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A covariance indices based method for fault detection and classification in a power transmission system during power swing

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ABSTRACT

This paper presents a new scheme based on a combination of the current signals covariance with the cumulative approach to identify faults in the power transmission system during the power swing conditions. Primarily, the covariance is used to extract the features which are useful to identify the fault from the current signals that measured at both terminals. The cumulative approach is used to enlarge the fault feature and then create a convenient index for detection and classification during the power swing. The proposed algorithm has been tested through different fault circumstances such as multiple fault locations, multiple fault resistances, and multiple fault inception time. Moreover, fault happened nearby the terminal, fault considering variable loading angles, sudden load change, power flow direction change, faults in the presence of series compensation and fault occurred in the presence of noise are also considered. The empirical results show that the approach proposed in this study has made a reasonable time response, where the fault could be detected within a few milliseconds after the fault inception. Additionally, the simple computation process depicting our proposal makes it more suitable and efficient for practical engineering applications.

1. Introduction

Faults may cause long-term power outages once it occurs on power transmission lines and may harmfully affect the connected equipment. Therefore, relays must quickly detect and isolate the faulted line and then fault classification is a necessity to be conducted [1,2].

Many researchers have introduced different techniques for the faults detection and faulted phase identification in power transmission lines. However, many of these techniques did not give enough attention to the faults that occur during the power swing condition. Usually, they rely on the blocking function of the power swing (PSB) which is often provided in most of the modern distance relays [3]. Moreover, if a fault condition occurs in the presence of a power swing, the distance relay should be qualified enough to deal with the fault condition and isolate it accurately. In that case, the power swing blocking function should be in inactive condition [4]. In some cases, it was observed that the distance relay fails to discriminate the stable power swing from the fault condition, which may retard the decisions of the relays [5]. Additionally, if a fault occurs instantaneously within the blocking period, the blocked distance relay may not achieve the target correctly. Therefore, distinguishing the faults during power swings is necessary to be provided to the distance protections.

Many schemes of power swing detection depend on the traveling speed of the impedance trajectory towards the operating zone of the distance relay to specify the power swing condition [6]. However, a fault occurring during the power swing will accelerate the impedance trajectory towards the operating zone, which makes the relay not operate correctly due to the blocked status of the relay. The schemes proposed in [7,8] used the morphological technique for detecting the fault condition during the power swing. However, the mathematical approaches are practically hard, and some complexity has been applied. The technique of swing center voltage has been used for identifying the swing condition in [9]. It is provided better dependability except it takes more than two cycles to detect the power swing condition since it waits until the apparent impedance appears in the tripping zones [10], and also there are some difficulties to set an appropriate threshold [6]. The scheme [11] proposed an integrated approach for fault detection based on Teager–Kaiser energy operators of instantaneous zero sequence voltage and phasor of negative sequence current. The proposed scheme achieved great results regarding unsymmetrical ground faults and line-to-line faults as well as its independence of the threshold earn it an advantage. However, it has more complex computation in addition to the need of zero-sequence of system voltage and current. Techniques which are based on concentric characteristic and blinder methods for

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distinguishing the power swings need a wide range of offline stability studies to perform an appropriate setting. Furthermore, a power swing condition could be detected before the impedance trajectory entering the tripping zone, which gives a chance for activating the blocking function if it is desirable [12]. Algorithms which used superimposed components are less sensitive to the faults that occur during the power swing. Neuro-fuzzy techniques have been used for power swing blocking (PSB) scheme in [13]. Due to its needs a primitive data for the training process, artificial neural network methods become challenging to be realized in a complex system [14–17]. Wavelet techniques have been employed for accomplishing the power swing condition in [18,19]. However, it requires a multi-level filter and good knowledge with mother wavelet and decomposition level to obtain a reasonable accuracy [20]. Methods that are situated on a symmetrical component to accomplish the faulted phase selection schemes require the transmission line parameters such as the positive, negative, and zero sequence impedance [21,22]. The scheme in [23] is proposed to perform the short-circuit detection during the power swing by using fisher asymmetry coefficient. However, it needs to measure the voltage and current as well as the output of the asymmetry filter obtained.

Toward this end, the proposed scheme is presented to avoid an extra computational cost that required in obtaining the transmission line parameters (positive, negative and zero sequence components), offline data for training process as in artificial intelligence, low-high pass filters as in wavelet techniques. Additionally, the proposed scheme does not rely on the impedance calculation which needs voltage and current measurement; it relies exclusively on the current measurement. This feature makes the proposed scheme is the best option for identifying the fault condition and also identifying the faulted phases during the power swing.

The main contribution of the proposed scheme represented in the applying the covariance of the current signals with the cumulative technique, where the covariance is used to extract the useful features of the fault from the current signals that measure at both terminals. The cumulative approach is a widely used technique for amplifying the abrupt changes that result due to a fault occurring during the power swing. The results from the combination process referred to as covariance indices are used to perform the fault identification and classification during the power swing in power transmission line. It is found that during fault condition the faulted phases have indices much higher than zero while the healthy phases have a zero index.

This paper is discussed in four section. The first section presents an introduction, the second section defines the principle of the proposed scheme, the third section discusses the simulation model and tests results, and the fourth section concludes the work.

2. The principle of the proposed scheme

This section is discussed in two subsections; the covariance measure basic theory is presented in Section 2.1, the next subsection examines the application of the proposed scheme in fault detection and faulted phase identification during the power swing.

2.1. Covariance measure basic theory

The covariance is a measure of the linear association between two random variables x and y along data size S. Moreover if the covariance value is positive indicates a positive relationship and if the covariance value is negative indicates a negative relationship.

$$\rho_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{S-1} \tag{1}$$

Eq. (1) is used for obtaining the covariance between two variables. However, for one variable $(x_1, \ldots x_n)$, the covariance will be achieved in relation to its mean. It can be obtained as in the following expression [24].

$$\rho = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(x_i - \bar{x})^T}{n-1} \tag{2}$$

where T denotes to matrix transpose, and n indicates data size. Eq. (2) shows the expected value of the deviation of the variable x from its mean. Therefore, it will be positive when x increased, and negative when x decreased. In the proposed scheme x represents the current signals; these current signals are time-synchronized samples captured from both ends of the transmission line. It is obtained over cycles, where the current signals of each phase in each terminal collected and then the resultant current signals of the sending and receiving terminal gathered based on the following expression:

$$\begin{cases} I_1 = I_{s1} + I_{r1} \\ I_2 = I_{s2} + I_{r2} \\ I_3 = I_{s3} + I_{r3} \\ I_0 = \frac{I_1 + I_2 + I_3}{3} \end{cases} \tag{3}$$

where the symposium $s\&r$ denote the sending and receiving end current signal, I_{s1}, I_{s2}, I_{s3}, are the current signals measured at the sending end at instant t. Similarly, I_{r1}, I_{r2}, I_{r3}, are the current signals measured at the receiving end at the same instant t. The currents signals are measured in the assumed direction from sending end to receiving end. All the currents are single-phase quantities, where I_1, I_2, I_3, and I_0 denote the resultant current summation of phase A, B, C, and zero-sequence respectively. The values I_1, I_2, I_3, and I_0 are used instead of x in Eq. (2) to obtain the covariance of the current system ρ. Then, the sum of the current covariance per cycle can be calculated as follows

$$\Phi(k) = \left| \sum_{j=k-N+1}^{k} \rho(j) \right| \tag{4}$$

where N represents the number of samples in the cycle; j, k represents the sampling instant.

2.2. Proposed scheme application for fault detection and classification during the power swing

During the power swing, a significant change will appear in system current (I) and voltage (V) magnitudes [25]. Accordingly, the covariance of the current signals has followed this change. It is observed that the covariance of the current system Φ of the faulted phases is much higher than Φ of the healthy phases. For more robustness, a cumulative sum approach is used to amplify the differences of the fault feature from the health state, as follows.

$$CI(i) = \max[0, (CI(i-1) + \Phi(i) - Th)] \tag{5}$$

where $i = 2, \ldots, k$, CI represents the covariance indices of the current system during power swing, $CI(i-1)$ represents the starting point where $CI(1) = 0$. The symbol *definedasathresholdwhichistakentwohundredtimes* defined as a threshold which is taken two hundred times Φ during the safe operating condition (pre-fault condition). Zero-sequence current threshold ($Th0$) is taken five hundred times the value of the zero sequence current covariance (Φ_0) during the safe operating condition. This is due to the amplitude of zero sequence current during the fault condition is too much higher compared to the magnitude of the zero-sequence current in the health condition, so it becomes necessary to use a high threshold.

It is observed that the output of Eq. (5) is zero when the value of Φ less than the threshold, and this is the case of the no-fault condition. On the other hand, the initial output of Eq. (5) will take high values when Φ becoming much higher than the threshold, and this is the case when there is a fault condition. Therefore, the situation $CI = 0.0$ is considered as an indicator of the health condition, and the situation $CI > 0.0$ considered as an indicator of the fault condition. Fig. 1 explains the

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