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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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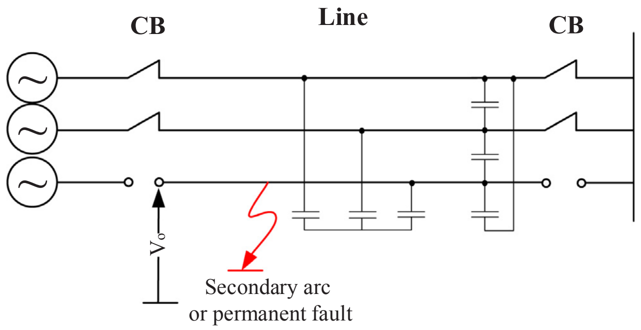

**Fig. 1.** Isolation of the single-phase fault [7].

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

simulator, PMUs and appropriate controllers.

## 2. Autoreclosering considerations and solutions

The proposed AARS includes various features for single-phase and three-phase reclosing. Some of these features are considered only for single-phase reclosing, while some others are considered for both single and three-phase reclosing.

It is worth noting that the proposed AARS requires voltage and current synchrophasors from PMUs installed at both sides of the CBs throughout the grid [21].

### 2.1. Specific considerations for single-phase autoreclosing

This section presents how the proposed AARS distinguishes between temporary and permanent single-phase faults. In addition, it shows how the method detects when the single-phase temporary fault is removed.

#### 2.1.1. Detection of the fault type (Temporary or Permanent)

It is almost impossible to distinguish between temporary and permanent faults before opening the CBs. In fact, transient and permanent faults behave similarly during the primary arc; therefore, it is not possible to distinguish between them by analyzing the voltage or the current of the primary arc [10].

Fig. 1 shows a distribution feeder where, due to a single-phase fault occurrence, one of phases of the CB is opened while the other two phases are still connected to the grid. In this case, due to the capacitive and inductive mutual coupling between the phases, the healthy phases induce voltage on the faulted phase [8]. If the fault is temporary, i.e., there is no established path for the fault current to flow (as it is for permanent faults), this induced voltage forms an unstable secondary arc after the phase isolation and extinction of the primary arc. Thus, the formation of the unstable secondary arc is a key note for distinguishing between temporary and permanent faults [10]. It is clear that this idea is not applicable for three-phase faults as the secondary arc is initiated by the voltage that is induced by the other two healthy phases.

The inducted voltage from the other healthy phases also depends on the arc's resistance [7]. The resistance of a permanent fault has a constant value whereas the arc resistance of a temporary fault varies with time, due to the nature of this type of faults [10]. Therefore, in case of a permanent fault, the voltage of the faulted phase after the CB opening, $V_0$, remains almost constant [8]. The simulation-based analysis of a faulted phase voltage, presented in [11], supports this idea. In fact, these simulation results illustrate that the derivation of the magnitude of this voltage remains close to zero within several cycles after the line isolation. On the other hand, the secondary arc, formed in case of a temporary fault, has an unstable behavior. Therefore, the voltage of the isolated phase not only varies with time, but also becomes distorted with harmonics due to the non-linear characteristics of the arc's resistance [7]. Fig. 2 compares the voltage of the isolated faulted phase for a permanent and a temporary fault.

In this work, the variation of the phasor of the opened-phase voltage, $V_o$, with respect to time is used as a metric to enhance fault type detection, as detailed below.

The opened-phase voltage can be presented as:

$$v_o(t) = V_{om}Cos(\omega t + \varphi) \tag{1}$$

The phasor representation of (1) is defined as:

$$V_o = (V_{om}/\sqrt{\,}2)e^{j\varphi} = \left(\frac{V_{om}}{\sqrt{2}}\right)(Cos\varphi + jSin\varphi) \tag{2}$$

$$= V_{or} + jV_{oi} \tag{2}$$

In order to determine the difference between any two consecutive measured phasors, both the amplitudes and the angles are used to compute a total vector difference (TVD) index, as defined below:

$$TVD_{V_o} = \sqrt{\frac{(V_{or}(n+1) - V_{or}(n))^2 - (V_{oi}(n+1) - V_{oi}(n))^2}{V_{or}(n)^2 + V_{oi}(n)^2}} \tag{3}$$

where $V_{or}(n+1)$, $V_{oi}(n+1)$, $V_{or}(n)$ and $V_{oi}(n)$ are the component of the two consecutive measured phasors.

It is clear from (3) that, $TVD_{V_o}$ is calculated by use of the voltage phasors of the faulted phase. Therefore, it is necessary to install phasor measurement units (PMUs) where circuit breakers (CBs) are installed. It is noted that currently available protection relays are equipped with synchrophasor functionalities [22], hence, they can operate both as a PMU and a relay. Therefore, the required synchrophasor measurements can be obtained by utilizing the PMU functionalities of the existing relays with no need to dedicated PMUs.

The $TVD_{V_o}$, as described in (3), is a differential index which is presented herein and is used to detect the fault type. For a permanent fault, $TVD_{V_o}$ is close to zero; therefore, in the proposed method it is assumed that if the $TVD_{V_o}$ remains less than a pre-defined threshold for N consecutive cycles, then the fault is identified as a permanent fault; otherwise, as a temporary one.

A pre-defined threshold is used to prevent mal-operation due to errors in measurement devices, etc. The $TVD_{V_o}$ threshold is set to 5%, which means that if the TVD of the consecutive measured voltage phasors stay less than 5%, the voltage is considered to be stable. In addition, N is set to 5 to evaluate the index for 5 consecutive cycles.

It is worth noting that, the thresholds selected for $TVD_{V_o}$and N are safety margin to prevent the unnecessary operations of the AARS. The values of these thresholds have been determined according to a wide range of simulation results. Indeed, to select the appropriate thresholds, several cases have been simulated and the behavior of voltage waveforms were investigated.

#### 2.1.2. Detection of secondary arc extinction

As mentioned before, in case of a temporary fault, the extinction of the secondary arc determines the fault clearance which is the correct time for a reclosing attempt. The right-side waveform in Fig. 2 shows the opened-phase voltage before and after the secondary arc extinction. As the figure illustrates, after the secondary arc extinction, the opened-phase voltage remains constant and behaves as a stable waveform. Indeed, the secondary arc can be considered as a transient phenomenon, which causes variations on the magnitude and the angle of the opened-phased voltage. Hence, when this arc is extinguished, the voltage becomes stable [11]. Therefore it can be concluded that the temporary fault is cleared when the voltage deviation settles to zero [14,15]. Although in this case, the voltage of the opened-phase behaves similar to that of a permanent fault, its magnitude is significantly higher than that of the permanent fault. Therefore, the *TVD* is still applicable for fault clearance detection. Hence, once the temporary fault is detected, the reclosing algorithm should still receive voltage phasors and calculate the *TVD* for the consecutive cycles. Similar to the procedure described in Section 2.1.1, if the *TVD* remains less than 5% for five consecutive cycles, the voltage is assumed to have stable behavior; which means that the temporary fault is removed. To enhance the accuracy of the method, the voltage magnitude of the last considered cycle, named as $V_L$, is also compared with the voltage magnitude of the first cycle of the cycle-set, used for fault-type detection, named as $V_I$. Thus, the secondary arc is assumed to be extinguished when the TVD is less than 5% for five consecutive cycles and the magnitude of $\frac{V_L}{V_I}$ is more than 1.5.

### 2.2. General consideration for both single- and three-phase reclosing

As the fault type and the arc extinction time are not detectable for three-phase reclosing, the proposed AARS includes the following considerations to provide a successful auto-reclosing. These considerations are also included for the single-phase reclosing to distinguish between the permanent and semi-permanent faults. It is worth noting that semi-permanent faults are those which occur after falling a tree branch on

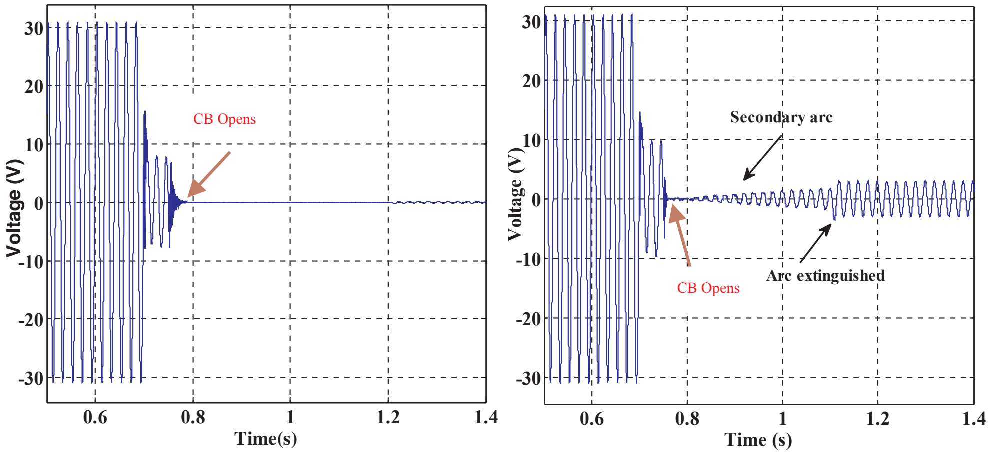

**Fig. 2.** Faulted phase voltage, $V_o$, in permanent (left) and temporary (right) faults.

the line or a bird spans a line. In such faults, reclosing after a time delay, could restore normal operation of the feeder.

### 2.2.1. Power system stability

It is well known that any fault occurrence negatively impacts system stability. When the faulted section is isolated from the rest of the power system, the system often returns back to a stable operating condition after the oscillations, caused by the fault, are damped. In strong networks, with high damping capability, the network will become stable quickly; however, for weak networks, oscillation damping takes more time. On the other hand, when a network has not yet settled down to a stable operating point, applying another fault may lead to instability. In addition, for weak networks even a temporary fault may lead to instability. Therefore, before reclosing a CB, it is necessary to estimate the stability condition of the related network and reclose only if the network is stable and strong enough, i.e., the network's eigenvalues are not close to the imaginary axis and there is a safe margin for node voltages with respect to voltage stability limit. In this way, it is more likely that, even if the CB recloses before the fault clearance, the healthy part of the network is able to damp oscillations and returns to a stable operating point.

In the proposed AARS, the PMU-based algorithms presented in [23] and [24] have been utilized to estimate the network margins for both voltage stability and small-signal stability. By utilizing these algorithms, the reclosing scheme determines if the system tolerates a reclosing attempt or not. If the margin is too small, the reclosing is blocked until the network returns back to an adequately stable operating point.

### 2.2.2. Thermal stress on system components

When the fault type and/or arc extinction time is not detectable, the recloser may operate several times to restore the network. If the fault persists, the fault current will flow multiple times through both faulted and healthy sections of the grid due to the multiple reclosing attempts.

The current-temperature relationship of conductors from the knowledge of ambient conditions can be described by [25]:

$$q_c + q_r + mC_p\frac{dT_c}{dt} = q_s + I^2R(T_c) \tag{4}$$

where *qc* is the rate of heat loss due to convection, *qr* is the radiated heat loss, *mCp* is the heat capacity of the conductor, *Tc* is the conductor temperature, *qs* is the solar heat gain, *I* is the current through the conductor and *R(Tc)* is the resistance of conductor at temperature $T_c$.

According to (4) each reclosing attempt causes the temperature of the conductors and the other series components to increase [26]. Although the temperature decreases slightly during the opening intervals between the reclosing attempts (dead time), the net temperature of the conductors and the other series components rises. This applies additional thermal stress on the network components. Hence, the temperature rise due to multiple reclosing attempts is a concern on auto-reclosing schemes [27].

In the proposed AARS, the real-time conductor temperature is utilized so that the reclosing attempt is applied only if the conductor temperature is adequately below its permissible limit. The real-time conductor temperature can be obtained by various means. Power Donut is one device that can be used to accurately measure and record conductor temperatures [28]. A reasonable accuracy of ± 2 °C is provided by solid-state thermoelectric sensors that are used for temperature measurement [29]. In this work, we use the method presented and implemented in [30]. The proposed AARS method receives estimations on the temrature rise the next planned reclosing attempt causes on the conductors in series. The AARS operates only if the estimations confirm that the conductors in series can tolerate another possible short-circuit.

## 3. Proposed adaptive auto-reclosing scheme

### 3.1. Flowchart

Fig. 3 illustrates the flowchart of the proposed adaptive auto-reclosing scheme. The flowchart includes all solutions for the reclosing requirements, presented in Section 2. The proposed scheme activates by a CB opening following the receiving of a trip command from a protection relay. Required information regarding the fault specifications such as L-G or 3L-G, location of the fault, etc., will be sent to this application by the system protection scheme. In the case of two-phase or three-phase faults, all three poles of the corresponding CB are opened; hence, the faulted feeder becomes completely isolated from the rest of the system. As mentioned before, in this case, due to the absence of the induced voltage and secondary arc, it is not possible to detect the fault type (i.e. temporary or permanent) and arc extinction time. Therefore, the CB may perform a reclosing attempt only if the healthy section of the network can tolerate it, i.e., the network has safe margins in terms of both stability and conductor temperature. If any of the thermal or stability indices are not within acceptable limits, the CB will not be reclosed. In this case, if they do not return to acceptable ranges after a predefined time, the reclosing process will be locked and the CB remains open. If the operational conditions of the network allow for a reclosing attempt, the CB will be reclosed. In this case, if the fault is already cleared, the CB remains closed and the network returns back to the normal operation; otherwise, i.e. the fault is still on the feeder, the CB will be opened again by the protection relay trip signal and the reclosing loop will start from the beginning. The reclosing loops stops running if the fault clears (in case of temporary or semi-permanent faults) or the number of reclosing attempts exceeds the physical

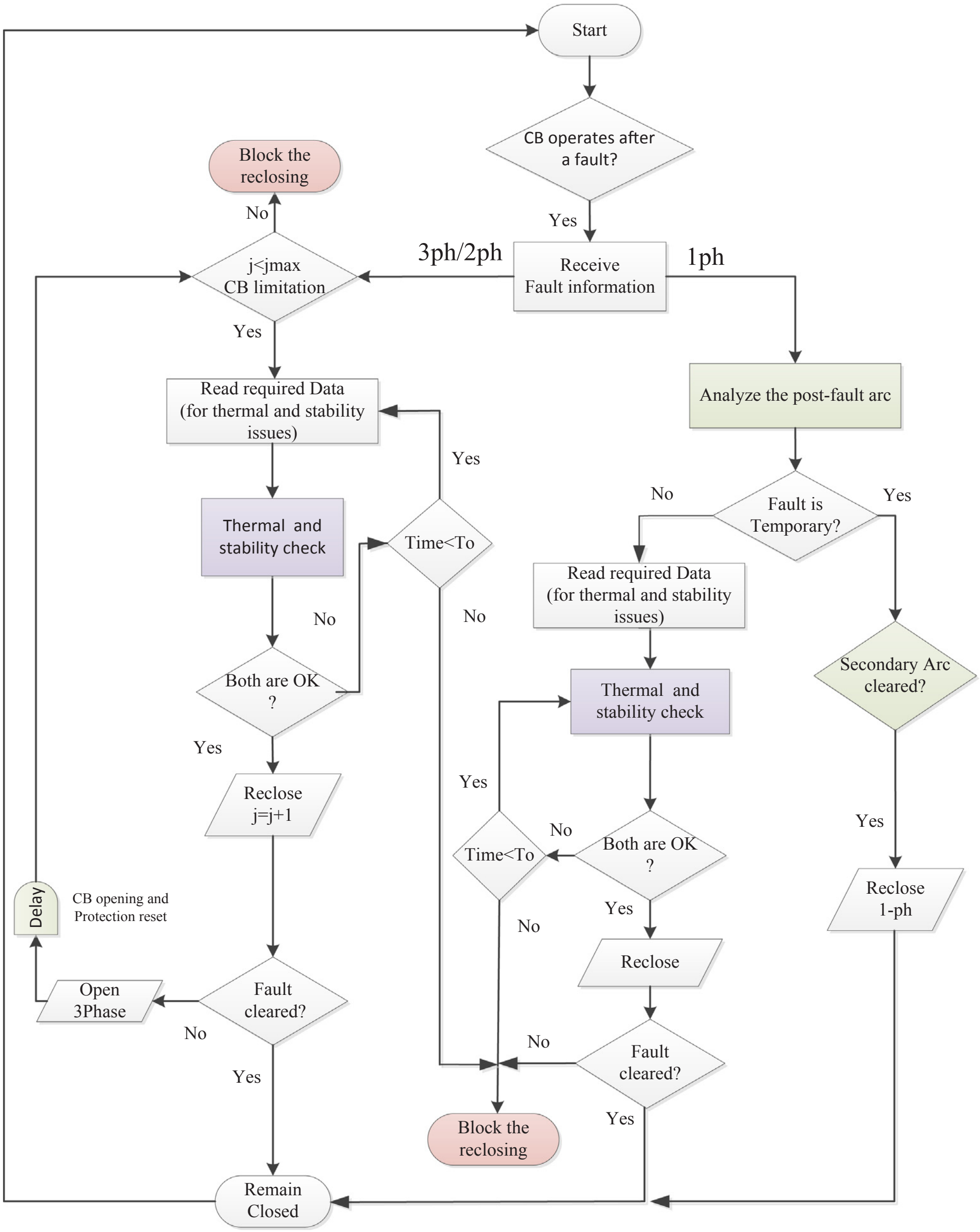

**Fig. 3.** The algorithm of the proposed AARS.

limitation of the CB.

In the case of single-phase faults, after the corresponding pole of the CB opens, the phasor of the opened-phase voltage is analyzed as explained in Section 2. If the fault is detected as temporary, the CB will be reclosed after the fault clearance as described in Section 2. Otherwise, the fault is either permanent or semi-permanent. In this case, because it is not possible to distinguish between permanent and semi-permanent faults, one reclosing is attempted only if the operational conditions of the network allow it. This is to determine if the fault is semi-permanent or not. In case the fault persists, it is assumed to be permanent and the CB will remain open.

Note that semi-permanent faults are a type of fault that is naturally permanent but it will be removed after one or two reclosing attempt(s) [31]. In other words, semi-permanent faults are the permanent faults that are transformed to become temporary after the operation of the recloser. For example, if a bird short-circuits two phases of an overhead line, from the network view, it is a permanent fault. But, after a reclosing attempt, the bird's body disjoints by the second fault current flowing through it. In this case, the permanent fault is changed to become temporary. Therefore, after the second recloser attempt, the semi-permanent fault is seen as a temporary fault. Accordingly, the method that was presented for temporary fault is used for semi-permanent faults, as well.

### 3.2. Coordinated operation of autoreclosers

The proposed autoreclosing method executes separately for each CB. Indeed, each CB recloses without considering the operation of the other CBs. This is acceptable when the faulted zone is connected to the rest of the network from only one point (e.g. when fault occurs in Zone 4 of Fig. 4). However, when several healthy zones are connected to a faulted zone, the coordinated operation of all the connected zone's CBs is necessary. For example, following the fault detection in Zone 3, CB3 and CB4 open and each of them starts its reclosing process independently. According to the network conditions at the healthy side of each CB, the CB recloses after a time delay; this delay is not necessarily

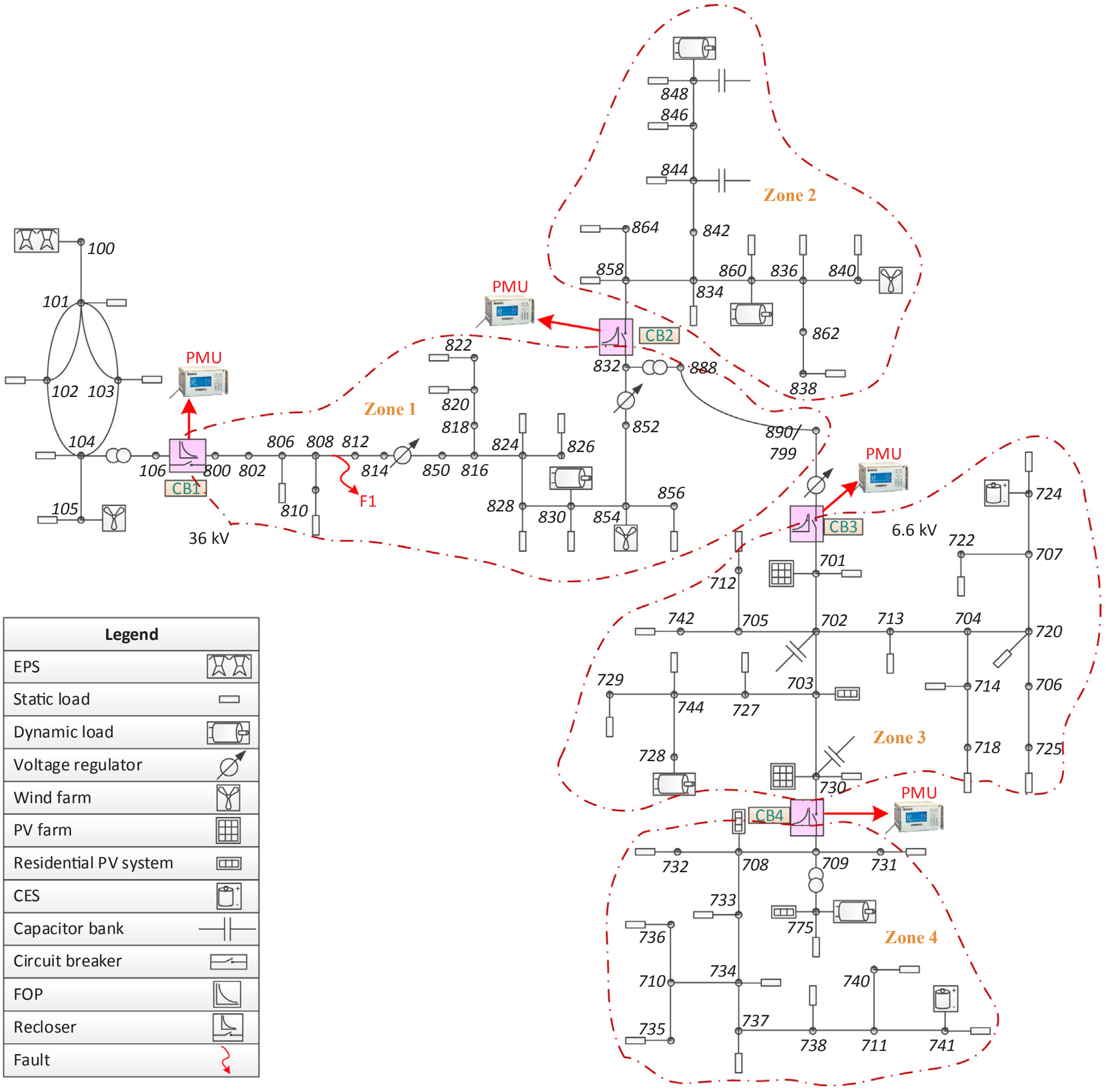

**Fig. 4.** The study network.

the same for all CBs that have started the reclosing process. In fact, in this case, since CBs operations are not coordinated, the network may experience additional stress in both the faulted and healthy zones. In other words, this uncoordinated operation is due to the local decision making by each CB. To prevent this problem, in this work, a centralized processing unit (CPU) is considered for each distribution system to supervise the separate reclosing applications. The CPU is assume to be located at the control room of the main substation.

The CPU receives the operational conditions of all zones (i.e. the indices that are used for the execution of the autoreclosing methodon in each CB) and determines the zone with the most suitable conditions to perform the reclosing attempts. Indeed, for each reclosing attempt, only the recloser of the zone with the most acceptable stability and thermal indices operates and the other CBs remain open. This coordinated operation not only may reduce the risk of damages to healthy zones but also reduces the number of CBs' operations.

Acoordingly, the proposed AARS runs based on local (de-centralized) decision making and centralized coordination.

## 4. Hardware-in-the-Loop Real-Time simulation setup

### 4.1. Study network

The study grid in this work is a 79-bus network that has been developed using the distribution network, modeled and presented in [32]. The study grid, shown in Fig. 4, is connected to the transmission system through a 132/36 kV substation.

The grid includes different types of single- and three-phase DGs. The CBs, shown in Fig. 4, are governed by protective relays that receive voltage and current measurements from both sides of the CBs. The relays are of the type that can compute synchrophasors of voltages and currents; hence, they can operate as PMUs as well.

### 4.2. Hardware-in-the-loop testbed

Fig. 5 shows the architecture of the hardware-in-the-loop (HIL) simulation setup used to assess the proposed AARS. The study network is modeled using MATLAB/Simulink and executed in the OPAL-RT real-time simulator. The feeder voltages are monitored by PMUs, which are SEL-421 from Schweitzer Engineering Laboratories. The PMU data are then sent to a phasor data concentrator (PDC) which streams the data over TCP/IP to a workstation computer holding the Smartgrid's

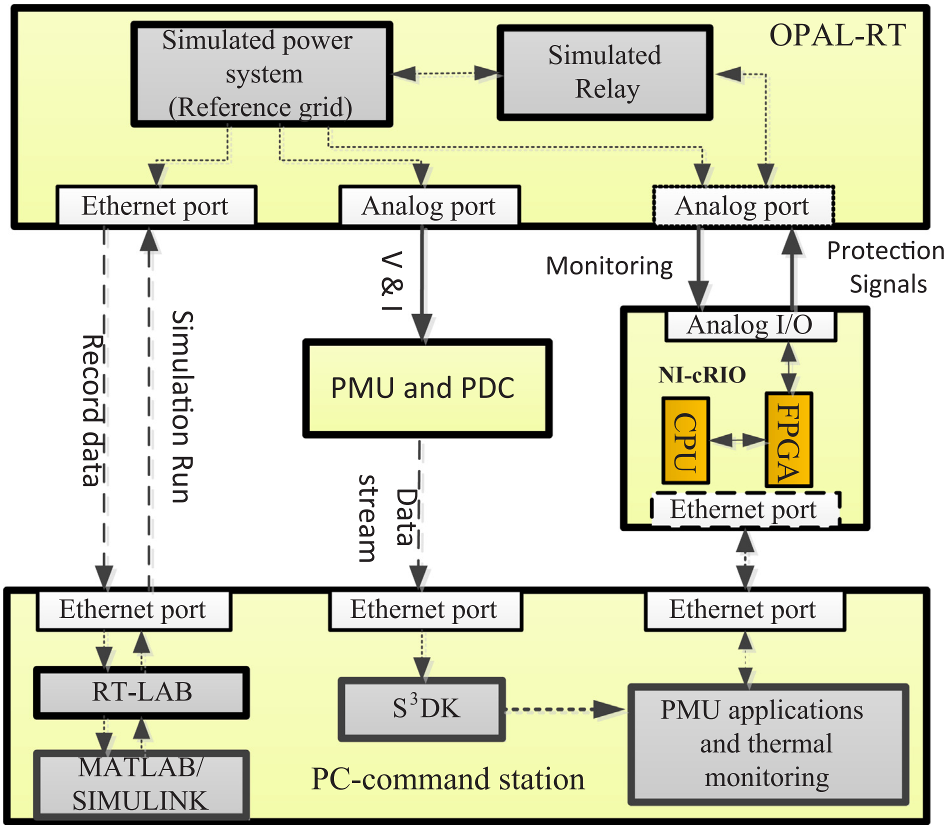

**Fig. 5.** The architecture of the HIL simulation setup.

**Fig. 6.** KTH SmarTS lab: The HIL test-bed.

Synchrophasor Development Kit (S3DK) [33], which provides a real-time data mediator that parses the PDC data stream and makes it available to the user in the LabVIEW environment. PMUs reporting rate is 50 per second; i.e., one data frame is generated and reported for each cycle. The proposed AARS runs on a Compact Reconfigurable IO systems (CRIO) from National Instruments Corporation, programmed with LabVIEW graphical programming tools. The reclosing command, determined by the implemented scheme, is sent back to the model, from the NI-CRIO to the OPAL-RT real-time simulator. The elements of the HIL testbed at KTH SmarTS lab are shown in Fig. 6.

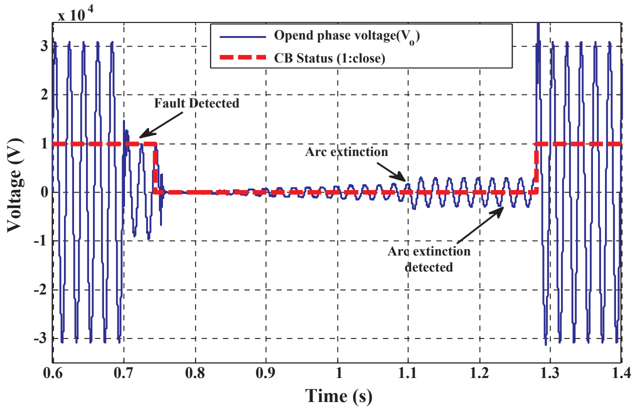

**Fig. 7.** The voltage of the faulted phase and the CB status.

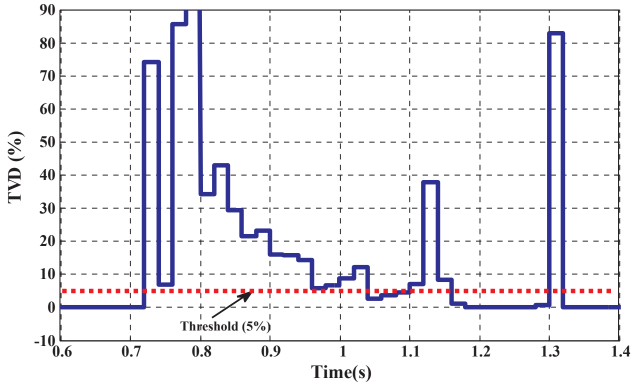

**Fig. 8.** The TVD index of the consecutive cycles.

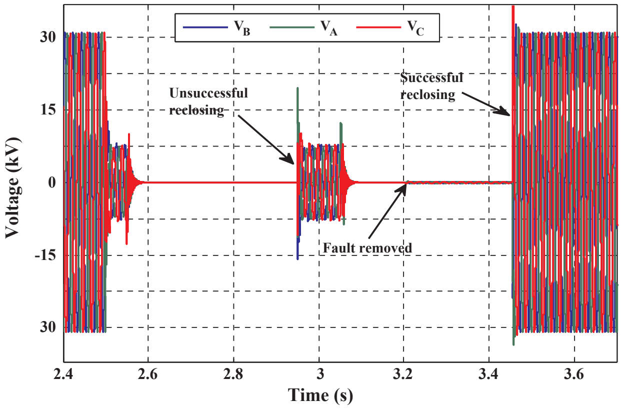

**Fig. 9.** Three-phase voltage during the AARS operation.

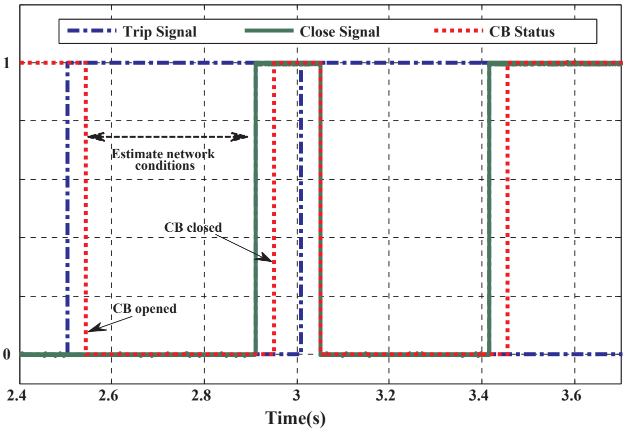

**Fig. 10.** The protection signals and CB status.

## 5. Experimental results

### 5.1. Case study 1: occurrence of a temporary single-phase fault

In the first case study, it is assumed that a single-phase fault, F1, has occurred in the study network at $t = 0.7s$. Following the fault occurrence, the corresponding relay detects the fault and opens the related pole of CB1. Figs. 7 and 8 show the voltage of the faulted phase and the TVD of the consecutive cycles of this voltage, respectively. Fig. 8 illustrates that the TVD index is larger than 5% during the secondary arc; while, it has a constant and small value (close to zero) after the secondary arc extinction. Fig. 7 also shows that the AARS is able to detect the arc extinction around 6 cycles after the arc extinction. Therefore, without considering the other operational limitations of the CB, the close command is sent at $t = 1.24s$.

### 5.2. Case study 2: occurrence of a temporary three-phase fault

In this case study, it is assumed that F1 is a temporary three-phase fault and has occurred at t = 2.5s; so, three poles of the corresponding CB are opened at t = 2.55s. Fig. 9 shows the voltage of the three phases during the fault and the AARS operation. Fig. 10 shows the protection signals in which, after the fault detection and opening of the CB, the network estimator system starts to estimate the stability and the thermal conditions of the network. Assuming that it takes approximately 350 ms to obtain the new system stability estimates and conductor temperature margins, the reclosing command is sent by the AARS at t = 2.92s. After reclosing the CB, because the fault still persists, the relay sends the trip signal again and the reclosing process repeats. The fault is cleared at t = 3.2s and the system returns back to the normal operation after a second reclosing shot.

## 6. Conclusions

This paper presented a new phasor-based adaptive auto reclosing scheme (AARS). The method has utilized the PMU data to detect the fault type, arc extinction and network conditions. In the case of a single-phase fault occurrence, the results showed that the method is able to detect the fault type and sends the reclosing command around 6 cycles after the extinction of the secondary arc. For three-phase faults, because, the reclosing command is generated after estimating the network conditions, the dead time of the proposed scheme depends on the operational conditions of the network, i.e., small-signal stability and conductor temperature.

As future work, the authors will evaluate the performance of the proposed methods in distribution system hosting high amount of distributed generation.

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