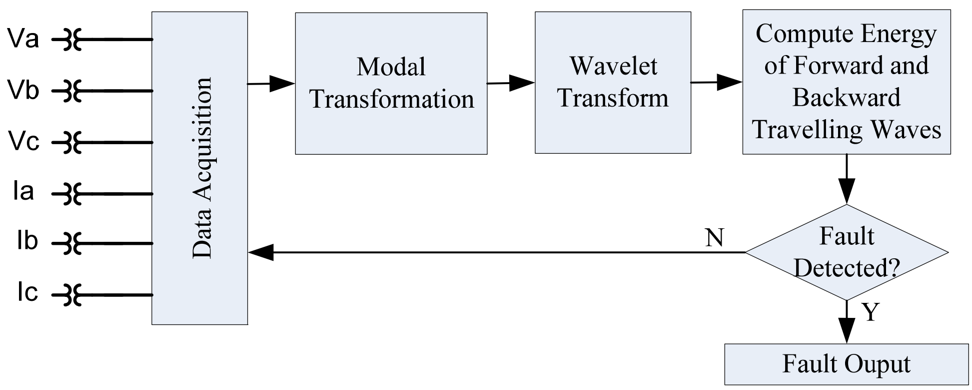

Fig. 3. Implementation diagram of symmetrical fault detection during power swing

B. Data Requirements

The proposed symmetrical fault detection during power swing requires data acquisition for all three phase voltages and currents. Those data can be obtained directly from measurement units of advanced digital relays. Most wavelet transform based methods require high frequency sampling rate. The detection method proposed can be used in a wide range of sampling rates. The sampling rate can be as low as 10 kHz, which is used by most existing advanced digital relays.

C. Selection of Mother Wavelet

Selecting the appropriate mother wavelet is very important to implement the wavelet analysis. When wavelet analysis is used to detect transient disturbances, the mother wavelet shape should be close to the shape of the detected disturbance in order to reach the higher efficiency. In the proposed method, an orthogonal wavelet should be adopted to satisfy energy conservation of the Parseval’s Theorem. Among those mother wavelets, Daubechies wavelet family is one of the most suitable orthogonal wavelets in multi-resolution analysis due to their powerful performance. Different Daubechies wavelets have different filter lengths, which determine the performances of Daubechies wavelet family. The longer the length of the wavelet the higher the computation burden of the filter. The smoother the wavelet waveform in the time domain the better the localization capability in the frequency domain. Based on these considerations, multi-resolution analysis based on Daubechies-8 (Db8) wavelet was selected. Db8 wavelet is compactly represented in time, and this is advantageous for the short and fast transient analysis due to its better localization performance in frequency. It is relatively easy to localize and detect the fault part under power swing by extracting features of transients in the wavelet domain.

D. Fault Detection Criteria

In order to quantify the high frequency component, the wavelet energy spectrum is used to calculate the transient energy in different frequency bands. From Parseval's Theorem, the energy of the analyzed signal can be represented by the energy in each expansion components and their wavelet coefficients if the used scaling function and wavelets form an orthogonal set, which can be shown as [14]:

$$\int \left| f(t) \right|^2 dt = \sum_{k \in Z} | c_{J,k} |^2 + \sum_{j=1}^{J} E_j \qquad (1)$$

where $E_j = \sum_{k \in Z} \left| d_{j,k} \right|^2$ is the norm value or the energy of the signal component at j level after wavelet transform is applied.

The criterion for the symmetrical fault detection is defined as:

$$k_e = \frac{E_f}{E_b} \qquad (2)$$

where E_f and E_b are the energy of the d1 wavelet component for the forward and backward travelling waves respectively. According to the principles discussed above, E_f and E_b only exist after fault occurs, and are not only limited to symmetrical faults. Because of the reflection effects at the bus boundary, E_f is bigger than E_b after the reflection at the boundary. Thus the fault detection criteria will be defined as: if $k_e \geq k_{e0}$, the symmetrical fault occurred. The threshold value of k_{e0} is determined by the bus reflection coefficient.

4. **Case Study**

A. Test System Model

The power system model for the case study is based on the EMTP reference model for transmission line relay testing, which is introduced by the IEEE PES Power System Relaying Committee (PSRC) WG D10 [15]. The one-line diagram of the studied system is shown in Figure 4.

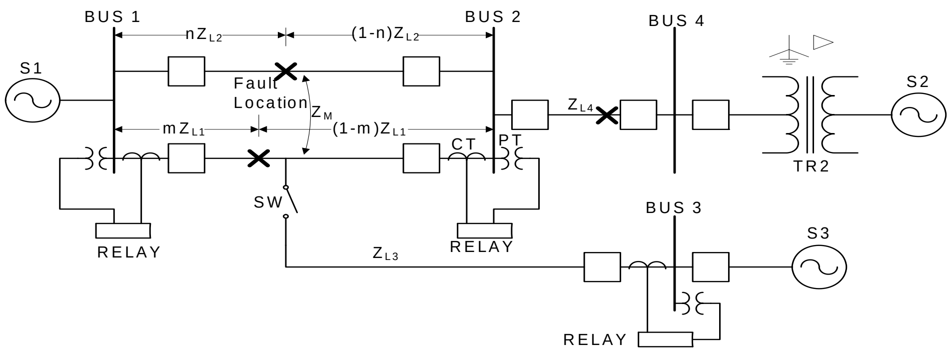

Fig.4. One-line diagram of IEEE EMTP reference model

B. Results

In this part, some case results are illustrated to test the performance of the proposed fault detection method during power swing. The typical voltage waveform of a symmetrical fault during power swing is shown in Figure 5. The values of criteria factor k_e around the fault point are shown in Figure 6. In this case, there is at least one point where the value of k_e is greater than the preset threshold value, which means a fault occurred during power swing.

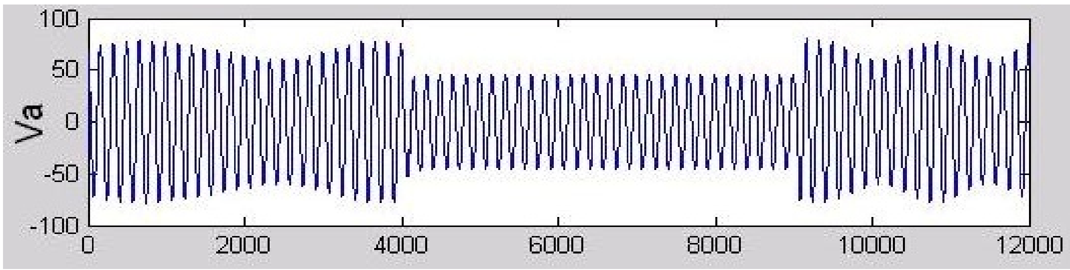

Fig.5. Typical voltage waveform for a symmetrical fault during power swing

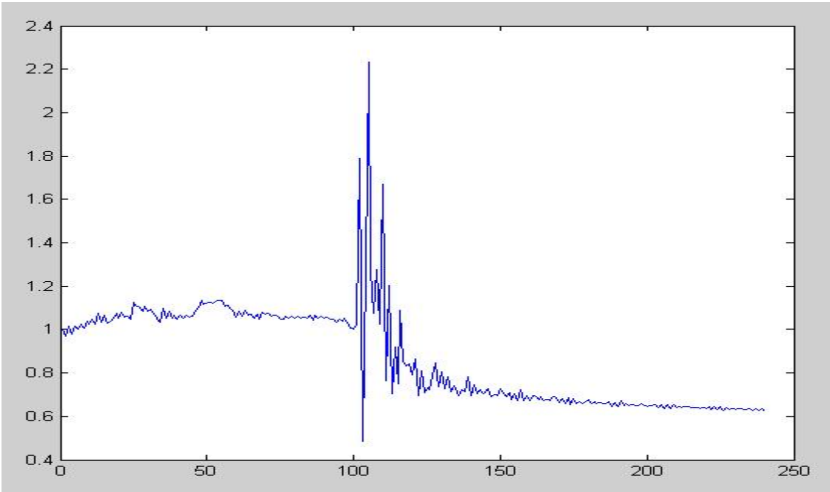

Fig.6. Values of criteria factor k_e around the fault point

The proposed scheme is also immune to the variety of fault types and locations. In order to validate the effectiveness of this scheme, the cases of one single-phase-to-ground fault (Fault AG) and one double-phase fault (Fault AB) are studied and results are equally good without loss of generality. Table I shows the results for different locations when the power swing is present. All the results show the proposed scheme is effective under the various conditions selected for this study.

TABLE I

SIMULATION CASE FOR DIFFERENT FAULT LOCATIONS UNDER POWER SWING

Case	*Fault Distance (mile)*	*Maximum Value of k_e*	
		Fault AG	*Fault AB*
1	0	1.2454	1.2200
2	4.5	1.3141	1.2951
3	13	1.3440	1.3589
4	19.5	1.2703	1.2720
5	42	2.2097	2.2511

5. **Conclusions**

This paper presents a novel and fast symmetrical fault detection scheme during power swing, which could be used to avoid possible distance relay misoperations during power swing conditions. The proposed scheme is very fast. It does not need to calculate the timing of the movement of the measured impedance as the traditional method do. The sampling rate for data acquisition can be as low as 10 kHz, which fits the requirements of most modern microprocessor based distance relays. Daubechies-8 wavelet is a good choice as the selected wavelet. It is good for the short and fast transient analysis due to its better localization performance in the frequency domain.

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