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Determining secondary arc extinction time for single-pole auto-reclosing based on harmonic signatures

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ABSTRACT

In this paper, a new algorithm based on harmonic signatures is proposed to detect extinction of secondary arc for single-pole auto-reclosing (SPAR). In the proposed algorithm, the TT-transform is used to highlight harmonics of healthy phase voltages. The criterion for the detection of extinction of secondary arc is harmonics amplitudes, which is calculated after the TT-transform. The algorithm is noncommunication and the threshold value is adaptive; therefore, for various transmission systems no special adjustment is needed. To evaluate the accuracy of the proposed scheme, numerous simulations under different conditions including fault location, fault inception angle and line compensation are performed, in all of which the highest reliability is achieved.

1. Introduction

Statistics has shown that more than 80% of faults in overhead lines are of the transient type and, with similar percentage they are single phase to ground faults [1]. Transient faults are caused by lightning or falling of external bodies on the lines; such faults are always associated with arcs [2]. In transmission lines, fault arcs are categorised into two classes, namely primary and secondary. The primary arc happens after inception of the fault, caused by the lightning strike or other reasons, which lasts until the tripping of the faulty phases. On the contrary, the secondary arc occurs after the circuit breakers (CBs) trip as it is sustained by the capacitive and inductive coupling between the healthy and opened phases. Single-pole auto-reclosing (SPAR), which means that only the faulted phase is opened, is the most recommended switching procedure to eliminate transient faults. Fundamentally, extinction of secondary arc is the main factor for success of SPAR. In conventional SPAR, the dead time is set to a predefined fixed value, varying from 500 ms to 2 s [3], assuming the arc will extinguish within this dead time. In some cases, the opened phase is reclosed in excessive time because this fixed dead time can be quite large. For short dead time, reclosing can be occurred on an existing transient fault [4]. Generally, to improve reliability of a power system, it is important to reduce dead times and reclose breakers as fast as possible after the arc extinction. Thus, it is crucial to accurately know the exact extinction of secondary arc time.

Thus far, several methods are proposed to detect extinction of secondary arc. Spectral energy of high frequency (HF) current and voltage transients are used in Refs. [5] and [6] in order to determine extinction of secondary arc. These methods rely on the capturing of the high-frequency harmonics generated by the secondary arc to determine the moment when the arc extinguishes. During the period of secondary arc, spectral energy is calculated and, when it is less than a threshold value, the arc is assumed to be extinguished. The drawback of these algorithms is necessity of high sampling frequency [5,6]. The presented algorithm in Ref. [7] computes the root mean square (RMS) value of the opened phase voltage to detect the extinction time of secondary arc. Here, extinction of secondary arc is indicated when the difference between the present and previous RMS in each time step is greater than or equal to a certain threshold level. However, this algorithm is sensitive to severe changes in voltage signal. The presented algorithm in Ref. [8] detects extinction of secondary arc based on calculating low frequency components of the opened phase voltage waveform. In this method, a harmonic distortion index (HDI) is introduced and the extinction time of secondary arc is detected by comparing a suitable threshold value and HDI. In Ref. [9], differential protection principles, which are applied to the zero sequence power at both ends of the line, are used to identify the extinction time of secondary arc. However, this scheme requires communication channels at the line terminals. In Ref. [10], the total harmonic distortion (THD) value of the opened phase voltage is obtained and it is shown that after extinction of secondary arc, the THD has a great decrease. This scheme is not applicable for compensated transmission lines. The presented scheme in Ref. [11] uses current and voltage phasors at both ends of the line. The presented algorithm calculates the angle of post-fault arc voltage at the measurement point after the CB is opened and, if this angle is less than a threshold, the secondary arc is extinguished. In Ref. [12], the third harmonic of the

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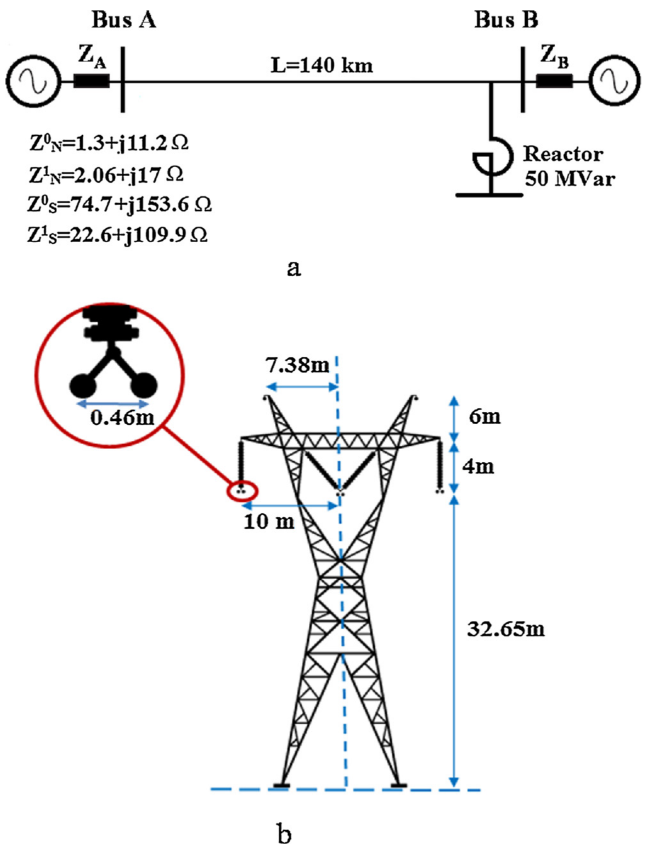

Fig. 1. Test power system. (a) Single line diagram. (b) Structure of tower.

Table 1
Transmission line parameters.

Length of line	140 km
Positive sequence impedance (per unit)	$Z^+ = 0.03116 + j0.334$
Zero sequence impedance (per unit)	$Z^0 = 0.3792 + j1.05$

zero sequence voltage (V_3) is used to evaluate the extinction time of secondary arc. It is mentioned that during the period of secondary arc, V_3 is high and, as the secondary arc is quenched, its value decreases to a low value. In Ref. [13], an algorithm based on the Gaussian mixture model (GMM) is introduced to detect extinction of secondary arc time. The presented scheme uses two classes of GMM. These GMMs are trained by post-fault signals and the secondary arc signal, respectively. If the likelihood probability of GMM1 is higher than the output of GMM2 during the period of secondary arc detection, the arc is extinguished. In Ref. [14], a communication based method is presented to predict the opened phase voltage from both ends of the line by using the synchronized voltage phasor after single-phase opening and arc extinction. Therefore, the extinction time of secondary arc can be detected when the opened phase voltage magnitude and angle are close enough to the predicted ones. A noncommunication based algorithm is presented in Ref. [15] by analysing the local voltage signal using the adaptive cumulative sum method (ACUSUM) algorithm. ACUSUM is employed to detect three consecutive events in the voltage signal during a fault, i.e. two decrease and one increase, where the third event indicates extinction of secondary arc. Another perspective analyzes the voltage magnitude and angle pattern of the faulty phase, after the line single-phase opening, in order to detect extinction of secondary arc [16]. In Ref. [17], an algorithm is presented, which calculates the ratio of even harmonics to odd harmonics of the opened phase voltage to detect the extinction of secondary arc. The algorithm shows that the even and odd harmonics of the opened phase voltage have different characteristics after the CB is opened. Moreover, in this study, it is mentioned that the algorithm is applicable for transmission lines with shunt reactors. In Ref. [18], the difference between the actual and calculated values of the opened phase voltage magnitude is used for detection of secondary arc extinction. At the instant of arc extinction, because of a sudden change in the voltage, the calculated voltage magnitude does not match the measured voltage magnitude. In Ref. [19], a reclosing technique is presented to determine the extinction time of arc of a transient fault by using the harmonics of the opened phase voltage. The presented technique uses the magnitude of the DC component of the opened phase voltage for detecting the extinction of secondary arc. If the energy coefficient of the DC component is greater than zero, it means that the arc is extinguished. The presented scheme in Ref. [20] uses phase space (PS) from the local voltage signal to detect extinction of secondary arc. The PS describes dynamics of the system in a mathematical space. The specifications of system in the PS during the period of secondary arc and after extinction of secondary arc is different. Although the results presented in Ref. [20] seem appropriate, it needs to select constantly predefined thresholds.

In this paper, a new algorithm based on harmonic signatures is proposed for detection of the secondary arc extinction time. The presented approach uses the TT-transform to magnify the harmonics of voltage signals of healthy phases. The magnitude of the boosted harmonics gives the appropriate criterion, which remains high during secondary arc, whereas the extinction of secondary arc is happened when the criterion is decreased. The results of simulations under different conditions show that the proposed algorithm can be employed as an effective tool for detecting the extinction of secondary arc.

The rest of this paper is organized as follows. The secondary arc is discussed in detail in Section 2. Sections 3 introduces the TT-transform. The proposed algorithm is described in Section 4. The simulated power system and the obtained results are explained in Section 5. The paper concludes in Section 6 with the main highlights and achievements.

2. Secondary arc

2.1. General consideration

A single phase transient fault can cause a primary arc between the faulted phase and ground. By using SPAR, can isolate the faulted phase from the power system. During the single pole opening, a voltage in the open phase conductor is induced by capacitive and inductive coupling between the open phase and healthy phase conductors. Because the air around the fault is already ionized by the primary arc, this induced voltage can create a secondary arc and sustain it for a given time after the phase opening. Various experimental studies and field tests have shown that the secondary arc is an extremely complex phenomenon, which is influenced by different parameters. The extinction time of secondary arc depends on several factors, some of which are as follows: magnitude of secondary arc current, recovery voltage, line compensation level, magnitude of line voltage and line length. These factors are also affected by weather conditions such as wind speed, temperature and humidity.

2.2. Modeling

In simplified studies, the fault arc is modeled by a resistor or a square voltage source. More complicated models describe the arc by piecewise characteristics. These models do not represent real interaction of the arc and the electromagnetic transient correctly. The differential equation of the arc conductance for existing secondary arc models is defined as [21]:

$$\frac{dg_s}{dt} = \frac{1}{T_s}(G_s - g_s) \tag{1}$$

where g_s and G_s are the time-varying and stationary arc conductance