Electric Power Systems Research 132 (2016) 94–103

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Ultra-high-speed protection of transmission lines using traveling wave theory

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ARTICLE INFO

Article history:
Received 14 August 2015
Received in revised form 29 October 2015
Accepted 20 November 2015
Available online 21 December 2015

Keywords:
Transmission line
Protection
Traveling waves
Teager energy operator
Decision tree

ABSTRACT

A new traveling-wave-based algorithm is proposed in this paper for the protection of transmission lines. In the proposed algorithm, Teager energy operator is used to extract traveling waves. Teager energy operator has a high computational efficiency and extracts traveling waves with high resolution. The amplitude of the first detected traveling wave as well as that of the traveling waves which are detected in $2L/v$ and $2(L-x)/v$ seconds ("L" is the line length, x is an initial guess about the fault location, and "v" is the traveling wave propagation speed) after the first one are used to discriminate internal and external faults. Then the traveling wave propagation speed and the time difference between the first and the second traveling waves are used to find the fault location. This process can also be used for the internal fault identification. Finally, two decision trees and the amplitude of initial current traveling waves in different modes are used for the fault type classification and faulted phase selection. The feasibility of the proposed algorithm is investigated by test signals which are simulated in PSCAD/EMTDC, and the algorithm is implemented in MATLAB.

1. Introduction

The protection scheme used for a power system should be fast and reliable so as to prevent any damage (caused by short circuit faults) to the system equipments. Traditional protection schemes make use of fundamental frequency components of voltage and current signals. In [1], a neuro-fuzzy system and a set of novel features, in [2], stationary wavelet-transform (WT) along with support vector machine (SVM) and support vector regression (SVR), and in [3], the average of superimposed components are used for the internal fault identification and fault type classification.

Traveling-wave (TW)-based protection schemes are faster and more accurate alternatives for traditional algorithms. In TW-based protection algorithms, different methods are used to extract TWs from the voltage and current signals. Fast-Fourier-transform (FFT), which is used in [4], can only extract frequency information of TWs. WT is widely used for this purpose [5–7] but has some drawbacks such as its complex computations and the low resolution of its output. S-transform (ST) is used in [8,9] for the TW extraction. ST has previously been used in power quality issues [10] and transformer differential protection [11]. Because of its very high computational burden and its low output resolution, ST is not an appropriate choice for the TW-based algorithms. Time–time-transform (TTT), which is used in [12], is even more complex than ST and WT. In some references, heuristic methods such as principal components analysis (PCA) [13] are used for the TW extraction.

A single-ended fault location algorithm is presented in [14] which uses TW natural frequencies and a non-linear objective function (constructed by several natural frequencies) to locate the fault. In [15,16], protection algorithms are presented for the protection of HVDC transmission lines. The algorithm presented in [15] uses a startup and two auxiliary criteria. The algorithm presented in [16] is based on the comparison of the amplitude of the first forward and backward TWs. A double-end fault locator is presented in [17] which utilizes the least error square (LSQ) principle in order to locate the fault. By employing support vector machine (SVM), Hilbert–Huang transform, and the direction and the instantaneous amplitude of the fault-generated high-frequency transient current, a protection algorithm is presented in [18] to simultaneously protect bus bar and the connected transmission line for EHV substations. In [19], TW theory is used for finding the fault location in the distribution systems.

Some studies have conducted the fault type classification and faulted phase selection. Reference [20] uses numerical criteria for

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http://dx.doi.org/10.1016/j.epsr.2015.11.014
0378-7796/

the fault type classification. In [21,22], internal fault identification and fault type classification is performed for parallel transmission lines. Protection schemes are presented in [23–25] for the protection of three- or multi-terminal transmission lines. A wide-area TW fault location system [26] has also been used for the protection of power systems.

With regard to the drawbacks of previous algorithms, a new protection algorithm is proposed in this paper for internal fault identification, finding fault location, fault type classification and faulted phase selection. The algorithm uses information from a local bus and there is no need for a communication link to communicate between the two sides of the protected line. Here, Teager energy operator (TEO) is used for the TW extraction. Computational efficiency of the TEO is higher than other methods [25]. Moreover, each point for the output of the TEO is generated by only three samples of input signal and, as a result, the resolution of the TEO is higher than that of other techniques which need at least a quarter of a cycle to generate their output. Besides, the output resolution of the TEO can be increased by increasing the input sampling frequency. In this paper, the amplitudes of three TWs are used for the internal fault identification. The first one is the first detected TW (W1). The second one is the TW which is reflected from the local bus towards the remote end bus and then reflected back from the remote end bus towards the local bus (W2). The third TW is the one which arrived from the fault point to the remote end bus and then reflected back from the remote end bus towards the local bus (W3). Then a decision tree is utilized to classify different types of faults. Using the decision tree leads to a very simple, fast, and accurate classification algorithm.

It is also known that current transformer (CT) and capacitor coupling voltage transformer (CCVT) are used to capture current and voltage signals, respectively. There are energy storage equipments in the structure of CT and CCVT. Therefore, these devices have a limited frequency bandwidth. Due to a limited frequency bandwidth, CT and CCVT impose considerable effects on the TWs. The impact of CT and CCVT on the current and voltage TWs is considered in the paper. The main contributions of the paper are as follows:

1- A very simple and ultra-high-speed single-ended algorithm is proposed which includes internal fault identification, fault type classification, faulted phase selection, and fault location.
2- Compared to previous algorithms, closer faults with smaller inception angles are correctly identified.
3- Using decision trees is proposed for fault type classification. Accordingly, the amplitudes of TWs of different modal components are precisely investigated and effective decision trees are constructed.
4- TEO is used in this paper to extract the amplitude along with the polarity of TWs.

2. Basic principles

When a short circuit fault occurs in a transmission line, TWs traveling from the fault point to both ends of the line are generated. When a TW reaches a discontinuity point in which the characteristic impedance of the transmission line changes, a part of the wave passes the point and the remaining part is reflected backward.

2.1. Phase to modal transformation

In order to analyze the TWs, three dependent phases of the system are converted to three independent modal components. For this purpose, Karenbauer's phase to modal transformation is utilized with the following formulation:

$$\begin{pmatrix} \alpha \\ \beta \\ 0 \end{pmatrix} = \frac{1}{3}\begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 1 & 1 & 1 \end{bmatrix}\begin{pmatrix} a \\ b \\ c \end{pmatrix} \tag{1}$$

In (1), α and β are the aerial modes which show the relationship between phases A and B, and phases A and C, respectively, and 0 is the ground mode. To have a parameter for showing the relationship between phases B and C, a redundant matrix is defined as the following:

$$\begin{pmatrix} \alpha \\ \beta \\ \gamma \\ 0 \end{pmatrix} = \frac{1}{3}\begin{bmatrix} 1 & -1 & 0 \\ 1 & 0 & -1 \\ 0 & 1 & -1 \\ 1 & 1 & 1 \end{bmatrix}\begin{pmatrix} a \\ b \\ c \end{pmatrix} \tag{2}$$

2.2. Teager energy operator

TEO which was first developed by Teager [27] is a non-linear signal operator. This is then proved by Kaiser [28] that TEO can be used to extract the energy of a specific signal. To explain TEO, a power system signal is considered as (3):

$$x(t) = \sum_i A_i(t)\cos\left(\Theta_i(t)\right) = \sum_i a_i e^{\sigma_i t}\cos(\omega_i(t)t + \phi_i) \tag{3}$$

where a_i, ω_i, σ_i and ϕ_i are the amplitude, frequency, damping and phase of the ith signal component respectively.

Continuous and discrete forms of TEO can be defined by Eqs. (4) and (5), respectively:

$$\psi_c[x(t)] = \left[\frac{dx(t)}{dt}\right]^2 - x(t)\frac{d^2x(t)}{dt^2} \tag{4}$$

$$\psi_d[x(n)] = x^2(n) - x(n-1)x(n+1) \tag{5}$$

By considering (3) and (5):

$$\psi_d[x_i(n)] \approx A_i^2(n)\sin^2\left[\Omega_i(n)\right] \tag{6}$$

where $\Omega_i(n) = \omega_i(n)T$. By use of the discrete form of TEO and by applying ψ_d to both $x_i(n)$ and $y_i(n)$, which $y_i(n) = x_i(n) - x_i(n-1)$, $\Omega_i(n)$ and $A_i(n)$ can be derived by the following equations:

$$\Omega_i(n) = \arccos\left(1 - \frac{\psi_d[y_i(n)] + \psi_d[y_i(n+1)]}{4\psi_d[x_i(n)]}\right) \tag{7}$$

$$A_i(n) = \sqrt{\frac{\psi_d[x_i(n)]}{1 - \left(1 - \left(\psi_d[y_i(n)] + \psi_d[y_i(n+1)]\right)/4\psi_d[x_i(n)]\right)^2}} \tag{8}$$

3. The proposed algorithm

In order to construct the protection algorithm, the power system presented in Fig. 1 is simulated in PSCAD/EMTDC.

In this algorithm, AB is the protected line and the relay is located in bus A. Voltage and current signals are continuously sampled by CCVT and CT and then analyzed by the relay. For example, Fig. 2 shows three phase current signals related to an ABg fault which occurs at 40 km from the relay location with the fault inception angle of 36 degrees. Note that the sampling frequency is 200 kHz.