

Single-ended travelling wave-based protection scheme for double-circuit transmission lines



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ABSTRACT

In this paper, a new single-ended travelling wave-based protection scheme for double-circuit lines is proposed. It is developed to operate in parallel with traditional phasor-based protective relays and is able to accelerate the tripping time in most fault scenarios. The proposed method considers the propagation of travelling waves in a loop formed by the faulted and healthy line circuits. Disturbances within a given protected zone can be reliably detected according to the amplitude, polarity and time difference between the arrival instants of travelling waves that reach the monitored terminal. Also, the accumulative cross-differential current deviation is used to confirm internal faults, distinguishing them from other non-fault events. From the analysis of massive digital fault simulations and actual field records, it is attested that the proposed protection is feasible and effective.

1. Introduction

Quick and reliable fault clearance is of utmost importance for high voltage transmission lines, since it improves the system stability, reduces fault-induced overvoltage and avoids the spread of power supply interruptions [1]. Double-circuit lines have been increasingly used in recent decades, since they have larger transmission capacity and smaller land occupation than two separate single-circuit lines with the same rated voltage [2]. However, protective relays used in double-circuit lines are more complex than those used in single-circuit ones due to two main reasons: (1) Inter-circuit and cross-circuit faults may occur on double-circuit lines, requiring more effective faulted phase selection approaches; (2) Special treatment for current reversal and zero sequence mutual coupling between the two lines are needed [3]. Furthermore, mal-operations of a double-circuit line relay can cause serious stability problems, such as cascading faults, disconnection of interconnected sub-systems and large scale power supply interruptions. Therefore, the development and improvement of double-circuit line protection schemes have been topics of great interest for utilities and researchers [4,5].

Unlike fundamental component-based protective relays, high frequency-based protection devices have shown to be immune to current transformer (CT) saturation, power swings and fundamental current reversal. Besides, these devices have more potential for speeding up the fault clearance procedure, which is becoming an urgent requirement, as

the number of double-circuit lines increases in modern power grids [6].

High frequency based protection relays for double-circuit lines have been divided into two categories: directional comparison relay, and cross-differential relay [1]. Directional comparison relays can protect the whole line [7,8], but they require two-terminal data, thereby the use of communication channels is crucial. As a consequence, the application of directional comparison relays is usually expensive and requires high precision time synchronization of the two-terminal measurements if the unity line protection is required. On the other hand, cross-differential relays detect internal faults as well, but requiring data taken from one-terminal only. However, it is not able to distinguish transients induced by faults from those induced by the opening of circuit breakers [9]. To overcome this problem, two kinds of methods have been reported. The first is based on the impedance seen by the relay, which requires the analysis of voltage signals [4,10,11]. Consequently, it is affected by the transient response of coupling capacitor voltage transformers (CCVTs), which normally attenuate high frequency components [6]. The other method is based on the analysis of travelling waves induced by the opening of remote end breakers [12–14]. Nevertheless, it is difficult to obtain the time sequence of the local and remote circuit breakers' opening, since the breakers at both line terminals usually trip automatically and separately according to their associated protection schemes. Furthermore, in general, the existing high frequency-based protection methods are prone to mal-operation in cases of non-fault disturbances, such as lightning strokes and switching

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maneuvers, which is often reported in the literature as a drawback.

In practice, most frequent transmission line faults have the following features: fault inception angles are not close to zero, making the first induced travelling waves easy to be detected; fault resistances are small and do not drastically change; and the amplitudes of fault currents increase sharply. For the sake of simplicity, hereafter, faults with the aforementioned features will be referred to as common faults. For years, the analysis of field records has proven that initial current transients induced by common faults are easy to capture, making travelling wave-based protection schemes feasible and suitable for line protection [6,15,16]. Therefore, although it is quite difficult to design a protection element that has simultaneously fast response, high sensitivity, selectivity, high reliability and full coverage, irrespective of the fault type, the development of reliable and secure high-speed protection algorithms for certain protected zones is still feasible, which can improve the system transient stability in common fault cases.

For most double-circuit lines, both circuits are usually in service, so that the information about the waves that travel along the healthy line circuit can be used to enhance the selectivity and reliability of the transient data-based fault identification process. The healthy circuit can be considered as a “communication channel” between the local and remote line ends, allowing the development of more reliable and faster single-ended protection methods, without the need for actual communication systems. Based on this idea, a new single-ended protection algorithm for double-circuit lines is proposed in this paper. Compared with other travelling wave based protection methods, the method makes use of travelling waves extracted from the faulted and healthy lines, overcoming the need for communication channels and time synchronization of local and remote measurements. Besides, it has the following advantages: (1) fast response; (2) no deadzone for close-in faults; (3) selectivity for tapped lines. The obtained results show that the proposed protection is able to speed up the trip decision in common fault cases, providing an instantaneous trip prior to conventional protective relays.

2. Proposed algorithm

Most substations in modern power networks have several lines connected, resulting in looped circuits along which fault-induced voltage and current electromagnetic waves travel. Since the reactance of transformers and shunt reactors are much greater than the surge impedance of the connected lines, they can be nearly considered as open-circuit for high-frequency travelling waves components [17], as will be discussed in the next section. Based on that, a typical equivalent topology of a double-circuit line in loop can be expressed as shown in Fig. 1, where u_f is the voltage at the fault point, R_f is the fault resistance, $i_{backward}$ represents the waves travelling toward the monitored Bus M, $i_{forward}$ represents the waves travelling toward the monitored Bus N, n_m and n_n are the number of lines connected to the monitored buses M and N except the faulted line, respectively, and L_s , x_m and x_n stands for the line length, and the fault distance from the monitored buses M and N, respectively.

In this paper, the initial backward current waves that travel from the fault point toward the monitored terminal are defined as the dominant waves. The proposed protection algorithm makes use of the

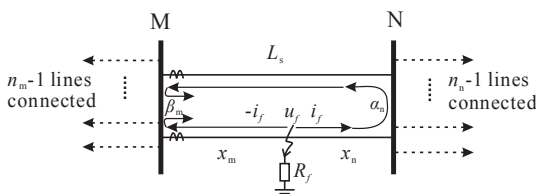


Fig. 1. Propagation of travelling waves along a double-circuit line in loop.

dominant waves at the same terminal taken from the faulted and healthy lines. The detection of dominant waves can be implemented according to the difference in polarities and amplitudes features between the faulted line and the healthy line. The detailed analysis of the travelling waves' propagation in double-circuit lines and their polarities and amplitudes features are addressed in the Appendix A.

The healthy line of the double-circuit line is considered as a “communication channel”, through which additional remote-side fault information is sent to the monitored terminal. The proposed algorithm works as follows: Firstly, disturbances inside the protected zone are identified from the analysis of dominant waves in the looped circuit, and, then, the fault occurrence is confirmed according to the cross-differential currents after the disturbance inception. To perform these procedures, the algorithm is divided into three steps: (1) initialization; (2) detection of dominant waves; and (3) fault confirmation. Phase currents are captured using high sampling rates $f_{sH} = 64$ kHz to perform the dominant wave detection and fault confirmation steps. On the other hand, the initialization step does not require the use of very high sampling rates, thereby a lower sampling rate $f_{sL} = 10$ kHz is used in this step to reduce the computational burden of the proposed algorithm. To facilitate the understanding of the proposed algorithm, in this paper, RMS quantities and constants are represented using capitalized Italic font, whereas instantaneous values are represented using lowercase Italic font, while sampling rate f_s is the only exception.

2.1. Initialization

In this stage, to initialize the proposed algorithm, the loop detection is performed. The algorithm verifies if the faulted and healthy lines are forming a loop in the monitored circuit, i.e., the proposed protection scheme is enabled whenever the loop is available. It should be pointed out that the loop detection does not trigger the algorithm, but it blocks the protection operation as soon the loop is not detected in the monitored double-circuit line.

Loop detection is based on the RMS values of phase currents. The RMS value is estimated by using downsampled version of the digitized signal sampled at f_{sL} in a sliding window. Then, the algorithm checks whether phase currents RMS values of both circuits are above a threshold using:

$$I_{k,p} \geq I_{th}, \quad (1)$$

where $I_{k,p}$ stands for the RMS value of the p phase current in the line k , $k = 1, 2$; $p = a, b, c$; I_{th} stands for the threshold, which can be set as 5% of the RMS value of the rated current to avoid the misjudgment due to the influence of the coupling of line phases in cases in which there is only one circuit in-service and the other circuit is off-service, considering the fact that the maximum percentage of the coupling component cannot be greater than 5%.

The proposed algorithm assumes that a loop exists as soon as (1) is satisfied for both circuits of the monitored line. If the loop is detected, an internal disturbance is determined if the difference between the sum of instantaneous current values sampled at f_{sL} taken from both circuits in a short time-period ε exceeds a threshold I_{op} :

$$\left| \sum_t^{t+\varepsilon} i_{diff}(t) \right| = \left| \sum_t^{t+\varepsilon} i_{1,p}(t) - \sum_t^{t+\varepsilon} i_{2,p}(t) \right| \geq I_{op}, \quad (2)$$

where $i_{k,p}(t)$ is the instantaneous value of the p phase current in the line k ; ε is the analyzed time-period, which is set as 3 ms in this paper. In some non-fault cases, currents in both circuits may be different, leading (2) to present a small value. For the sake of security, the threshold I_{op} of 10% of the rated current is suggested.

In the proposed algorithm, (2) is only a starting element to detect internal disturbances, being the trip decision made after the evaluation of other security conditions. The phase which satisfies (2) is selected as the faulted one. The first time instant t for which (2) is satisfied is taken

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