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Design and real-time implementation of a PMU-based adaptive auto-reclosing scheme for distribution networks

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ABSTRACT

This paper presents an adaptive auto reclosing scheme (AARS), applicable to active distribution systems, which are equipped with Phasor Measurement Units (PMUs). The scheme differentiates between temporary and permanent faults by taking into account the operational conditions of the network when determining the reclosing dead time. The performance of the proposed scheme is assessed through a real-time hardware-in-the-loop (HIL) simulation test setup.

1. Introduction

Power system faults can be divided into three categories: transient, semi-permanent and permanent faults. These faults may cause interruptions to a zone of costumers, hence they reduce the network's reliability. However, using Smart Grid features, new advanced protection methods can be utilized in power systems to enhance their reliability and operation [1,2].

Self-clearing transient faults are the most frequently occurring faults in power systems [3]. During these faults, the faulted network can be restored by circuit reclosing when the fault is removed. Accordingly, automatic reclosers are widely used in distribution and transmission networks to minimize outage duration and to provide service continuity [4,5]. Auto-reclosing can also enhance power system stability and reliability [6]. However, unsuccessful reclosing is one of the main concerns about autorecloser operation. Reclosing on a permanent fault, or on a transient fault that is not yet removed imposes additional stress to the network, which can cause system instability and damage to the network equipments [6,7]. Depending on the number of faulted phases, one or three poles of the circuit breaker (CB) will be opened; hence, autoreclosing operation is categorized into single-phase and three-phase operation. In the case of single-phase faults, that is the most frequent type of faults, reclosing is applied only on the faulted phase. In this case, the network enters unbalanced operation conditions and has to be returned to normal operation before system components are damaged. Therefore, fast single-phase reclosing is necessary to prevent the negative impacts of unbalanced operation [8].

1.1. Paper motivation

To provide a safe reclosing and to prevent any damage to the network, it is necessary to reclose when the fault is removed completely or when the network is determined to be stable enough to tolerate another shock (due to the possible existence of a permanent fault). However, these issues are not considered during the operation of conventional autoreclosers. In a conventional autorecloser, which operates regardless of fault type (i.e., temporary or permanent) and network conditions, a fixed open interval is set before reclosing the CB [9]. This open interval is a key factor in the reclosing process, which can lead to a successful or an unsuccessful reclosing. If the fault is removed and its consequent arcs are extinguished during the open interval, the network returns to normal operation. However, in the case of permanent faults or cleared temporary faults with arcs not completely extinguished within the opening interval, reclosing the CB results in reapplying the fault to the network. Due to this uncertainty, the use of adaptive reclosers has been proposed in recent research as an alternative solution [7,8,10,11]. Adaptive reclosing can also minimize the dead time between the reclosing attempts; hence, it reduces the overall duration of the reclosing process.

If the fault type and its clearance time are not detectable, an adaptive auto reclosing scheme (AARS) can be utilized to evaluate the network's operating conditions and reclose the CB only if the system is strong enough to tolerate a possible shock, i.e. it has a safe stability margin.

In sum, an AARS is needed to be able to: first discern between temporary and permanent faults; second, in the case of temporary

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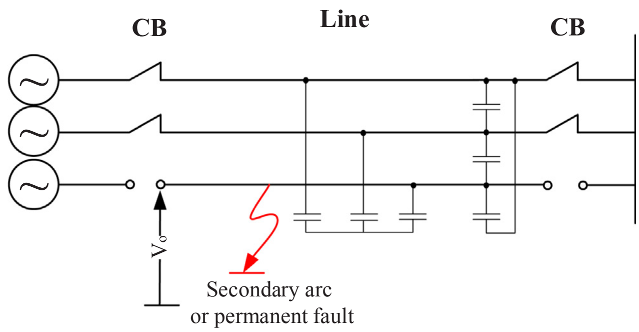

Fig. 1. Isolation of the single-phase fault [7].

faults, reclose when the arc is completely extinguished; and third, in the case of permanent or non-detectable faults, reclose only when the healthy part of the network (upstream the CB) is stable enough to tolerate another reclosing attempt. A literature survey shows that regardless of how advanced the presented methods are, most of the advanced AARSs have not considered the above-mentioned factors.

1.2. Literature review

As mentioned above, the main purpose of the AARS is to prevent reclosing when a fault has not been fully removed or the network is not stable enough to tolerate a new fault. Considering that in overhead distribution systems, temporary faults are more than 80 percent of the total number of faults, the AARS should be equipped with an effective method to detect the optimum time for network reclosing. For example, in case of a single-phase fault occurrence, a temporary fault is followed by a secondary arc which does not appear in the case of a permanent fault [11]. This arc impacts the induced opened-phase voltage (V_o in Fig. 1); hence, specific properties of V_o have been used as a mean to detect the fault type and arc extinction time. Accordingly, the specifications of V_o at the sending and receiving end of power lines have been used in several papers to detect the arc extinction time. In [6,7], the fault type is determined through the harmonic analysis of V_o and the sudden decrease of THD of V_o has been used as an indication that the secondary arc is removed. Moreover, the presented method in [12], uses the specifications of the low frequency components of the faulted phase voltage or current waveforms. Indeed, in this method, a decision-making index has been introduced based on the harmonic analysis of both voltage and current waveforms. However, harmonic-based methods may be affected by external harmonics generated by the other sources. Using the differences between the faulted phase voltage waveforms before and after a permanent or transient fault were also used in [13]. In case of a transient fault, the nonlinear behavior of arcs distorts the voltage waveform; while, in the case of a permanent fault, the main frequency component of the voltage keeps its sinusoidal characteristics. Accordingly, the high-frequency energy of the voltages was calculated and used in [13], in which the spectral energy of two time-windows were calculated. In the case of transient fault occurrence, the spectral energy of these two windows are different while, in the case of permanent faults, they are almost the same.

In [14], the root mean square (RMS) value of V_o is used to determine the fault type and arc extinction time. In this method, if the RMS value of V_o during a pre-specified time window becomes less than a pre-defined threshold, it is considered that the secondary arc was extinguished. In [11], the fault type is determined by analysis of the deviation of the opened-phase voltage magnitude. In [15], a permanent fault is detected by use of the separate and simultaneous analysis of the magnitude and angle of V_o. Moreover, the arc extinction is detected when the derivation of V_o's magnitude and angle close to zero. Similarly, both angle and magnitude are used separately in [8] to detect the fault type; while only the angle is investigated for arc extinction detection. These adaptive autoreclosing schemes were proposed for single-phase faults; however, they are unable to detect the fault clearance and the arc extinction time for two-phase and three-phase faults. In [17] the RMS value of the secondary arc current was used to present a real-time adaption for the autorecloser's dead-times. This method, however, needs to be equipped with a fault locator scheme that is not always available in distribution systems.

A time domain analyzer using the principles of Gaussian Mixture Models (GMM) was presented in [16] to classify the fault types. The GMM was used due to their capabilities in providing a fast and flexible classifier. This method, however, not only needs a training process for the GMM but also is designed based on the time consuming mathematical equations that may affect the speed of the autorecloser.

In [17] the artificial neural networks (ANNs) have been used to discriminate between the temporary and permanent faults and detect the arc extinction time. In this method, the fault voltage waveforms are analyzed by use of the Prony method and then the features of that waveform are fed to an ANN. The ANN, then, determine the fault type and the optimum reclosing time. The AARS presented in [18] uses an Adaline network, that is one of the earliest linear building blocks of the neural networks. In this ANN- based autorecloser, the terminal voltage of the faulted phase is analyzed to estimate the secondary arc time extinction. ANN-based methods have also been used in [3] where they were used to determine the voltage harmonics of the faulted line. Then the, total harmonic inverse factor was used to discriminate between the temporary and the permanent faults. However, the ANN-based methods need to be trained by accurate and wide range of data that are not always available. Moreover, the ANN-based methods can not present a generic autoreclosing method and they should be designed according to the specification of each line.

Due to the limitations of communication-based and intelligent-based methods, the proposed AARS in [9] has been designed based on the phase space (PS) criteria. In this method, the PS information of the local voltages are determined and used to determine the fault type. Moreover, in the case of temporary faults, the achieved PS information is used to determine the arc extinction time. Another non-communication based AARS was presented in [19] in which the local bus voltage is processed by a simple digital filter named adaptive cumulative sum method (ACUSUM). This filter is used to monitor the voltage amplitude and detect the voltage increment and decrement. The AARS sends the close command to the breaker when two successive decrement and one increment in the local bus voltage are detected.

Note that, as mentioned in Section 1.2, an AARS is needed to be able to monitor the network stability and thermal conditions and reclose only when the healthy part of the network is stable enough; however, the above literature survey shows this issue was not considered in most of the already presented AARSs.

1.3. Paper contributions

Network reliability is becoming a major concern at the distribution level [20]. In order to address this issue, adaptive auto-reclosing schemes can be utilized to enhance the reliability of distribution systems. Therefore, this paper presents a comprehensive AARS, applicable to distribution systems, which utilizes PMU measurements as an emerging measurement system at the distribution level, to implement the above-mentioned features. The main contributions of this paper are:

- The paper proposes a PMU-based method to discriminate between the temporary and permanent single-phase faults.
- The paper presents a comprehensive auto-reclosing method for all fault types. In this method, in order to prevent the negative effects of the reclosing attempts on the grid, the AARS operates considering the stability and thermal constraints of the grid.
- The performance of the proposed method has been assessed through a hardware-in-the-loop (HIL) test-bed consisting of an OPAL-RT