

One Terminal Digital Algorithm for Adaptive Single Pole Auto-Reclosing Based on Zero Sequence Voltage

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Abstract: This paper presents an algorithm for adaptive determination of the dead time during transient arcing faults and blocking automatic reclosing during permanent faults on overhead transmission lines. The discrimination between transient and permanent faults is made by the zero sequence voltage measured at the relay point. If the fault is recognised as an arcing one, then the third harmonic of the zero sequence voltage is used to evaluate the extinction time of the secondary arc and to initiate reclosing signal. The significant advantage of this algorithm is that it uses an adaptive threshold level and therefore its performance is independent of fault location, line parameters and the system operating conditions. The proposed algorithm has been successfully tested under a variety of fault locations and load angles on a 400KV overhead line using Electro-Magnetic Transient Program (EMTP). The test results validate the algorithm ability in determining the secondary arc extinction time during transient faults as well as blocking unsuccessful automatic reclosing during permanent faults.

Keywords: Adaptive Auto-reclosing, Secondary Arc, Transmission Line Protection, Zero Sequence Voltage.

1 Introduction

Statistics show that above 80% of faults on overhead lines are transient, with more than 90% of these are single phase to earth faults. The most common causes of transient faults are over voltages induced by lightning, which result in flashover of insulator. Other possible causes are swinging wires and temporary contact with foreign objects. For such faults, single pole auto-reclosing (SPAR) provides a means of improving transient stability and reliability. Furthermore, as in SPAR only the faulted phase is tripped, 58% of transmission capacity is still retained via the two healthy phases [1].

Conventional single pole and three pole auto-reclosing techniques applied to extra high voltage (EHV) transmission lines adopt fixed time interval reclosing techniques [1]. However employing a fixed prescribed dead time can pose problems. In the case of an arcing fault, for example, a fault restrike due to insufficient time for the fault path to fully de-ionise can threaten system stability and reliability. On the other hand, unsuccessful reclosing during a permanent fault may

aggravate the potential damage to the system and equipment [2]. For some EHV lines, especially near generating plants, the classical automatic reclosing of breakers cannot be used and therefore adaptive reclosing schemes have been introduced over the past decades [3]. Such schemes prevent unsuccessful reclosing on permanent faults, and during arcing faults reclosing is done only after full extinction of the secondary arc and complete deionisation of the arc path.

Many approaches have been proposed for adaptive reclosing. In [1] the root mean square (RMS) value of faulted phase is calculated over a period and when the difference between present RMS and the previous one at each time step attains a value above a certain threshold level, a reclosing command signal is generated. The authors of [1] have stated that the threshold value is dependent on the application environment.

Ref. [2] uses the current of one of the two healthy phases and compares its power of high frequency components with a threshold level. The disadvantage of this approach is the dependency of the threshold value to fault conditions and system parameters.

In [4] the value of voltage induced from healthy phases to the faulted one is used. Results from this approach also vary under different load conditions and fault locations. To overcome this problem the authors of [5] proposed a discriminator based on fuzzy logic, which its shortcomings are complication of developing fuzzy rules. Since the voltage waveform of the faulted phase

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during the secondary arc is greatly distorted compared with the same one after the secondary arc extinction, in [6] the total harmonic distortion (THD) value of this voltage is used to determine an appropriate time for reclosing. The fundamental component of the zero sequence power at both ends of a line is used in [7] to detect the extinction time of the secondary arc. The authors of [7] stated that their auto-reclosing setting should be adjusted according to the total transmission line length.

In [8] by use of Fourier Transform various components of the faulted phase voltage is extracted and applied to an artificial neural network (ANN), which is trained by more than 25000 permanent and transient single phase to earth faults.

In [9] Wavelet Transform of the faulted phase voltage is obtained in four levels and used as input data for ANN. However, for application of ANN it must be trained for each individual transmission system considering line length, system parameters, operation voltage, short circuit level, etc.

In this paper a novel algorithm with dynamic threshold level is presented which uses the post-fault zero sequence voltage at the relay point after the circuit breaker opening. The proposed algorithm does not require an artificial intelligence tool like ANN nor does it need to define any fixed threshold level, so its results are independent of the system and fault conditions.

2 System Model for Simulation Study

Fig. 1 illustrates the single line diagram of a 400KV transmission line used for the simulation study of the proposed algorithm. The 144.4Km transmission line parameters are given as:

$$R_1 = 0.01537 \Omega / \text{km}, L_1 = 0.8858 \text{mH} / \text{km},$$

$$C_1 = 0.013 \mu\text{F} / \text{km}$$

$$R_0 = 0.04612 \Omega / \text{km}, L_0 = 2.6574 \text{mH} / \text{km},$$

$$C_0 = 0.0043 \mu\text{F} / \text{km}$$

Subscripts 1 and 0 stand for positive and zero sequence quantities, respectively, whilst the negative sequence values are the same as the positive sequence ones.

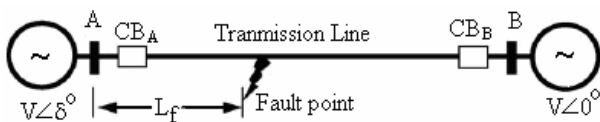


Fig. 1 Single line diagram of the simulated transmission system.

The Thevenin equivalent impedances at Buses A and B are described using mutual coupled R-L circuit as:

$$R_1 = 0.06 \Omega, L_1 = 39.99 \text{mH}$$

$$R_0 = 0.13 \Omega, L_0 = 23.71 \text{mH}$$

The distributed line parameter model of EMTP is used to account for transient behaviour of the system under unsymmetrical fault conditions.

3 Modeling of Arcing Faults

Arcing faults have been modelled as presented in [10]. From a modeling point of view, arcing faults can be classified as high current primary arc during the fault and low current secondary arc after the faulted phase is isolated. The secondary arc is sustained by mutual coupling between the healthy and faulted phases [10].

3.1 Primary Arc Model

It can be shown that the primary arc model is represented by a time dependent resistance with the value given by:

$$\frac{dg_p}{dt} = \frac{I_p}{2.85 \times 10^{-5} I_p} \left(\frac{|i|}{15I_p} - g_p \right) \quad (1)$$

where g_p is the time varying primary arc conductance, I_p is the peak value of primary arc current, l_p is the primary arc length; $|i|$ is the absolute value of the primary arc current.

3.2 Secondary Arc Model

The secondary arc is a highly complex phenomenon, and is influenced by a number of factors [10]. The secondary arc can be modelled by:

$$\frac{dg_s}{dt} = \frac{I_s(t_r)}{2.51 \times 10^{-3} I_s^{1.4}} \left(\frac{|i|}{75I_s^{0.4} I_s(t_r)} - g_s \right) \quad (2)$$

where g_s is the time varying secondary arc conductance, I_s is the peak value of the secondary arc current, $I_s(t_r)$ is the secondary arc length, t_r is the time from the initiation of the secondary arc.

The arcing fault model has been implemented in the TACS field of EMTP and corresponding voltage of faulty Phase-a measured at Bus A is illustrated in Fig. 2. In Fig. 2, following the fault occurrence at instant $T1=0.02s$, the bus voltage reduces. At the instant $T2=0.1s$, the breaker interrupt the fault current and isolate the faulty phase.

The interval between the instants $T2$ and $T3$ illustrates the behavior of the recovery voltage during the secondary arc period. At the instant $T3 \cong 0.62s$, the secondary arc is quenched and the recovery voltage DC offset appears due to the residual voltage of the transmission line.

This voltage waveform of the faulty phase is similar to the results obtained in [10], which validates the simulation accuracy of this paper.

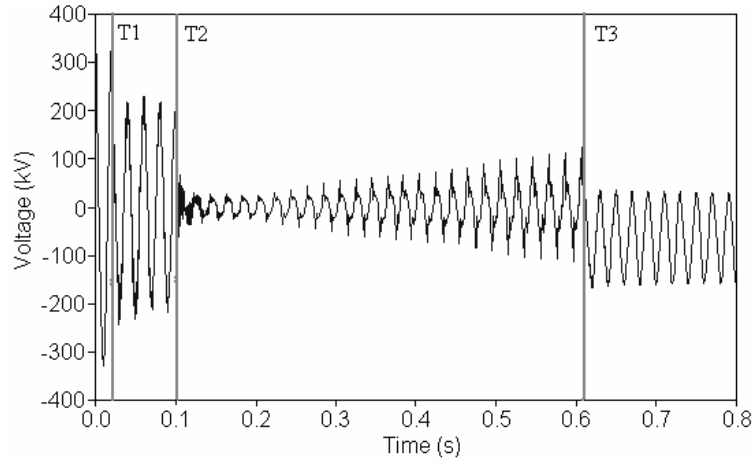


Fig. 2 Voltage waveform of the faulty phase a during a single phase to ground arcing fault.

4 The Algorithm

The proposed algorithm in this paper uses the zero sequence voltage for an adaptive reclosing. The time domain zero sequence voltage can be obtained using the Fortescue Transform as follows [11]:

$$v^0(k) = \frac{1}{3}(v_a(k) + v_b(k) + v_c(k)) \quad (3)$$

where $v^0(k)$ is the k th sample of the zero sequence voltage, $v_a(k)$, $v_b(k)$, $v_c(k)$ are the k th sample of a , b and c phase voltages, respectively.

4.1 Distinguish of Permanent Faults from Arcing Faults

During arcing faults there is a recovery voltage DC offset after extinction of the secondary arc. However, in permanent faults there is no DC offset because of persistence of the fault. The algorithm uses this fact to distinguish permanent faults from the arcing ones by calculating the mean value (DC offset) of the zero sequence voltage. The absolute value of the DC offset of zero sequence voltage, $M(k)$, can be obtained from:

$$M(k) = \left| \frac{1}{N} \sum_{n=k-N+1}^k v^0(n) \right| \quad (4)$$

where, N is the number of samples per cycle; Δt is the sampling time interval. Fig. 3(a) shows zero sequence voltage waveform and corresponding M signal during a permanent single phase to earth fault for a 2Ω fault resistance, whereas Fig. 3(b) shows the same parameters for an arcing single phase to earth fault.

It can be seen in Fig. 3 that in case of arcing fault after secondary arc quenching, M has a non-zero value, but in the permanent fault it remains equal to zero.

This feature has been used to distinguish between permanent and transient faults, i.e. if M does not change and remains at the zero value, it is a permanent fault,

otherwise, the fault is recognized as an arcing one as given by Eq. (5):

$$f(k) = \begin{cases} 1 & M(k) > 0 \\ 0 & M(k) = 0 \end{cases} \quad (5)$$

where f takes 1 for transient fault and 0 for permanent fault.

4.2 Recognition of Secondary Arc Extinction

It should, however, be noted that the method described in the previous section cannot be used to determine the instant of arc extinction, this is because the M variations during secondary arc period are dependent on different parameters including arc characteristic, fault location, line length, etc. In this section a technique is proposed to identify the instant of arc quenching.

The nonlinear characteristic of arcing faults causes distortion of the arc voltage. By scouting the harmonic spectrum of the zero sequence voltage, it is found that the 3rd harmonic is the most appropriate and reliable indicator of the secondary arc extinction. Therefore, the proposed technique here uses the 3rd harmonic amplitude of the zero sequence voltage to recognise the instant of arc extinction. The 3rd harmonic is estimated by recursive Discrete Fourier Transform (DFT) given by the following Equations:

$$v_{3-c}^0(k) = v_{3-c}^0(k-1) + \frac{2}{N}(v^0(k) - v^0(k-N)) \times \cos\left(\frac{3 \times 2\pi k}{N}\right) \quad (6)$$

$$v_{3-s}^0(k) = v_{3-s}^0(k-1) + \frac{2}{N}(v^0(k) - v^0(k-N)) \times \sin\left(\frac{3 \times 2\pi k}{N}\right) \quad (7)$$

$$v_3^0(k) = \sqrt{(v_{3-c}^0(k))^2 + (v_{3-s}^0(k))^2} \quad (8)$$

where $v_{3-c}^0(k)$ and $v_{3-s}^0(k)$ are the k^{th} sample of real and imaginary components, respectively, from which the k^{th} sample amplitude of the 3rd harmonic, $v_3^0(k)$, is calculated.

The k^{th} sample value hence derived is added to the 3rd harmonic samples of zero sequence voltage taken in the previous time steps and so an accumulative signal S is formed as follows:

$$S(k) = \Delta t \sum_{n=1}^k V_3^0(n) \quad (9)$$

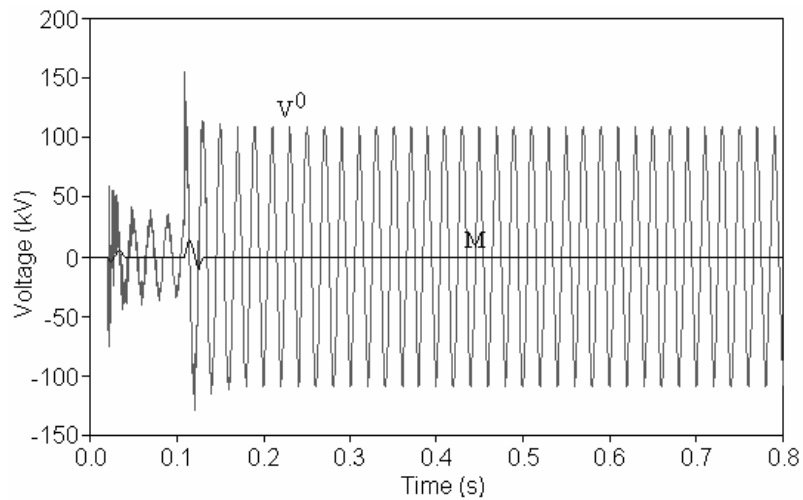
where V_3^0 is the amplitude of 3rd harmonic of zero sequence voltage, v_3^0 , after passing through a low pass

filter which its function is to eliminate undesirable effects of short duration oscillations of v_3^0 .

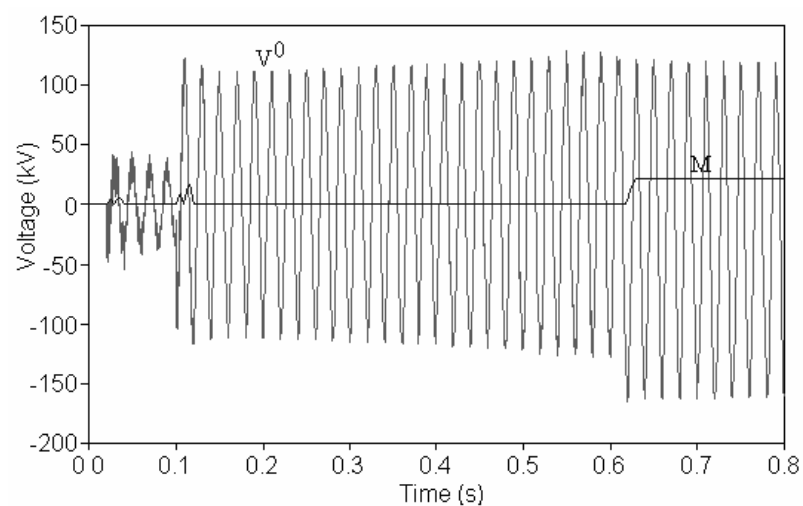
Fig. 4 illustrates the behavior of S and V_3^0 signals during an arcing fault. It is obvious that during secondary arc period, V_3^0 is more than S and as the secondary arc is quenched its value reduces to less than the S value. Therefore, without the need to define any fixed threshold level, the diagnostic signal e is formed as follows:

$$e(k) = \begin{cases} 1 & S(k) \geq V_3^0(k) \\ 0 & S(k) < V_3^0(k) \end{cases} \quad (10)$$

In practice, e represents the secondary arc extinction time.



(a)



(b)

Fig. 3 Zero sequence voltage and corresponding M signal during: (a) permanent fault and (b) arcing fault.

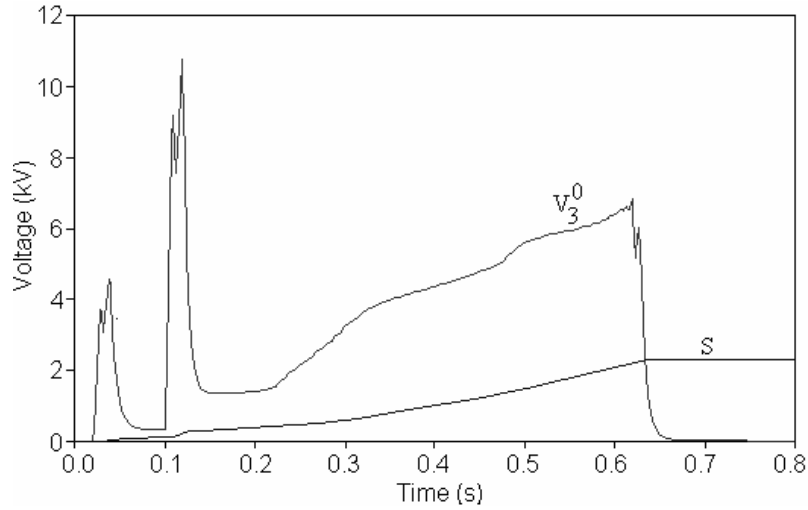


Fig. 4 Variation of S and V_3^0 signals during a single phase to earth arcing fault.

5 The Algorithm Implementation

The proposed algorithm has been implemented by using the TACS field of EMTP as shown in Fig. 5. The signals S , M and V_3^0 generated by the algorithm are manipulated as shown in the logic diagram of Fig. 6. In Fig. 6 to prevent the variation effect of the zero sequence voltage during normal operation of the system and before opening the breakers, AND#1 is used which its output will change to 1 whenever the fault is detected by the relay and the breakers become fully opened. The output of AND#1 is delayed by one cycle to overcome the transient produced during opening period of the circuit breakers.

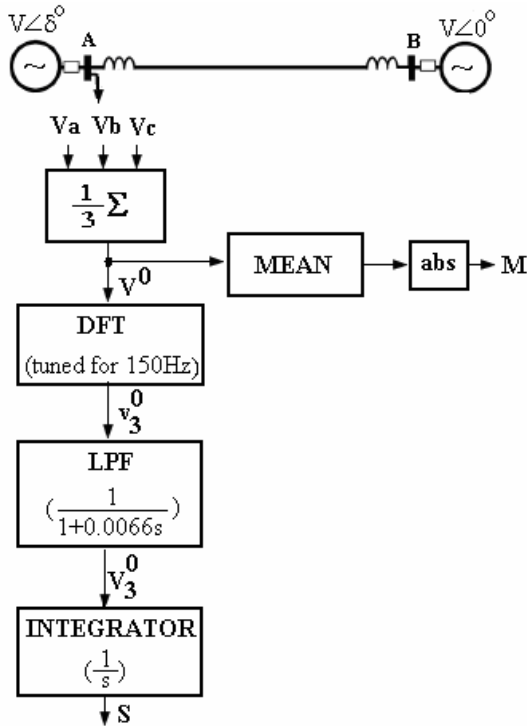


Fig. 5 Block diagram of proposed algorithm.

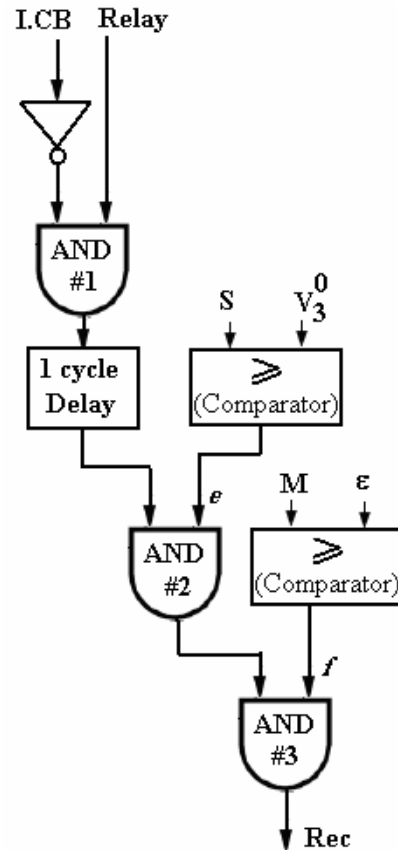


Fig. 6 Proposed logic to generate reclosing signal (Rec).

In this way the algorithm is performed only if the relay decision (Relay) is high and the fault current is diminished for a time greater than 20ms. It should be noted that speed of the algorithm is not affected by the specified time delay, since during permanent faults no reclosing signal is generated and during arcing faults the secondary arc lasts at least for few cycles. By comparing S and V_3^0 at each sample, e is formed according to Eq. (10).

The output of AND#2 will change to 1 whenever the fault is cleared by the breaker and also e becomes unity, which means that the secondary arc has been quenched completely.

In theory, to distinguish permanent faults from arcing faults and to generate f , M only needs to be compared with zero. In practice, M is compared with a small value ε to overcome low amplitude variations of the zero sequence voltage during permanent faults. In the 400KV simulated test system the amount of ε is considered 40V. However, numerous simulations have proved that increasing ε up to 400V, and even higher, has no effect on the algorithm output, because it is evident that during arcing faults, the value of M after arc extinction gets much higher value than 0.1% of the system nominal voltage. Hence determining the exact value of ε is not necessary, and even one could not be concerned about defining it at all.

As mentioned, in the case of arcing faults, f has a value of 1 and hence e transfers to the final output Rec without any change. However, in the case of permanent faults, since f is 0, probable changes in e never appear on the final output Rec . In other words, a permanent

fault does not change the status of Rec and therefore reclosing command signal is not generated.

6 Simulation Study

The proposed algorithm has been validated by numerous simulation tests under different fault conditions including different load angles, line lengths, and fault locations. Only some selected test results are given here for the purpose of brevity.

Fig. 7 shows the algorithm performance under arcing and permanent faults. It is evident in Fig. 7(a) that during the arcing fault the status of the reclosing signal Rec is changed to 1 about half cycle after quenching the secondary arc. On the other hand, Fig 7(b) shows that in the case of permanent fault the Rec status does not change and hence no reclosing is allowed.

Fig. 8 shows that the load angle change has no effect on the relay performance. Fig. 9 illustrates the validity of the algorithm for a different fault location.

To show that the proposed algorithm is independent to the arc characteristic, the test result is shown in Fig. 10 for a short duration secondary arc.

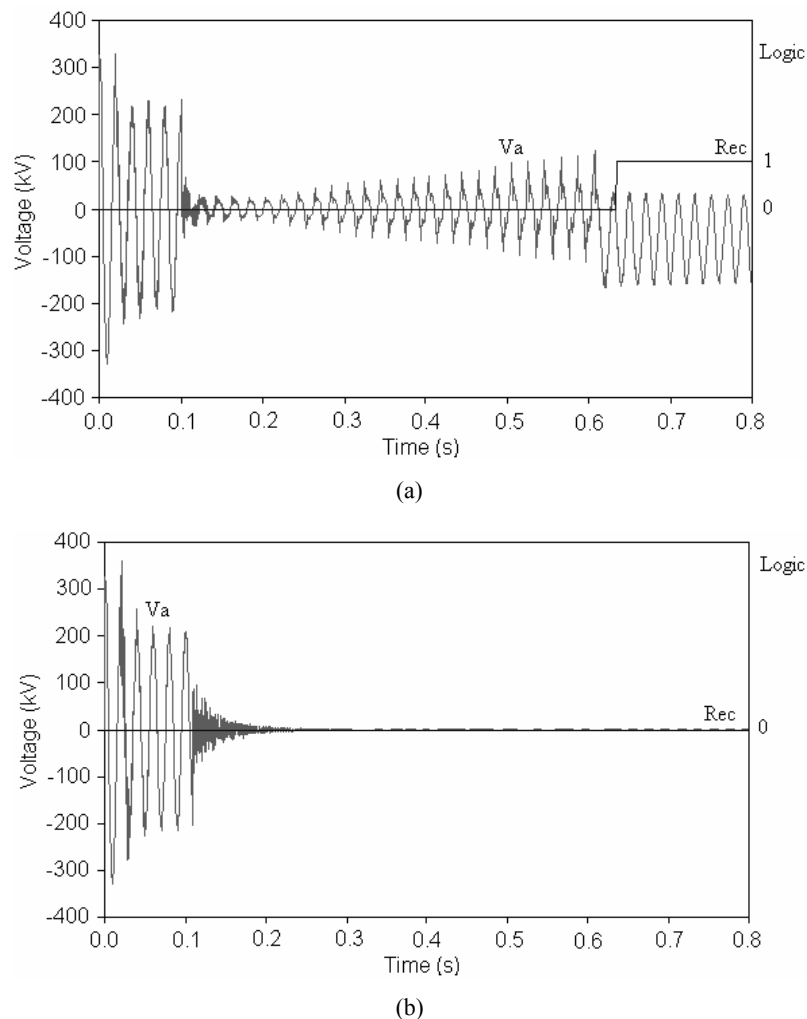


Fig. 7 Generated reclosing signal in: (a) arcing fault and (b) permanent fault, both at $L_f = 36.1\text{Km}$, $\delta = 0^\circ$.

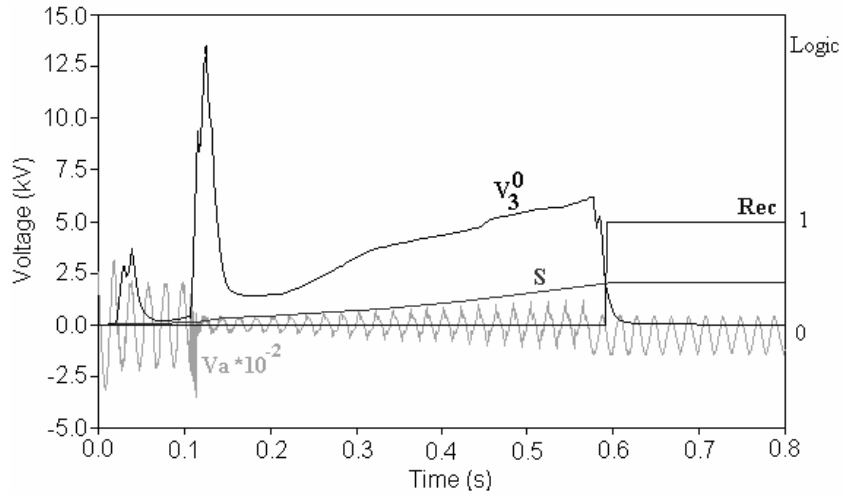


Fig. 8 Results of further simulations during an arcing fault at $L_r = 36.1\text{km}$, $\delta = 45^\circ$.

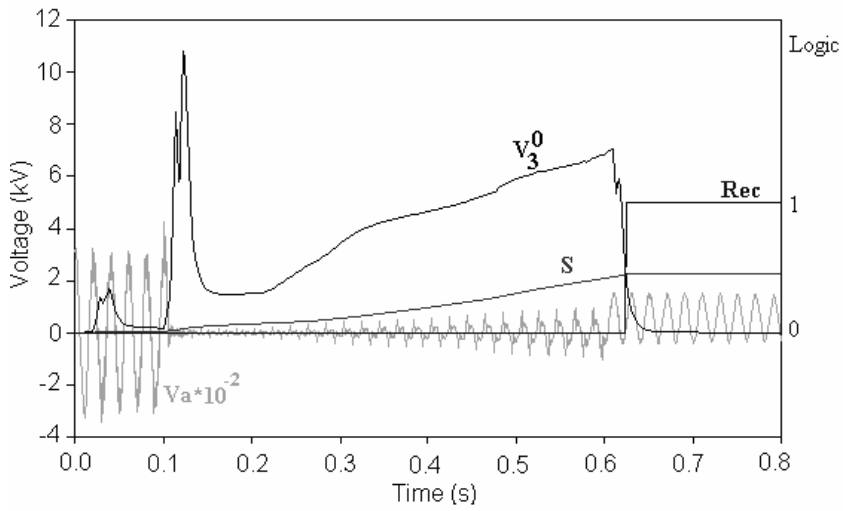


Fig. 9 Results of further simulations during an arcing fault at $L_r = 108.3\text{km}$, $\delta = -20^\circ$.

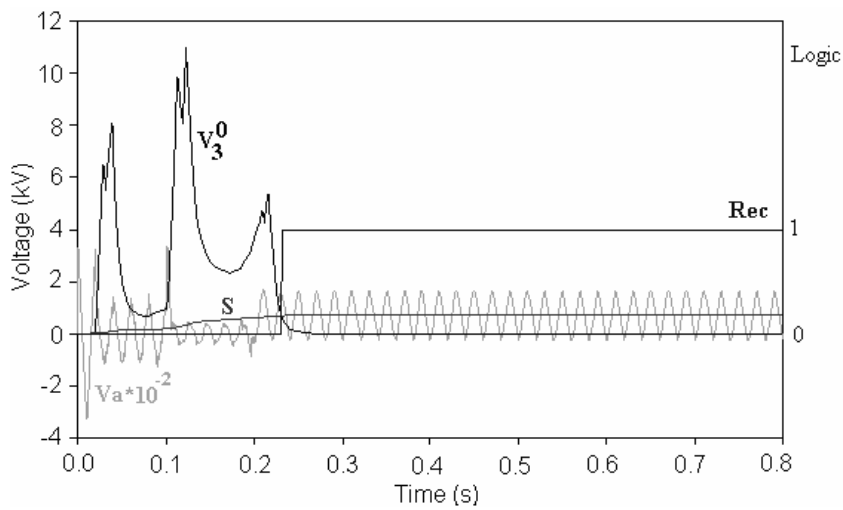


Fig. 10 Result of algorithm in case of short duration secondary arc at $L_r = 10\text{km}$, $\delta = -10^\circ$.

7 Conclusions

A new adaptive single pole auto-reclosing based on the zero sequence voltage has been introduced. Permanent faults are distinguished from arcing faults by using the mean value of the zero sequence voltage. For transient faults the extinction time of the secondary arc is estimated by evaluating the amplitude of the 3rd harmonic component.

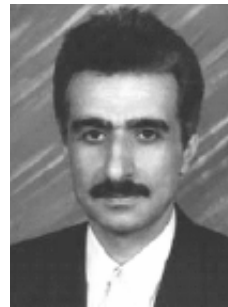
The proposed algorithm has the advantage that it does not require a fixed threshold level to identify the instant of arc quenching. Therefore the generated reclosing signal by the algorithm is independent to the line parameters, pre-fault operational conditions and fault locations.

An arcing fault model and the proposed algorithm has been simulated in the TACS field of the EMTP program.

The algorithm has been tested for different load angles, fault locations and arc characteristics. The results validate the algorithm performance.

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