Fast Distance Relay Scheme for Detecting Symmetrical Fault During Power Swing

Chengzong Pang, *Student Member, IEEE*, and Mladen Kezunovic, *Fellow, IEEE*

***Abstract*—The power swing caused by various disturbances will affect distance relay behavior and may result in relay misoperation. This paper provides a fast detection scheme for symmetrical fault during power swing for distance relay, which is based on extracting the high-frequency component energy of forward and backward traveling waves induced by faults. The multiresolution analysis based on wavelet transform has the ability to decompose the analyzed signals into different frequency bands. The selection of mother wavelet and the number of levels of wavelet transform are carefully studied. The fault can be identified by feature extracting from the d1 component of Daubechies-8 (Db8) wavelet transform. The proposed approach is verified by using the IEEE reference model implemented by using the Alternate Transients Program and the test results have been presented in this paper. This proposed method can be used for distance relay operation blocking or monitoring.**

***Index Terms*—Fault detection, power swing, relay misoperation, traveling wave, wavelet transform.**

I. INTRODUCTION

POWER SYSTEM security and stability are becoming even more challenging and important characteristics due to the increasing complexity of power system operations. Since transmission lines are the vital links that enable delivering electrical power to the end users, improved dependability and security of transmission-line relays is required. According to the historical data [1], relay misoperation contributes to 70% of the major disturbances in the U.S. Finding effective means to monitor and improve distance relay operations is very important for understanding and mitigating relay misoperations on high voltage transmission lines.

Power swing is a phenomenon of 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 instability of synchronous generators. It is often caused by transmission line faults, loss of generator units, or switching heavy loaded transmission lines. The occurrence of power swings is very difficult to predict since they are quite unexpected [2]–[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]. For example, the Northeast Blackout in 2003 was caused by distance relays operation in zone 3 under the overload and power swing condition, which stressed the system and made the system collapse at the end [9].

To ensure the security of operation, most modern distance relays detect and block the operation during the power swing [10]. 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 relay [11].

To solve this problem, many schemes using different methods have been proposed. Mechraoui and Thomas present fault detection method based on load angle differences identification [4]. They did not consider the symmetrical fault in their case studies. Benmouyal *et al.* present a fault detector based on tracking the power swing center voltage (SCV) [12]. Choosing the appropriate thresholds is still very difficult to implement. Su *et al.* introduced an improved method for a fast detector [13]. Their scheme still needs two cycles to finish the fault detection, which is not good enough when applied in an extremely high voltage (EHV) system. Brahma introduced the use of wavelet transform (WT) to detect the symmetrical fault quickly and reliably [14], but the sampling rate of 40.96 kHz is needed to satisfy all of the studied cases.

Ultra-high-speed (UHS) protection schemes have been introduced based on the traveling wave detection techniques [15]–[18]. Some are limited by their weakness in reliability and feasibility. With the development of signal processing tools, the improved UHS protection schemes, such as the mathematical morphology (MM)-based method [19]and WT-based method [20], [21] have been proposed. Although the traveling wave protection scheme may not substitute the traditional protection methods right now, it provides a feasible method for fault detection with fast response and immunity to power swing and other influences.

Pang and Kezunovic [22] have shown that appropriately selected wavelet-based method could detect and classify transmission-line faults during the power swing, which is aimed at avoiding possible relay misoperations. This paper extends this study by introducing a high-speed symmetrical fault detection method for transmission lines under power swing conditions. By

Manuscript received June 07, 2009; revised October 21, 2009. Date of publication September 07, 2010; date of current version September 22, 2010. This work was supported in part by the Power System Engineering Research Center (PSerc) under Pproject S-29 tilted "Detection, Prevention and Mitigation of Cascading Events – Prototype Implementations" and in part by Texas A&M University. Paper no. TPWRD-00435-2009.

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Digital Object Identifier 10.1109/TPWRD.2010.2050341

extracting the forward and backward traveling wave at the relay point, wavelet analysis is performed to get the spectral energy. The criteria function and implementation framework are also discussed. This paper is organized as follows: Section II briefly discusses the fundamentals of power swing and relay behavior evaluation under power swing from [22]. Section III introduces the principle of the proposed detection method, which includes traveling wave theory and wavelet transform. The implementation of the proposed scheme is presented in Section IV. Section V presents the test cases and test results. Conclusions are given in Section VI.

II. Distance Relay Behavior During Power Swing

The responses of the power system to different disturbances depend on both the initial operating state of the system and the severity of the disturbances. The steady state power system operates at an equilibrium, which maintains the balance between the generated and consumed power. When system disturbances occur, such as various faults, transmission-line switching, sudden loss of load, loss of generators, loss of excitation, etc., the mechanical power input to the generators remains constant for a short time under those sudden changes in power system. This will cause the oscillations in machine rotor angles and result in power flow swings [2], [23]. 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^{circ} 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 occur and the system remains stable and returns to a new equilibrium state. [24]. However, large power swings, regardless of whether they are stable or unstable, will cause large fluctuations of voltages and currents, which may lead to relay misoperations and finally result in loss of synchronism between groups of generators.

Distance relays play an important role in assuring stability of power systems by eliminating faults on transmission lines leading to instability. The distance relays are proven to be influenced by power swing [2], [11]–[13]. When and only when the faults occur within the desired zone, distance relay should isolate the faults. It should not trip the line during the power swing caused by the disturbances outside the protected line. That is the reason why the power swing blocking function is intergrated in most of modern distance relays, so that the relays shall be blocked while power swing without faults occur.

Either a stable or unstable power swing will have impacts on distance relay judgment. The detailed reasoning and an example of the two machine system are given in [25].

If there is no fault on the considered transmission line, the impedance seen by distance relay at bus is

$$Z_c = \frac{\dot{V}_m}{\dot{I}_{mn}} = \frac{\dot{V}_m}{\frac{(\dot{V}_m - \dot{V}_n)}{Z_L}} = Z_L \left(\frac{1}{1 - \left|\frac{V_n}{V_m}\right| \angle\theta_{nm}} \right). \quad (1)$$

From (1), the apparent impedance Z_c seen by relay is determined by two variables: 1) the magnitude ratio (V_n/V_m) and 2) the angle difference $(\theta_{nm} = \theta_n - \theta_m)$ of the bus voltages at the two ends. Since the bus voltages will oscillate during power swing, Z_c will also vary accordingly. The plots of Z_c trajectories in the $R-X$ plane with respect to voltage magnitude ratios and angle differences is shown in Fig. 1, under the condition of $Z_L = 1\angle 80°$.

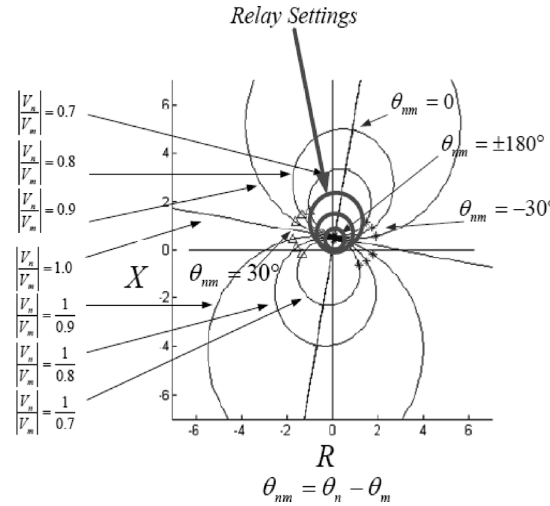

Fig. 1. Z_c trajectory in the R–X phase.

During the power swing, if certain values of the magnitude ratio and angle difference are satisfied, the impedance seen by the relay will reach the zone settings and relay misoperation will occur. The traditional method for power swing blocking is to measure the rate of change of impedance through the zones of relay [26]. The speed of impedance moving during the power swing is slower than during the fault condition. This is the basic theory of how a relay may be able to distinguish the power swing from a fault. However, as Brahma mentioned in [14], if a symmetrical fault occurs during a power swing, it is not possible to detect it based on the mentioned principle because both power swing and symmetrical fault are both balanced phenomena, which may result in the relay not being able to "see" the fault and clear it.

III. Principle of Detection Method

The system frequency during power swing only varies over the range around the nominal frequency, which can be as high as 4–7 Hz [12]. 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 prefault 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.

Wavelets are one of the relatively new mathematical tools for signal processing [27]. Wavelet-based signal processing technique is an effective tool for power system transient analysis and power system relaying. The applications of wavelet transform in power system have been reported for fault detection, fault classification, power system disturbance modeling and identification, power quality analysis, etc. [25], [27]–[30]. This paper presents a fast detection method for symmetrical faults by using wavelet analysis to extract the high frequency components from

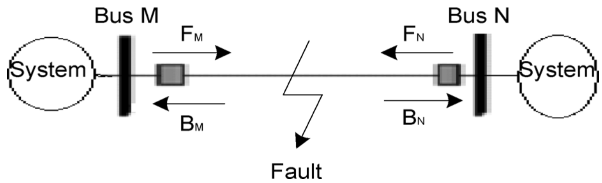

Fig. 2. Diagram for single phase transmission line.

the fault-induced voltage and current traveling waves propagating along the transmission line.

A. Traveling Wave Theory During Fault

When a fault occurs in the power system, the voltage and current signals could be decomposed into two parts: 1) the prefault steady-state component and 2) the fault injected component, or often called superimposed component. The superimposed component can be expressed in terms of traveling waves, including forward travelling wave and backward travelling wave. Fig. 2 shows a single line diagram of a transmission system. When a fault occurs, the traveling wave will propagate along the line. The wave propagation can be obtained by solving the partial differential equations, which are expressed as [21]

$$u(x,t) = u^{+}(x - vt) + u^{-}(x + vt) \tag{2}$$

$$i(x,t) = \frac{1}{Z_0}\left(u^{+}(x - vt) - u^{-}(x + vt)\right) \tag{3}$$

where v is the surge velocity, $v = 1/\sqrt{L_0 C_0}$, Z_0 is line surge impedance, $Z_0 = \sqrt{L_0/C_0}$, L_0 and C_0 are the inductance and capacitance per unit length, x represents the distance that a surge travels away from the fault point. u^{+} and u^{-} are the forward and backward travelling wave, respectively, which can be derived from (2) and (3) as

$$u^{+} = \frac{1}{2}(\Delta u + Z_0 \Delta i) \tag{4}$$

$$u^{-} = \frac{1}{2}(\Delta u - Z_0 \Delta i) \tag{5}$$

where Δu, Δi are the fault injected voltage and current, respectively. They can be obtained by subtracting the steady-state components from the postfault signals [31], and the steady-state components are those voltage and current waveforms one cycle before the fault. Thus, the forward and backward traveling waves can be calculated easily and fast.

B. Wavelet Transform Analysis

Wavelet transform (WT) is a relatively new and efficient signal processing tool, which was introduced first at the beginning of the 1980s [32]. The application of wavelet-based techniques has been widely spread in the field of mathematics, physics, and engineering because of its capability of time and frequency domain analysis, which is its unique characteristic. The fundamental theory and mathematics of the wavelet transform was extensively studied and can be found in [32]–[36].

The definition of continuous wavelet transform (CWT) for a given signal $x(t)$ with respect to a mother wavelet $\psi(t)$ (t) is

$$CWT(a,b) = \frac{2}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\, \psi\left(\frac{t-b}{a}\right) dt \tag{6}$$

where a is the scaling (dilation) factor and b is the shifting (translation) factor.

The application of the continuous wavelet transform in engineering requires the feasibility evaluation. Similar to the discrete Fourier transform, a discrete wavelet transform (DWT) is proposed by adapting the discrete forms of t, a, and b in (6), which can be written as

$$DWT(m,n) = \frac{2}{\sqrt{a_0{}^m}} \sum_k x(k)\, \psi\left(\frac{k - nb_0 a_0^m}{a_0^m}\right) \tag{7}$$

where m, n, and k are integer variables related to the sample numbers in the input signal. The scaling and shifting factors changed to the functions of m, n, and k.

The performance of the wavelet transform highly depends on the selection of the mother wavelet. All mother wavelets have the common characteristics: the mother wavelet should be attenuating and oscillating [32]. To perform wavelet transform, many approaches can be selected, such as Daubechies (Db), Symlets, Coiflets, Biorthogonas, etc. [35]. 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 multiresolution analysis (MRA) will be a best tool for decomposing the signal at the expected levels [34] by which the faulted-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.

Considering an acquired digitized time signal $y(t)$, the approximation coefficient (scaling coefficients) $c_j(n)$ and wavelet coefficient (detail coefficients) $d_j(n)$ after the decomposition at j scales can be computed as [21]

$$c_j(n) = \sum_k h(k - 2n) c_{j-1}(k) \tag{8}$$

$$d_j(n) = \sum_k g(k - 2n) c_{j-1}(k) \tag{9}$$

where $j = 1, 2, \ldots, J$. J is the total number of resolution levels. (The maximum value of J is determined by the number of sampling points.) $h(n)$ and $g(n)$ are the low-pass and high-pass filter, respectively. Fig. 3 shows the procedure of two-scale decomposition used by the MRA.

In order to represent the high frequency component in quantity, the wavelet energy spectrum is used to calculate the transient energy in a different frequency band. 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 basis, which can be shown as [27]

$$\int |f(t)|^2 dt = \sum_{k \in Z} |c_{J,k}|^2 + \sum_{j=1}^{J} E_j \tag{10}$$

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

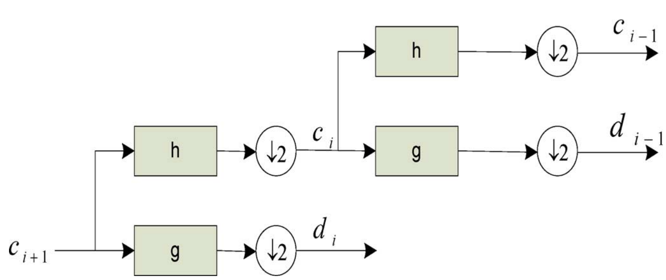

Fig. 3. Diagram of the MRA decomposition into two scales.

Multiresolution analysis is a hierarchical and fast solution. It can be implemented by a set of successive filter banks as shown above. An import issue remains for the wavelet analysis: choice of a suitable wavelet. A particular type of wavelet should be selected depending on the application purpose of wavelet analysis. The main concerns when selecting the appropriate wavelet are:

1) it should be one of the orthogonal wavelets;
2) it should be easy to implement and with acceptable performance.

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. However, the proposed method in this paper wants to extract the energy distribution at each frequency band in the detected signals. Thus, an orthogonal wavelet should be adopted to satisfy energy conservation of the Parseval's Theorem. Among those mother wavelets, the Daubechies wavelet family is one of the most suitable orthogonal wavelets in multiresolution analysis due to their powerful performance, which has been widely used in different fields [36]. Other orthogonal wavelets may also have the ability to function as well as Daubechies wavelets. But Daubechies wavelets are very easy to implement by using the fast wavelet transform with remarkable performance [35].

Different Daubechies wavelets have different filter lengths, which determined the performances of the 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. Literature [37] discussed the comparison results in fault diagnosis using Daubechies-4 (Db4), Daubechies-8 (Db8), and Daubechies-20 (Db20) wavelets, which shows that the wavelet with longer filter length is superior to the shorter ones. However, the computation burden is also an important factor to be considered when choosing the wavelets to implement the fast detecting scheme in this paper.

Based on these considerations, multiresolution analysis based on the Daubechies-8 (Db8) wavelet shown in Fig. 4 is selected for the investigations in this paper. Db8 wavelet is compactly represented in time, and this is good for the short and fast transient analysis due to its better localization performance in frequency [32]. It is relatively easy to localize and detect the fault part under the power swing by extracting features of transients in the wavelet domain.

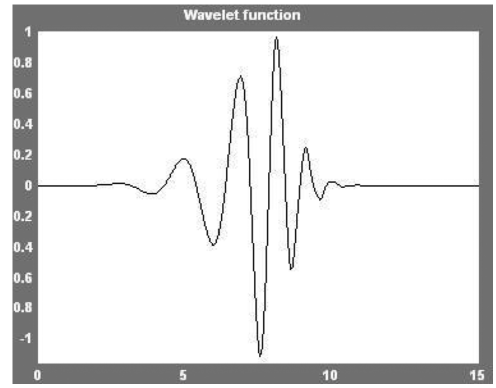

Fig. 4. Daubechies-8 (Db8) wavelet.

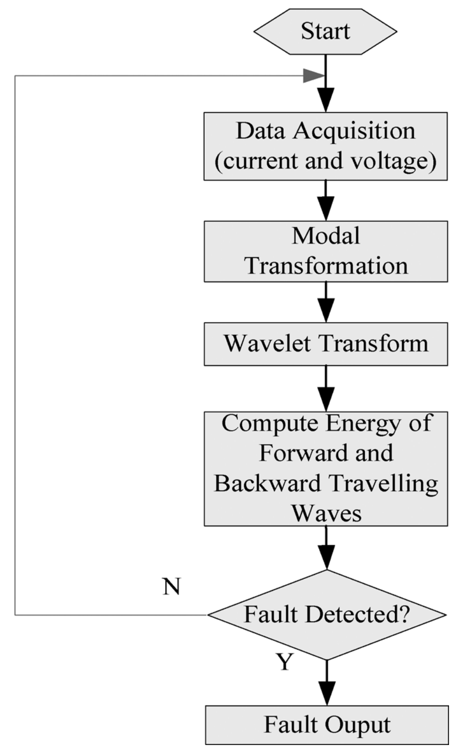

Fig. 5. Implementation diagram of symmetrical fault detection during the power swing.

IV. Implementation of the Detection Method

The diagram of the proposed symmetrical fault detection method based on the travelling-wave technique and wavelet transform is conceptually shown in Fig. 5.

A. Data Acquisition

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 in this paper can be used in a wide range of sampling rates. Considering advanced digital relays using sampling rate of 10 kHz, the same sampling rate is selected in this study, which can satisfy the requirements of the wavelet transform proposed in this scheme with good results. In order to avoid aliasing due to the fault transients and low sampling rate, an analog antialiasing filter needs to be employed before the sampling of the input waveforms coming from instrument transformers. There are many known solutions available for implementing the antialiasing filters; hence, no further discussion is given.

B. Modal Transformation

In three phase power transmission line, the electromagnetic coupling exists among three phases. Thus when a fault occurs in one phase, transient currents will be induced in the other phases due to the mutual coupling. The induced currents may distort the travelling waves on each phase, and it's difficult to solve the coupled equations describing wave propagation. Therefore, the modal transformation is adopted in the proposed scheme to uncouple the dependent phase components into three independent propagation modes. Clarke transformation is selected in this paper for three phase voltage and current, which is shown as

$$u_{0,\alpha,\beta} = T^{-1} u_{a,b,c} \tag{11}$$
$$i_{0,\alpha,\beta} = T^{-1} i_{a,b,c} \tag{12}$$

where T^{-1} is called the Clarke transformation matrix

$$T^{-1} = \frac{1}{3}\begin{bmatrix} 1 & 1 & 1 \\ 2 & -1 & -1 \\ 0 & \sqrt{3} & -\sqrt{3} \end{bmatrix}.$$

After Clarke transformation, three phase variables will be converted into earth mode 0, and two aerial modes α and β. 0 mode is prone to frequency dispersion and is not appropriate to be used since our goal is to extract the high frequency components. Since a symmetrical fault is considered, choosing between the mode α or β is not a critical decision. Here, the aerial mode α is selected to be used with the voltage and current signals.

C. Wavelet Transform Implementation

As mentioned before, the frequency of the system varies over a range around the nominal frequency during power swing. The fault will result in transient components of the voltages and currents, which may typically be dc or higher harmonics. In order to implement the proposed method, the levels of wavelet transform and the choice of key level for analysis are carefully studied. For a given signal, multi-resolution analysis based on Daubechies-8 (Db8) wavelet is performed. Different level components are the analysis results for different frequency bands, which can offer different information about given signals. Selection of sampling rate affects the frequency band for the wavelet transform. Based on the sampling rate of 10 kHz and Nyquist theorem, the wavelet level d1 will cover 2.5 kHz –5 kHz. Our study shows that the d1 component from the wavelet transform is able to capture the energy of the transients for all kinds of faults, which includes symmetrical fault, and it is sensitive to the fault occurrence irrespective of the occurrence of power swing condition. However, the high frequency transient component will disperse up to 100 kHz, so higher sampling rate will be helpful to improve the detection reliability.

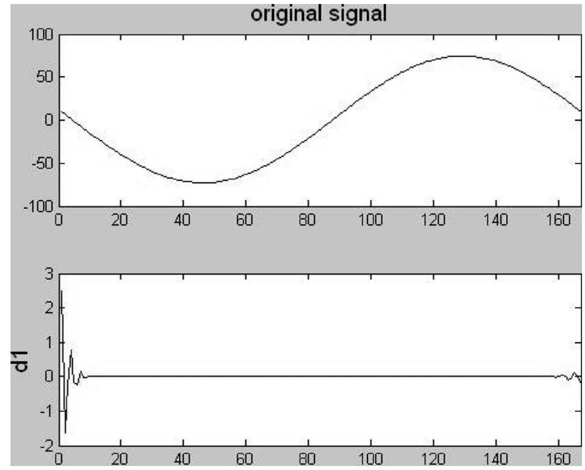

Fig. 6. Border distortion effect for wavelet analysis.

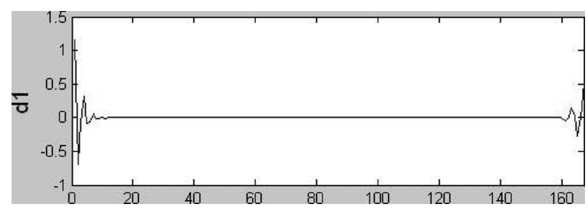

Fig. 7. Periodic-padding for wavelet analysis.

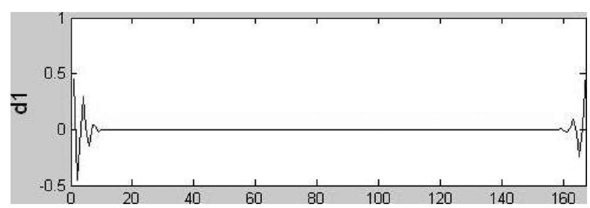

Fig. 8. Symmetric-padding for wavelet analysis.

When implementing the wavelet analysis, one cycle window data is calculated by wavelet transform. The moving speed of shifting data window can be set based on the requirements of system protection scheme. The proposed fault detection method could be running at point-by-point shifting, which is feasible with the aids of high-speed DSPs.

Since the data for wavelet analysis windowed the discrete signal, the results after wavelet transform will have border distortion, which is shown in Fig. 6. Although many extended signal methods have been used in FFT, WT, etc., such as zero-padding, symmetric-padding, smooth padding, periodic-padding, none of them could eliminate the border distortion effects completely. For example, Figs. 7 and 8 show the results after WT with periodic-padding and symmetric-padding, respectively, in which border distortion still exists although it has been improved by those signal extending methods.

The detection scheme proposed in this paper adopts a compromised method: discarding the first and last 10 coefficients in the d1 component after the wavelet transform. It will cause 1 ms time delay for the fault detection based on the sampling rate of

10 kHz. The proposed method is still fast enough to detect the symmetrical fault. The only factor to consider when introducing a detection lag is the time needed for calculations. The calculation burden is mainly coming from performing modal transform, wavelet transform, and wavelet energy spectrum. This is less than the calculation burden of newly transient-based ultra-high-speed directional protection relays that use the same wavelet transforms. It is estimated that they use less than 6000 multiplication and 5500 addition operations, which can be completed within 1.5 ms [21]. The method proposed in this paper is able to finish the fault detection within 2.5 ms after a fault occurs based on the sampling rate of 10 kHz. This detection scheme may be more rapid with faster DSPs and a higher sampling rate. For example, the time delay for discarding the 10 points will be 0.1 ms based on the sampling rate of 100 kHz.

D. Fault Detection Criterion

The criterion for the symmetrical fault detection is defined as

$$k_e = \frac{E_f}{E_b} \tag{13}$$

where E_f and E_b are the energy of the d1 wavelet component for the forward and backward traveling waves u^+ and u^-, respectively. According to the principles discussed before, E_f and E_b only exist after fault occurs, not only limited to symmetrical faults. Due to 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 occurs. When it is used in practice, in order to avoid the possible situation of dividing by zero, the values of E_f and E_b are being monitored. If any of them is close to zero (for example, less than 10^{-5}), the value of k_e is set to zero. The threshold value of k_{e0} is determined by the bus reflection coefficient. Here, k_{e0} is set to be 1.15 after a large number of simulation trials. More test cases are discussed in Section V.

V. Case Study

A. Simulation of Power Swing

In this paper, 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 [38]. This model is described as a "standard" system model, which can be used to generate uniform relay test scenarios. In order to generate the needed conditions, the Alternative Transient Program (ATP) is used to simulate the power swing [39]. The one-line diagram of the studied system and its ATP model are shown in Figs. 9 and 10, respectively.

B. Example Cases

In this part, some case results are illustrated to test the performance of the proposed fault detection method during power swing.

Fig. 11 shows the typical power swing voltage waveform generated by the model discussed before with the 5-level multiresolution wavelet analysis based on Db8. d1-d5 are the high frequency components at different wavelet level, respectively. It

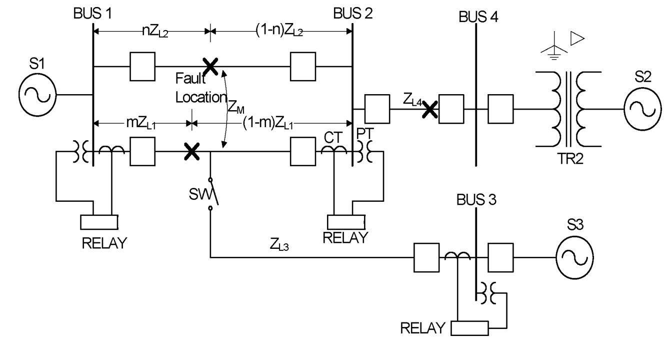

Fig. 9. One-line diagram of IEEE EMTP reference model.

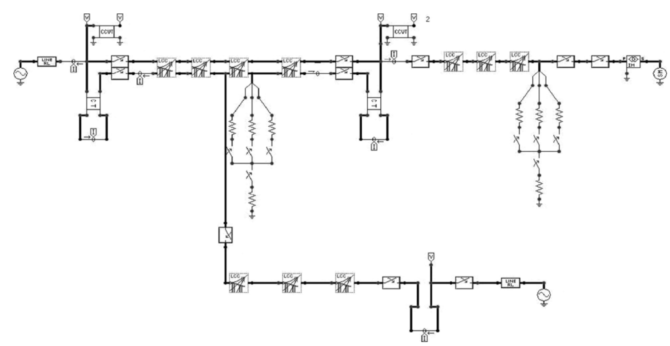

Fig. 10. IEEE EMTP reference model in ATP.

is obvious that the wavelet d1 component is "quiet" during the power swing.

Fig. 12 shows the three phase voltage of a symmetrical fault during the power swing. The values of criteria factor k_e around the fault point are shown in Fig. 13. In this case, there is at least one point that $k_e \geq k_{e0}$, which means a fault occurred during the power swing.

In order to validate that the proposed scheme is transparent to fault locations, a variety of scenarios under different locations has been conducted. Table I shows some typical simulation results for the three phase symmetrical fault under power swing.

The proposed scheme is also immune to the variety of fault types and locations, under both power swing and normal conditions. 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 II shows the case of simulated results for different fault locations of Fault AG and Fault AB when the power swing is absent, and Table III shows the results for different locations when the power swing is present. All of the results show the proposed scheme is effective under these conditions as well.

VI. Conclusion

A novel and fast symmetrical fault detection scheme for the distance relay during power swing is presented in this paper aiming at avoiding possible relay misoperations during power swing conditions. It extracts the traveling waves from transient signals induced by faults and calculates the energy of high frequency components extracted by using the wavelet transform. Based on the discussions presented in this paper, conclusions can be drawn as follows.

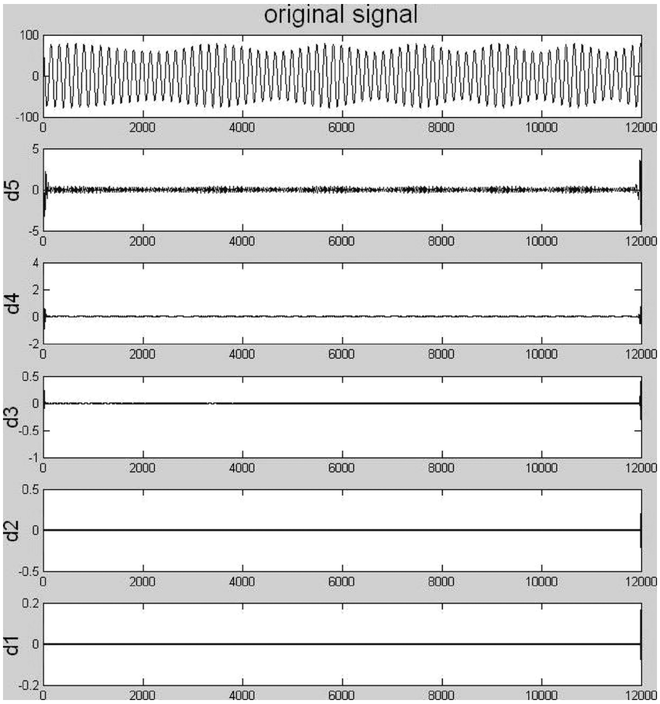

Fig. 11. Five-level Db8 wavelet transform results.

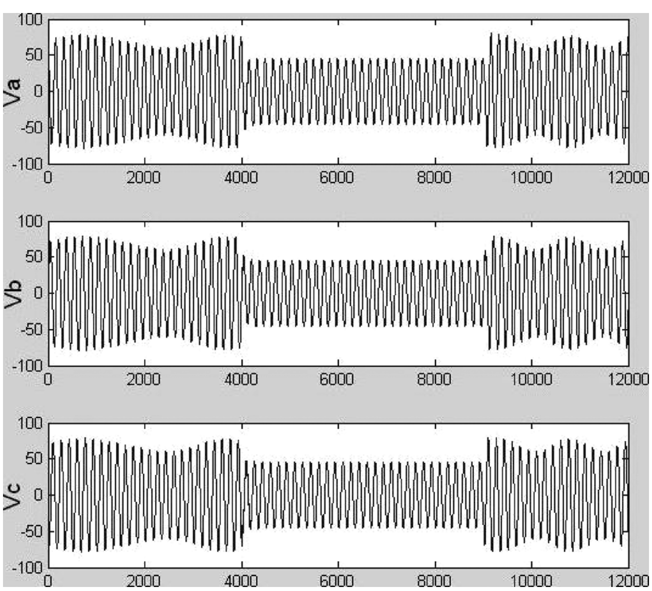

Fig. 12. Three phase voltage waveforms for a symmetrical fault during the power swing.

- The proposed scheme is very fast. It could detect the fault within 3 ms after the symmetrical fault occurs during the power swing, which could be beneficial for system protection, especially in the EHV system.
- The sampling rate for data acquisition can be as low as 10 kHz, which fits the requirements of most modern microprocessor-based distance relays. A higher sampling rate could offer better results.
- The implementation of the proposed scheme is straightforward since the theoretical research results may easily be transferred into practical application.

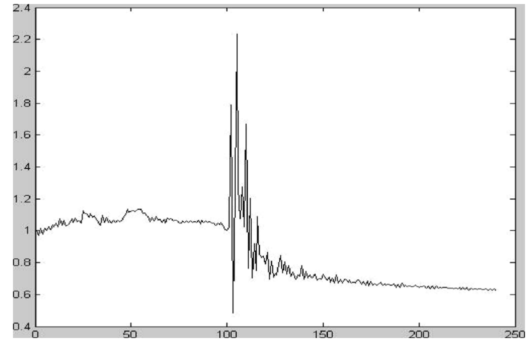

Fig. 13. Values of criteria factor k_e around the fault point.

TABLE I
SIMULATION CASE FOR DIFFERENT FAULT LOCATIONS FOR THE SYMMETRICAL FAULT UNDER POWER SWING

Case	*Fault Distance (mile)*	*Maximum Value of* k_e
1	0	1.2100
2	4.5	1.2958
3	13	1.3353
4	19.5	1.2717
5	42	2.2330

TABLE II
SIMULATION CASE FOR DIFFERENT FAULT LOCATIONS UNDER NORMAL CONDITIONS

Case	*Fault Distance (mile)*	*Maximum Value of* k_e	
		Fault AG	*Fault AB*
1	0	1.2777	1.2765
2	4.5	1.3142	1.2952
3	13	1.3435	1.3566
4	19.5	1.2705	1.2700
5	42	2.2246	2.0778

TABLE III
SIMULATION CASE FOR DIFFERENT FAULT LOCATIONS UNDER THE 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

- The proposed method is novel since applying the ultra-high-speed protection method based on traveling waves to fault detection during the power swing is considered for the first time.

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