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Equivalent traveling waves based current differential protection of EHV/UHV transmission lines

Aoyu Lei[a,*], Xinzhou Dong[a], Shenxing Shi[a], Bin Wang[a], Vladimir Terzija[b]

[a] State Key Laboratory on Power System, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China
[b] The School of Electrical and Electronic Engineering, University of Manchester, Manchester M13 9PL, UK

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ABSTRACT

Current differential protection is one of the most important primary protections of extra/ultra-high-voltage (EHV/UHV) transmission lines. Despite its wide application, there exist major adverse factors of synchronization misalignment, current transformer (CT) saturation and line capacitive charging current, which may lead to a mal-operation. To solve these problems, a new current differential protection method, based on the concept of equivalent traveling wave (ETW), is proposed. The protection method is immune to CT saturation and line capacitive charging current, operates at an ultra-high speed, and does not require synchronized sampling. In the protection method, wavelet transform modulus maxima (WTMM) are used to reconstruct the current ETWs and thus reduce the communication traffic to an appropriate level. The reconstructed ETWs are then used to establish the percentage restraint operation criterion. Besides, a blocking method is implemented to avoid possible mal-operation when an external fault occurs on a line that forms a parallel path but has no mutual coupling with the protected line. Extensive simulations verify that the proposed protection method can serve as a secure and reliable primary protection for non-, shunt-, or series-compensated transmission lines with high sensitivity, even on internal high-resistance faults.

1. Introduction

With the significant technological advances in digital communications, differential protection outscores alternatives like overcurrent and distance protection as fast primary protection for transmission lines due to its inherent simplicity, absolute selectivity, excellent sensitivity on internal faults, high security against external faults and disturbances, and besides, great robustness for various operation conditions [1]. However, the performance of differential protection is severely weakened by synchronization misalignment between samples at both terminals of the line, current transformer (CT) saturation, and prominent line capacitive charging current along the extra/ultra-high-voltage (EHV/UHV) transmission lines [1]. Those adverse influences make it difficult for the conventional percentage differential protection to determine an acceptable bias characteristic that provides adequate sensitivity and high security.

The ping-pong method can calculate the channel delay as long as the transmitting and receiving paths are identical which is however not always available in practical application [1]. The measurements can be precisely time stamped and synchronized by global positioning system (GPS) [2], but the economic cost and the possibility of GPS signal interruption are worth considering. The impact of CT saturation on differential protection has been analyzed [3] and scholars have presented CT saturation detection approaches [4,5]. In addition, some adaptive differential protection algorithms are proposed to increase security level against external faults when the CT saturates [6,7]. Nevertheless, the impact of CT saturation is not eliminated essentially and the sensitivity is consequently compromised to achieve enough security.

In order to reduce or completely eliminate the effect of line capacitive charging current, instead of the installment of shunt reactors, the solutions at present can be classified into the following three categories:

Solution 1. Calculate the line capacitive charging current and subtract it from the measured currents [8]. However, the phasor compensation algorithm can only compensate the steady-state line capacitive charging current, whereas the time-domain compensation algorithm is based on Π-equivalent circuit of the transmission line which is not an accurate model in a wide frequency band.

Solution 2. Constitute differential protection from the viewpoint of traveling wave (TW) that inherently considers the distributed capacitance of transmission line. The first type of TW differential protection is

Abbreviations: EHV, extra-high-voltage; UHV, ulta-high-voltage; ETW, equivalent traveling wave; TW, traveling wave; CT, current transformer; CCVT, coupling capacitor voltage transformer; WTMM, wavelet transform modulus maxima; DWT, dyadic wavelet transform

* Corresponding author.
E-mail address: lay13@mails.tsinghua.edu.cn (A. Lei).

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to compare the directional TWs of both terminals [9]. Another type of TW differential protection, which can also apply to series-compensated lines, makes a comparison of currents at a specified reference point that could be either terminal of the line [10] or any point within the line [11]. All TW differential protections mentioned above use low sampling rate and implement their algorithms with power frequency quantities, thus avoiding the shortcoming that the coupling capacitor voltage transformer (CCVT) cannot reproduce transient voltage TWs but making a concession to the operation speed. There also exist methods of TW differential protection that are based on high sampling rate and have the ability of ultra-fast clearance [12,13]. The methods in [12,13] both successfully reduce the amount of communication traffic which is a common challenge for TW differential protection with the high sampling rate, but the problem of CCVT still remains and prevents the two methods from being practical. To achieve ultra-fast clearance and avoid the usage of CCVT, a current-only TW differential protection is proposed and realized [14], but the method demands high-speed communication (up to 1 Gbps) which exceeds greatly the capability of communications in existing power systems.

Solution 3. Broaden the concept of differential protection and conceive new theories. The active current, extracted by tracking the voltage phase, is employed to develop the differential criterion [15], but this method cannot work well in the dead zone of voltage when severe close-in faults occur. Ref. [16] utilizes a 20 ms moving averaging window to obtain the dc component of currents and does not need voltage signal, but the filtered currents cannot eliminate the power frequency component of the fault superimposed current until 20 ms after a fault. Moreover, impedance differential protections were put forward [17,18]. Those differential impedances inherently take the line capacitive charging current into account and differ greatly between internal faults and external faults, but there are still individual deficiencies.

This paper aims at the implementation of current differential protection of EHV/UHV transmission lines with the advantages of the immunity to synchronization misalignment, CT saturation and line capacitive charging current. The current equivalent TWs (ETWs) are employed to establish the percentage restraint operation criterion. Since the current ETWs are part of the fault superimposed current, an adequate sensitivity on high-resistance faults is achieved without compromising the security. Besides, an existing TW direction element is supplemented to block potential mal-operation, when an external fault occurs on a line that forms a parallel path but has no mutual coupling with the protected line, and thereby terminating at the same buses. The proposed protection method utilizes high-sampling rate and achieves ultra-high-speed operation, but the method largely reduces the amount of communication traffic and avoids the problem of the limited bandwidth of CCVT.

The paper is organized as follows: the basic principle of differential protection and the introduction of ETW are given in Section 2. Section 3 elaborates the algorithm of the proposed protection method. In Section 4, extensive simulations are performed to evaluate the proposed protection method. Section 5 discusses the calculations and operation time. At last, Section 6 concludes this paper.

2. Basic principle

2.1. ETWs and their reconstruction

The concept of ETW is proposed recently and has few applications [13,19]. Here, ETW is briefly introduced as follows. When a fault occurs on a transmission line, the faulted network can be decomposed into a pre-fault network and a fault superimposed network according to superposition principle. Fig. 1 shows the fault superimposed network

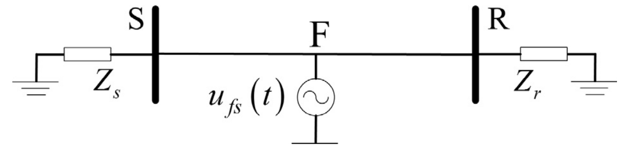

Fig. 1. The fault superimposed network of transmission system.

where F denotes fault point. The following discussions are made based on the fault superimposed network.

The fault superimposed source $u_{fs}(t)$, shown in the following expression, is identical to the opposite value of the pre-fault source after fault occurrence.

$$u_{fs}(t) = -U_f \sin(\omega t + \varphi) u(t - t_0) \tag{1}$$

where U_f is the amplitude, φ the initial angle, $u(t)$ the unit step function and t_0 the fault instant. According to Duhamel integral principle, we can get the response $y(t)$ with respect to the excitation $u_{fs}(t)$:

$$y(t) = \underbrace{-U_f \sin(\omega t_0 + \varphi) e(t - t_0)}_{p(t)} + \underbrace{\int_{t_0}^{t} -\omega U_f \cos(\omega \tau + \varphi) e(t - \tau) d\tau}_{q(t)} \tag{2}$$

where $e(t)$ is the unit step response. The response $y(t)$, which could be the voltage or the current captured at either terminal, is decomposed into two parts, namely $p(t)$ and $q(t)$. The first part $p(t)$ is actually the response to an equivalent dc source $u_{dc}(t)$ which applies to the same network at the same location and the same instant. The expression of the dc source is given by:

$$u_{dc}(t) = -U_f \sin(\omega t_0 + \varphi) u(t - t_0) \tag{3}$$

From the viewpoint of fault transient TW, the fault superimposed source $u_{fs}(t)$ produces real TWs, whereas the equivalent dc source $u_{dc}(t)$ generates the ETWs. Therefore, the ETWs can be regarded as the response $p(t)$ in the transient stage.

The response $y(t)$ and $p(t)$ contain the same discontinuities since the rest part $q(t)$ is uniformly continuous. These discontinuities, in essence, indicate the arrival of TWs and ETWs, hence there is the possibility of reconstructing the ETWs by detecting and extracting the TWs in $y(t)$.

If neglecting the attenuation and distortion of TWs, we can regard the transient $p(t)$ (namely ETWs) as the superposition of a series of step functions. If we get correctly the amplitude and arrival instant of each TW, then the ETWs can be reconstructed as follows:

$$\mathrm{ETW}(t) = \sum_{k} A_k u(t - t_k) \tag{4}$$

where A_k and t_k denote the step amplitude and arrival instant of the k-th TW respectively. In practice, the attenuation and distortion of TWs are inevitable due to the existence of the line resistance and the frequency dependence of line parameters. Fortunately, we simply spotlight the ETWs within a few milliseconds after fault, which means the attenuation and distortion are very slight and can be ignored.

The discrete dyadic wavelet transform (DWT) with the derivative of the cubic B-spline function as mother wavelet serves as a good option for analysis of TWs [20]. Wavelet transform modulus maxima (WTMM) are defined as the local maxima of the wavelet details. WTMM can represent the amplitude and the arrival instant of TWs, and thus reconstruct ETWs. It has been verified that the reconstructed ETWs are a good approximation of the real ETWs within a few milliseconds after fault [13,19].