Electrical Power and Energy Systems 96 (2018) 64–73

Contents lists available at ScienceDirect

Electrical Power and Energy Systems

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

Adaptive single-phase auto-reclosing method using power line carrier signals

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ARTICLE INFO

Keywords:
Adaptive auto-reclosing
ASPAR
Auto-reclosure
PLC
Power line carrier

ABSTRACT

This paper proposes a new method for adaptive single-phase auto-reclosing (ASPAR) that improves the rate of successful reclosing actions after the occurrence of a transient single-phase fault and prevents unsuccessful reclosing. After the occurrence of a fault, the only faulty phase is disconnected by the protection system (e.g., distance relays and circuit breakers). The proposed method deploys power line carrier (PLC) signals for determination of the secondary arc extinction time and releasing the reclosing signals to the circuit breakers. Despite the growing use of new communication systems (e.g., fibre-optic links), PLC systems are still widely used, and may not be considered for replacement in near future. Therefore, the proposed method can be utilized as an auxiliary application of PLC systems to enhance the resiliency of power grids. The simulation studies are carried out using EMTP-RV and MATLAB, and the advantages and disadvantages of the proposed method are discussed and compared with the existing ASPAR methods. According to the simulation results, the efficiency of the proposed ASPAR method is negligibly influenced by the following factors: fault location, faulty phase, system loading, transmission line transposition, shunt reactor, PLC carrier frequency, PLC operating mode, and the noises.

1. Introduction

A large number of faults in power transmission systems are transient [1,2], and auto-reclosing (AR) is an efficient approach to clearing such faults and avoiding long-time outages. As most of the faults in transmission lines are single-line-to-ground (SLG), single-phase auto-reclosing (SPAR) is developed for disconnection and reconnection of the only faulty phase [3,4]. Therefore, SPAR improves power system transient stability and reliability [4–7], as the non-faulty phases can be still used for power transmission in a grid. SPAR also decreases switching over voltages and generator shaft oscillations [1,4–6]. In the traditional AR and SPAR, the tripped circuit breaker (CB) stays open for a fixed and predefined dead time for the arc to extinguish [2–5]. However, the non-linear nature of an arc is influenced by a number of random factors such as convection of the plasma and the surrounding air, wind, humidity, and atmospheric pressure [8,9]. Thus, arc lifetimes randomly vary, and consequently, the following issues arise from the fixed-time dead times (i.e., conventional AR): (1) if the fault is permanent, reclosing actions put more stress on the power system components and decrease power system stability [10]. (2) In the case of a transient fault with a lifetime longer than the predefined dead time, reclosing actions re-energize the arc. Therefore, in addition to imposing more stress on power system equipment, it is probable that the transient fault becomes permanent [4,5,10]. (3) If the fault arc extinguishes before the predefined dead time, the power system profits less from AR. Accordingly, a CB should reclose immediately after the arc extinction [4]. Therefore, adaptive single-phase auto-reclosing (ASPAR) is introduced in the literature for accurate determination of the arc extinction time to reclose the CBs. According to the required data for determination of the secondary arc extinction, the proposed methods for ASPAR in the literature can be broadly divided into: (1) non-communication-based (single-ended) ASPAR that requires only the data from the local bus. (2) Communication-based (double-ended) ASPAR that requires the data from both local and remote buses.

Several methods for single-ended ASPAR are introduced in the literature. In [3], the proposed single-ended ASPAR relies on the waveform pattern of the local bus voltage after disconnection of CBs. The RMS value of the faulty-phase voltage is calculated, and it becomes relatively large once the secondary arc extinguishes. However, this method is relatively slow mainly due to the required time for calculation of the full-cycle RMS value. In [4], the proposed single-ended ASPAR utilizes local voltage measurements, and a sudden rise in the

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http://dx.doi.org/10.1016/j.ijepes.2017.09.033
Received 23 May 2017; Received in revised form 29 July 2017; Accepted 23 September 2017
0142-0615/

measured voltages, detected by cumulative summation (ACUSUM) filter, indicates the secondary arc extinction. In [5], a single-ended ASPAR is proposed that employs the voltage phasor of the faulty phase to distinguish between permanent and transient faults and also to detect the arc extinction time. In [10], a method is proposed in which the total harmonic distortion (THD) of the local measured voltage is calculated using discrete Fourier transformation (DFT) and the arc extinction time is detected according to the calculated THD level. In [11], a single-ended ASPAR is proposed that calculates the post-fault zero-sequence voltage of the local bus. Then, the third harmonic level in the zero-sequence voltage is utilized for detection of the arc extinction. In [12], a single-ended ASPAR is proposed in which the currents of the non-faulty phases are measured at a fixed sampling rate of 10 kHz, and then using wavelet packet decomposition (WPD), the summation of the absolute values of the calculated wavelet nodes are used as an index for distinction of permanent and transient faults and for identification of the arc extinction as well. In [13], the proposed single-ended ASPAR discriminates transient and permanent faults by comparing the voltage pattern of the faulty and non-faulty phases in a complex plane. A single-ended ASPAR based on numerical spectral domain is proposed in [14], which discriminates transient and permanent faults and also estimates the fault distance. This method utilizes the fundamental and third harmonic contents of the local voltage and current measurements to distinguish between the transient and permanent faults. However, it is not capable of detecting the arc extinction time. In [15], a single-ended ASPAR is proposed in which the frequency contents of the measured voltage at the local bus are analyzed using discrete wavelet transform (DWT) with Daubechies mother wavelet. Then, the secondary arc extinction is detected based on the levels of certain frequencies. In [16], a single-ended ASPAR is introduced that uses the local voltage of the faulty phase. It distinguishes between permanent and transient faults and estimates the arc extinction time using the adaptive linear neuron (ADALINE) method. Another single-ended ASPAR is proposed in [17] that is able to distinguish between permanent and transient faults under different fault types, including ground faults, cross-line faults, and interphase faults. This method is based on the summation of the faulty-phase recovery voltage with respect to time. The summation is almost zero for permanent faults, while it is large for transient faults. However, the method is not able to detect the arc extinction time.

Several double-ended ASPAR methods are proposed in the literature. The proposed double-ended ASPAR in [18] is based on synchronized current and voltage measurements at both ends of the faulty line. The time-synchronized measurements are converted to spectral domain using DFT. Then, permanent and transient faults are distinguished and the arc extinction time is determined based on the harmonic level in the frequency spectrum. This method is able to determine the arc resistance as well. However, it requires a capable communication link for data transfer and it is only proper for single circuit lines. The double-ended ASPAR in [19] utilizes the voltage and current phasors provided by synchronized phasor measurement units (PMUs) at both ends of the faulty line. Then, THD is calculated and used as an index for distinguishing permanent faults from transient faults. In [20], a double-ended ASPAR is proposed for only transposed transmission lines. This method predicts the faulty-phase voltage using the non-faulty phase voltages measured by PMUs. Once the voltage phasor of the faulty phase is close to the predicted value, the arc extinction is determined. In [21], an ASPAR method is proposed in which Prony analysis is utilized to extract the features of the voltage measurements during a fault. Then, the transient and permanent faults are discriminated using the extracted features and artificial neural network (ANN). However, the proposed method requires extensive off-line simulations for training the ANN-based decision-making process.

The applications of power line carriers (PLCs) in fault location and health monitoring of transmission lines are introduced in [22–24]. In this paper, the application of PLCs in the detection of the secondary arc extinction is proposed for the first time and a new double-ended ASPAR method based on PLC signals is proposed to detect the secondary arc extinction time and to prevent unsuccessful reclosing actions. The proposed method does not require high computational capabilities, and it can be implemented using commercial micro-controllers. As PLC systems are widely used all over the world [25], the proposed method can be considered as an auxiliary application of PLC systems. The efficiency of the proposed method is evaluated using simulation results. It is shown that the proposed ASPAR is not influenced by fault location, faulty phase, system loading, transmission line transposition, shunt reactors, PLC carrier frequency, and PLC operating mode. Also, it has a proper resiliency with respect to the measurement noise. However, the proposed method requires additional coupling components and its delay in detection of the arc extinction is almost half a power cycle.

The remainder of this paper is organized as follows: In Section 2, secondary arcs, the technical features of PLC systems, and the proposed method are described. In Section 3, the test cases and results are providedand discussed. In Section 4, the conclusion is presented. In Appendix A, the formulation describing the effect of the arc resistance on the received PLC signal is provided, and in Appendix B, line tuner units, coupling components, and the attenuation parameters of the transmission lines used in the test cases are presented.

2. Technical background and methodology

In this section, arc stages, technical features of PLC systems, and coupling methods are briefly discussed, and the proposed ASPAR method is then described through an illustrative example.

2.1. Transient faults and secondary arcs

An arc fault consists of two main stages: (1) before CBs disconnect the faulty phase, the arc is fed by the energy sources. This high current arc is called a primary arc. (2) After disconnection of the faulty phase, a relatively low amplitude current still flows to the earth through the arc channel which is fed by the trapped charge and the mutual inductance and capacitance among the faulty phase and the un-faulty phases. This low current arc is called a secondary arc, and it sustains for a relatively short period of time.

However, the CBs must stay open until the secondary arc is fully extinguished [2–8]. The dynamic behaviour of arcs is modelled as [26–29]

$$\begin{cases} R_{arc} = 1/g \\ \frac{dg}{dt} = 1/\tau(G-g) \\ G = \frac{|i_{arc}|}{V_{st}} \\ \tau = \tau_0\left(\frac{l_{arc}}{l_0}\right)^{\alpha} \end{cases} \tag{1}$$

where R_{arc} [Ω] is the time-varying arc resistance, g [S] is the time-varying arc conductance, G [S] is the stationary arc conductance, i_{arc} [kA] is the arc current, τ [s] is the variant arc time constant, τ_0 [s] is the initial arc time constant, α is the negative exponent of the time constant [29] which is in the range of -0.1 to -0.6 [28], l_0 [cm] is the initial arc length, and l_{arc} is the instantaneous arc length [28]. V_{st} [kV] is the stationary arc voltage, defined as

$$V_{st} = (u_0 + r\cdot|i_{arc}|) \times l_0 \tag{2}$$

where u_0 [V/cm] is the constant voltage per arc length and r [mΩ/cm] is the arc resistance per length.

2.2. Power line carriers

PLC systems generate carrier frequencies in the range of 30–500 kHz for communication over transmission lines [30,31]. This frequency range is sufficiently high to be isolated from the power frequency and power system noises [32]. A PLC system is coupled to a