Wavelet-Based Method for Transmission Line Fault Detection and Classification during Power Swing

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ABSTRACT: Power swing caused by various disturbances will affect distance relay behavior and may result in relay misoperation. This paper provides a new wavelet-based method for detection and classification of transmission line faults during power swing. The multi-resolution analysis based on wavelet transform (WT) has the ability to decompose the analyzed signals into different frequency bands. With the wavelet transform of the voltage and current signals acquired by distance relays, the different faults will be identified by feature extracting from the D5 component of Daubechies-8 (Db8) wavelet. The proposed approach is verified by using IEEE reference model implemented using EMTP. The test results, which include ground fault and phase fault, have been presented in this paper. This proposed method can be used for relay operation blocking or monitoring.

Keywords: Wavelet transform, fault detection, fault classification, power swing, relay misoperation.

I. INTRODUCTION

Power system security and stability are becoming 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 percent of the major disturbances in the United States. Finding effective means to monitor and improve relay operations is very important for understanding and mitigating relay misoperations.

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 distance relay operation, power swing blocking function is intergraded in most of modern distance relays to 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. In some fault conditions, the distance relay cannot distinguish the fault from a stable power swing, which may delay the operation of relay [11]. Thus the fault detection and classification during power swing is a very important issue.

To solve this problem, many schemes have been proposed [12] – [14]. None of them can provide the function of fault detection and fault classification during power swings. Wavelets are one of the newly developed mathematical tools for signal processing [15]. 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 disturbances modeling and identification, power quality analysis, etc [15] – [20]. This paper presents the application of wavelet transform to fault detection and classification of transmission lines under power swing conditions, which could be used to provide a suitable tool to block or monitor relay operations.

This paper is organized as follows: Section II introduces the fundamentals of power swing and relay behavior evaluation under power swing. The overview of wavelet transform and the method for faults detection and classification using wavelets are discusses in Section III. Section IV presents the test cases and test results. Conclusions of this paper are given in Section V.

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 happen, 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. It will cause the oscillations in machine rotor angles and result in power flow swings [2] [21]. 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. [22]. However, large power swings, no matter whether they are stable or unstable, will cause large fluctuations of voltages and currents, which may leads 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] – [14].When and only when the faults occurred within the desired zone, distance relay should isolate the faults. It should not trip the line during power swing caused by the disturbances outside the protected line. That is the reason why power swing blocking function is intergraded in most of modern distance relays, so that the relays shall be blocked while power swing without faults is occurring.

Either stable or unstable power swing will have impacts on distance relay judgment. The detailed reason and an example of two machine system are given in [23].

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

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

From the above equation, the apparent impedance Z_c seen by relay is determined by two variables: the magnitude ratio (V_n / V_m) and 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 figure of Z_c trajectories in the $R-X$ phase with respect to voltage magnitude ratios and angle differences is shown in Fig. 1, under the condition of $Z_L = 1\angle 80^\circ$.

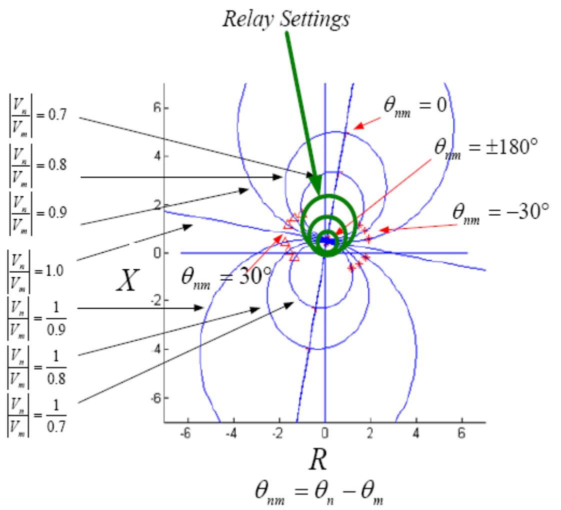


Fig. 1. Z_c trajectory in the $R-X$ phase

During power swing, if certain values of the magnitude ratio and angle difference are satisfied, the impedance seen by relay will reach the zone settings and relay misoperation will happen. Traditional method for power swing blocking is to measure the rate of change of impedance through the zones of relay [24]. The speed of impedance moving during power swing is slower than during fault condition. This is the basic theory of how a relay may be bale to distinguish the power swing from fault. However, as Brahma mentioned in [19], 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 balanced phenomena, which may result in the relay not being able to "see" the fault and clear it.

III. WAVELET-BASED METHOD FOR FAULT DETECTION AND CLASSIFICATION

Fault detection and classification of traditional distance relay is based on Fourier-based algorithm, which served the power system applications for many years. Fourier-based algorithm is not the perfect solution since it may not perform well under some conditions. Many improved or new algorithms, such as wavelet-based transmission line protection [15] [17] – [19], are introduced. But it may take some time before an algorithm as effective as the Fourier-based distance relaying algorithm is adopted. The wavelet-based method provided in this paper does not aim at substituting the existing distance relaying algorithm. Its objective is to monitor and analyze relay operation by using the samples of voltage and current. This method could function as a relay blocking or monitoring tool.

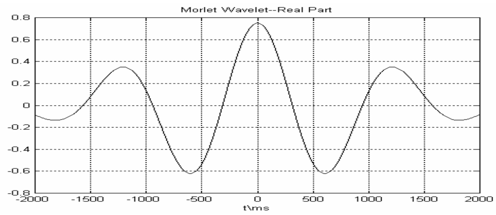
A. Selection of Mother Wavelet for Wavelet Transform

Wavelet transform (WT) is an efficient signal processing tool, which was introduced first at the beginning of the 1980s [25]. 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 a unique characteristic.

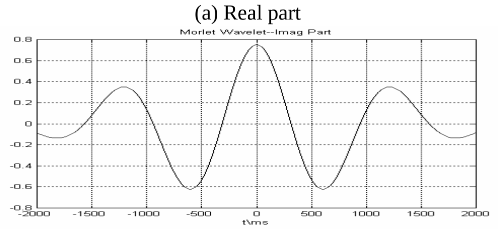
The performance of Wavelet transform highly depends on the selection of the mother wavelet. All the mother wavelets have the common characteristics, which came directly form its name "Wave-let" [25]. "Let", also "little", means the mother wavelet should be attenuating. "Wave" means the mother wavelet should be oscillating. For example, the real and imaginary parts of Morlet wavelet ($\psi(t) = e^{-\frac{t}{2}} e^{j\omega_0 t}$) are shown in Fig. 2.

To perform Wavelet transform, many other wavelets can be selected, such as Daubechies (Db), Symlets, Coiflets, Biorthogonas, etc [26]. The different mother wavelets will affect the performance of Wavelet-based methods. Not every mother wavelet based wavelet transform could detect and classify the different faults during power swing.

Power swing is mostly the phenomena of low frequency oscillation. The fault voltage or current contains high frequency transient signals. The multi-resolution analysis will be a best tool for decomposing the signal at the expected levels. Thus, we can easily extract the desired information from the input signals into different frequency bands related to the same related time period. Among those mother wavelets, Daubechies wavelet family is one of the most suitable wavelets in multi-resolution analysis due to their performance [27]. Lots of trials have been carried out to find the desired wavelet for fault detection and classification, particular to differentiate fault under power swing. The aim of these trials is to identify the most sensitive component, reflecting particular frequency band, which can clearly show fault starting and clearing times, but have less influence under power swing. Based on these considerations, multi-resolution analysis based on Daubechies-8 (Db8) wavelet is selected for the investigations in this paper after comparison with other wavelets.



(a) Real part



(b) Imaginary part

Fig. 2. Real part and imaginary part of Morlet wavelet

B. Implementation of Fault Detection and Classification

The frequency of the system varies over a range around the nominal frequency during power swing. However the fault will result in transient components of the voltages and currents, which may typically be DC or higher harmonics. These waveforms will vary depending on pre- and post-fault conditions and the instant and location of fault.

In order to implement the proposed method, the levels of wavelet transform and the choice of key level for detection and classification are carefully studied. For a given signal, 5-level multi-resolution analysis based on Daubechies-8 (Db8) wavelet is performed. An example is shown in Fig. 3. D1~D5, A5 are the analysis results under different frequency bands, which can offer different information of given signals. Here we use D5 component as the criterion for detecting and classifying different faults, which is sensitive to the fault occurrence irrespective of the occurrence of power swing condition. Fig. 3 shows that the D5 component keeps ‘quite’ during power swing.

A criteria function for fault detection and classification is defined as:

$$E(k) = \frac{1}{N}\sum_{n=k}^{k+N}\left|y(n)\right|^2 \qquad (2)$$

where k is the present sampling point;

N is the number of samples for the moving window;

$y(n)$ is the sampling value at point n;

The criteria function is used to analyze D5 component from Db8 analysis by scanning the output samples. When the value of criteria function is greater than the threshold value, it means change happened; either fault occurred or got cleared. Fault classification is implemented by comparing three phase results. More case studies are discussed in Section IV.

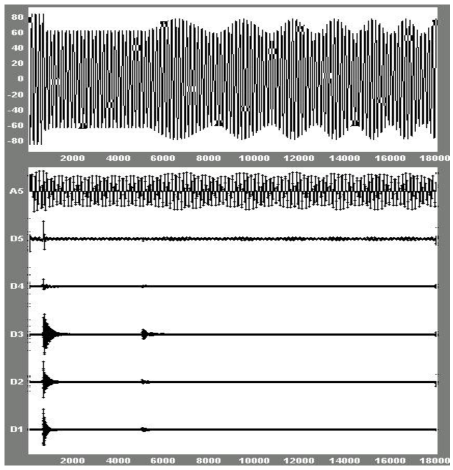


Fig.3. Db8 5-level wavelet analysis

IV. CASE STUDY OF WAVELET-BASED METHOD

A. Simulation of Power Swing

In this paper, the power system model for 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 [28]. 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, Alternative Transient Program (ATP) is used to simulate the power swing. The one-line diagram of the studied system and its ATP model are shown in Fig. 4 and Fig. 5 respectively. Waveforms resulting from the simulation are shown in Fig. 6.

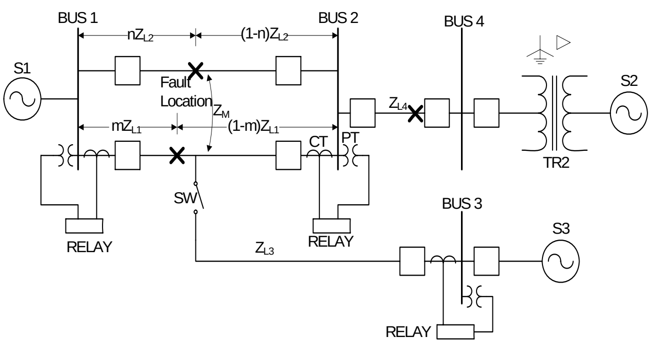


Fig.4. One-line diagram of IEEE EMTP reference model

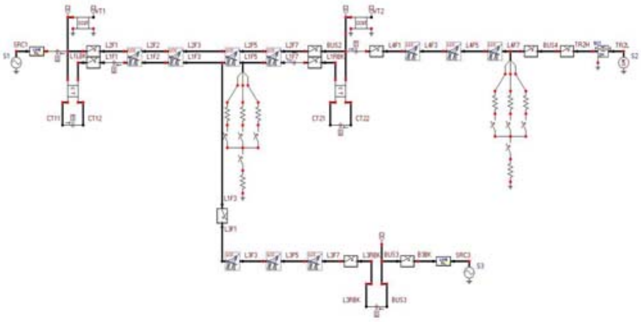


Fig.5. IEEE EMTP reference model in ATP

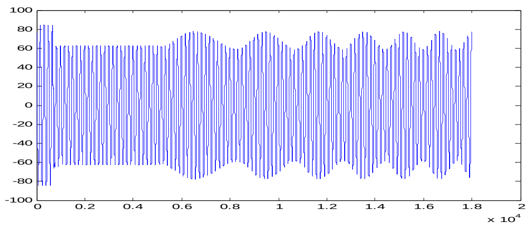


Fig.6. Power swing waveforms

B. Example Studies

In this part, some case results are illustrated to test the performance of the proposed fault detection and classification method.

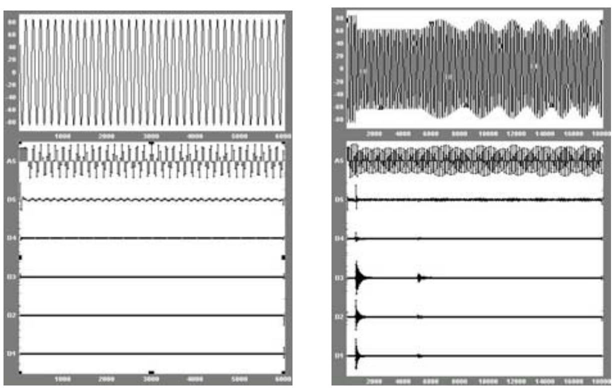
1) Normal and power swing scenarios shown in Fig. 7;

2) One phase-'A' to ground fault scenario during power swing shown in Fig. 8;

3) Two phase-'AB' fault scenario during power swing shown in Fig. 9;

4) Three phase-'ABC' fault scenario during shown in Fig. 10.

The first two bursts located at 0.065s and 0.5s on most components are coming from the power swing initiation, which correspond to the starting and clearing of a three phase fault. Component D5 is used as the criterion for detecting and classifying the different faults, which can be shown in Fig. 7-10. Fig. 7 shows that the proposed wavelet transform is not affect by the power swing. D5 component keeps stable when power swing happens. By feature comparison, it is easy to detect all kinds of faults. For fault classification, it is difficult to distinguish the two phase fault from two phases to ground fault only by D5, Combined with other components, such as D3, fault classification can be solved.



(a) Normal state (b) Power swing

Fig.7. Case results of normal and power swing scenarios

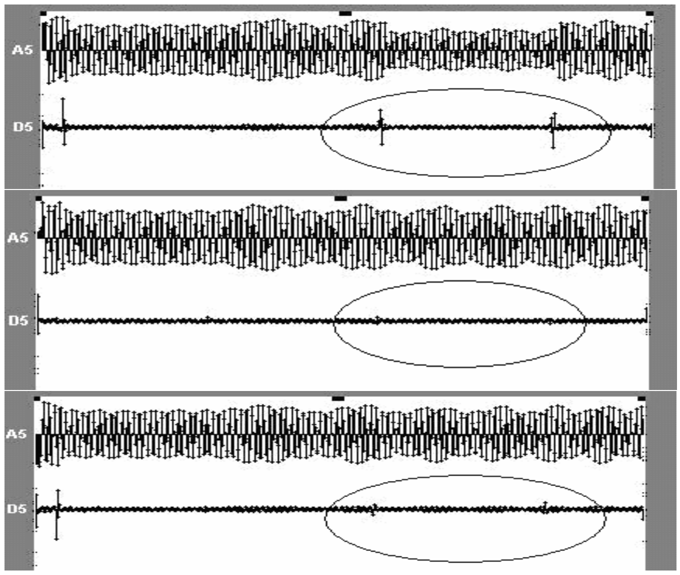


Fig.8. One phase fault-- A to ground fault during power swing scenario

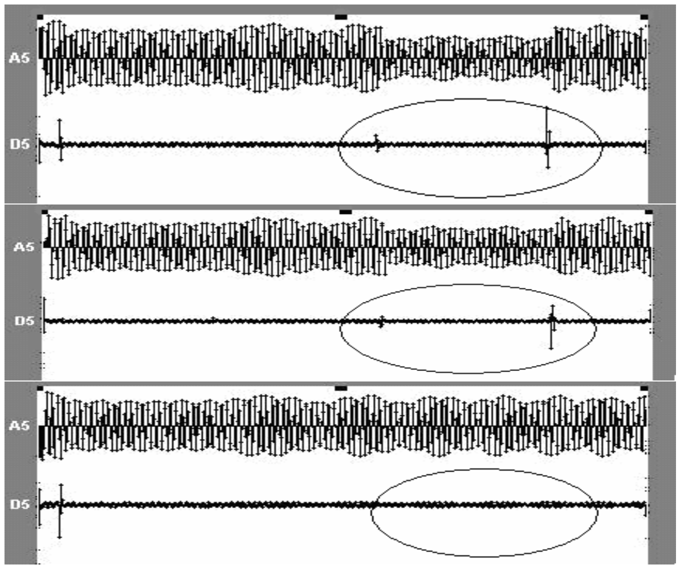


Fig.9. Two phase fault--AB fault during power swing scenario

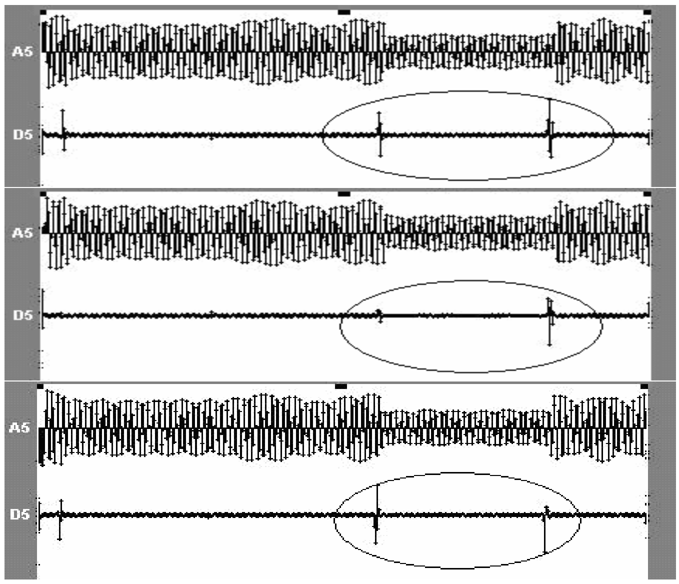


Fig.10. Three phase fault--ABC fault during power swing scenario

V. CONCLUSION

A new wavelet-based method for detecting and classifying transmission line faults during power swing presented in this paper is aimed at avoiding possible relay misoperations during power swing conditions. It functions as supplemental tool for blocking or monitoring relay operation.

The multi-resolution analysis based on wavelet transform (WT) is used as the signal processing tool, because of its ability to decompose the analyzed signals into different frequency bands. After comparison with other mother wavelet, Daubechies-8 (Db8) wavelet is selected to perform the implementation. The number of levels of wavelet transform and the choice of key level for detection and classification are carefully studied. The test results indicate that wavelet-based method performs well in distance relay detection and classification irrespective whether the power swing condition Exists. Different faults, which include ground fault and phase fault, are identified by extracting a feature from the components of wavelet transform results. Automated recognition and feature extraction can be accomplished for practical uses.

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VII. BIOGRAPHIES

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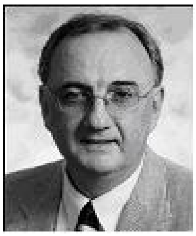

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