An Adaptive Single-Pole Auto-Reclosing Function

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***Abstract*—Single-phase to earth faults are the most common faults that occur on transmission lines. As these faults are temporary in their nature, they can be eliminated by de-energizing the faulted phase for a short period. This period is necessary in order for the arc to be extinguished and for the faulted phase to be reclosed. A special function called auto-reclosing function is included in distance relays to accomplish this action, i.e. reclosing the open phase at a suitable time. This paper presents a new adaptive auto-reclosing function by utilizing a specific feature of the voltage of faulted phase when the fault is completely eliminated. Using EMTP-RV®, we precisely simulated secondary arc and different system conditions to evaluate our proposed method. The simulation results are promising and show the validity of the proposed method**.

Keywords-Adaptive auto-reclosing, DC component, induced voltage, secondary arc, single-pole tripping

I. INTRODUCTION

Automatic reclosing (AR) of overhead lines is an effective solution to improve electric power security and quality during disturbances caused by transient line faults which constitute the majority of network faults. Worldwide experience has shown single pole auto-reclosing (SPAR) to be a very valuable feature, especially during multiple faults when power networks are heavily stressed. However, AR is not without its risks, which have to be balanced against the benefits. Some of the inherent risks have been overcome with improvement in circuit and logic design of the AR relay but the principle outstanding risks are those associated with reclosing onto permanent faults [1]–[3]. These may be summarized as follows:

- Circuit breaker (CB) fails to trip during subsequent retrips leading to a wide-area shutdown;
- System transient stability;
- Generator windings and turbine shafts damage.

Among the three main risks above, the first one is of high importance as it is related to CBs themselves while the second and third one can be ignored when AR is not done on the line directly connected to power plants.

A traditional AR scheme uses a fixed time delay following a CB trip to reclose the phase that suffered from the fault. This reclosing is not optimized to line conditions as there may be an unnecessary delay after deionization of the fault path during which dynamic stability is at risk or further faults occurring during the dead time are judged to be a repeat of the original fault (i.e., a permanent fault), and further reclose is locked out. Adaptive SPAR offers many advantages, such as increased rate of successful reclosure, improved system stability, and a reduction in system and equipment shock under a permanent fault [4]–[10].

In this paper, a specific feature of the voltage of the open phase that is created after fault elimination will be utilized to present a new adaptive SPAR function. This paper is organized as follows. In section II, the proposed method will be developed. In section III, the method will be evaluated by simulation results obtained by EMTP-RV. The feasibility of our proposed method will be discussed in section IV. At last, some conclusions are drawn in Section V.

II. PROPOSED ADAPTIVE RECLOSURE SCHEME

The proposed scheme is conceived on the basis of a specific feature of the voltage of faulted phase when the fault has been entirely eliminated from that phase. A fault is said to be eliminated when secondary arc is extinguished. At this time, since the faulted phase has opened from both ends and there is no longer a fault path, the initial state of voltage that was created on capacitance voltage will decay only via the resistance of line insulators that is very large. It means that a DC voltage will be created with a very long time constant. However, during primary and secondary faults, there is no such a decaying DC component. To mathematically demonstrate this feature, let's consider a simplified model of a three-phase system in which different phases have only capacitive coupling with each other (C_{ph}) as shown in Fig. 1. Ground capacitance of phase B and insulator resistance of that phase are shown by C_g and R_i respectively. It is assumed that phase B is open and healthy as well which means the fault on this phase is eliminated but still this phase is not energized. Moreover, all conductor resistances and conductor inductances including self and mutual ones are ignored as the induced voltage on the open phase is mostly due to capacitive coupling among the phases

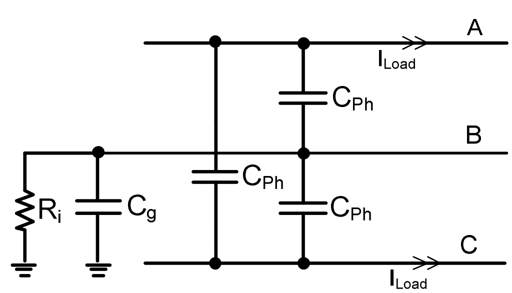

Fig. 1 A three-phase transmission line with open phase B

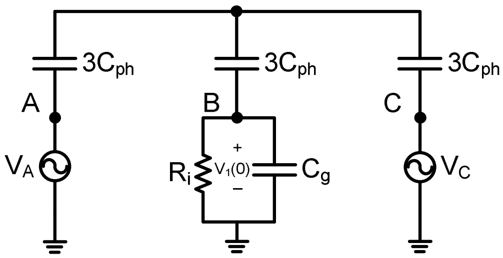

Fig. 2 Model of system shown in Fig. 1 used for obtaining V_B

that means the inductive coupling can be omitted. In this system, phase A and phase C is still energized while phase B is open at both ends following a phase B to earth fault. By using a Y-Δ conversion, the system in Fig. 1 can be represented by Fig. 2. In fact, Δ capacitive bank among the phases has been converted to a Y capacitive bank.

To solve the circuit shown in Fig. 2 and obtain phase B voltage, it would be helpful to use superposition principle as there are two kinds of voltage sources, i.e. the voltage sources V_A and V_C which are sinusoidal and the initial voltage of C_g on phase B which is actually a DC voltage. The initial voltage will be created once the secondary arc is extinguished. The sources V_A and V_B cause a voltage of fundamental frequency whereas the initial voltage causes the DC voltage.

To find the fundamental frequency voltage of phase B that is induced by two healthy phases, we should solve the same circuit in Fig. 2 without any initial voltage of capacitance C_g. Solving such a circuit leads us to the equation below:

$$V_B^{\,F} = \frac{C_{ph}}{\left[C_g + 2C_{ph}\right] - j\dfrac{1}{\omega R_i}}\left(V_A + V_C\right) \tag{1}$$

In (1), $V_B^{\,F}$ is the phase B voltage of fundamental frequency. For a typical value of R_i, the imaginary part of denominator in (1) is negligible in comparison with the real part and therefore, we obtain a simple equation as (2):

$$\left|V_B^{\,F}\right| = \frac{C_{ph}}{C_g + 2C_{ph}} V_{nominal} \tag{2}$$

To find the DC voltage we should solve the circuit shown in Fig. 3. Solving the circuit by Laplace transform, we will find:

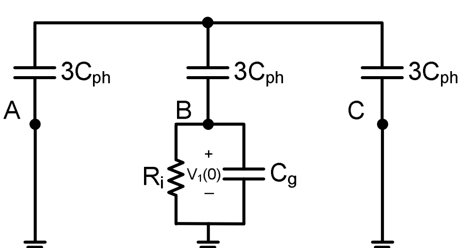

Fig. 3 Circuit used to obtain phase B voltage in the presence of initial voltage created after fault elimination

$$V_B^{\,DC} = \frac{V(0)}{1 + \dfrac{2C_{ph}}{C_g}} \cdot \frac{1}{s + \dfrac{1}{R_i(C_g + 2C_{ph})}} \tag{3}$$

Where, $V_B^{\,DC}$ is the DC component of phase B voltage. Equation (3) clearly shows the time constant for decaying DC component of V_B is as follows:

$$\tau = R_i\left(C_g + 2C_{ph}\right) \tag{4}$$

Equation (4) shows the decaying DC component has a very long time constant as the magnitude of R_i is very large. For appreciating this, let's consider the typical values for R_i, C_{ph} and C_g as below:

$$R_i = 5\times10^{9}\ \Omega/\text{km}$$

$$C_{ph} = 0.8646\times10^{-9}\ \text{F}/\text{km}$$

$$C_g = 7.272\times10^{-9}\ \text{F}/\text{km}$$

According to the above values, time constant will be obtained as:

$$\tau = 45.006\ \text{s}$$

As can be seen, the time constant is very long that means once the fault is entirely eliminated (secondary arc is extinguished), the relay will measure a long-lasting DC voltage on phase B that suffered from fault. As a result, such DC component of the voltage is a suitable criterion to detect the secondary arc extinction. In order for this criterion to work, we should only set a suitable threshold such that if the relay measures a DC voltage more than the threshold for a predefined period, then it will distinguish that secondary arc has been extinguished.

III. Simulation and Evaluation

In this section, we will evaluate our proposed method by using simulation results obtained in EMTP-RV®. To do this, two different power systems were considered including a single-circuit and a double-circuit transmission line. In our EMTP simulation, the model of secondary arc is adopted as the model presented in [11]. It is important to exactly model the secondary arc since we want to find there will be no constant DC voltage at all during secondary arc.

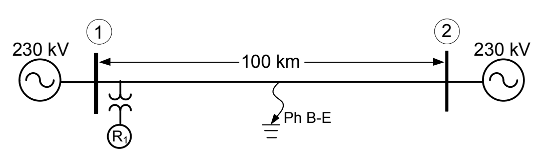

Fig. 4 Simulated system

Fig. 4 shows the simulated 230-kV single-circuit system. The fault scenario was assumed as follows. A primary arc occurs at t=60 millisecond on phase B. Following the fault occurrence, the relays located at two ends of the line will trip in their first zone in 50 milliseconds and send a trip signal to

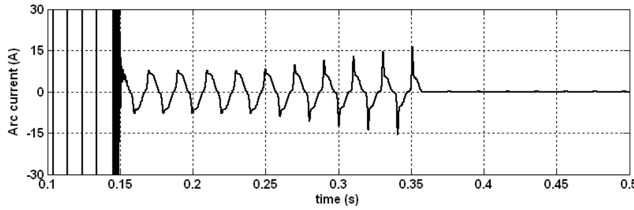

Fig. 5 Arc current at the fault branch for the 100 km-length single-circuit line

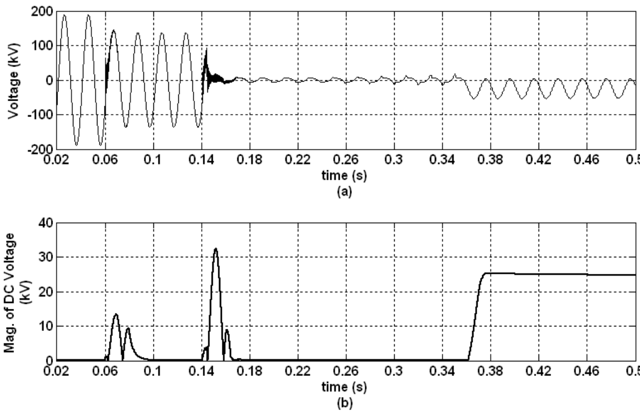

Fig. 6 Instantaneous voltage and its DC component measured by relay R_1 for the 100 km-length single-circuit line

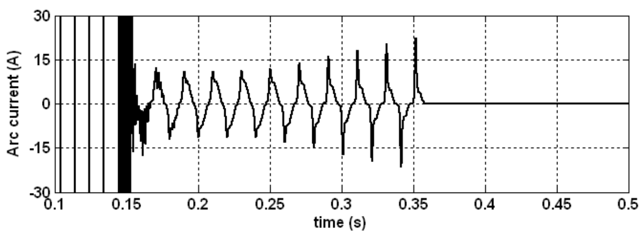

Fig. 7 Arc current at the fault branch for the 200 km-length single-circuit line

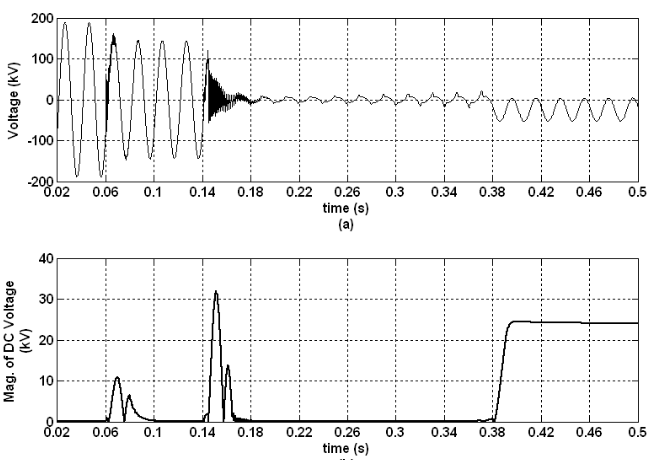

Fig. 8 Instantaneous voltage and its DC component measured by relay R_1 for the 200 km-length single-circuit line

corresponding circuit breakers (CBs) to open faulty phase (phase B). Considering a delay of 30 milliseconds in order to open the CBs contact, it was assumed that CBs will be open at t=140 millisecond. Since the CBs were assumed zero-current based that means they do not chop the current the primary arc will continue until the current will be zero. Once the primary arc current becomes zero, a secondary arc will begin and will be fed by induced voltage. In this case, the secondary arc will be extinguished at about t=360 millisecond as shown in Fig. 5. Fig. 6 shows the voltage and its DC component that is measured by relay R_1 on phase B. As shown, after t=360 millisecond the DC voltage begins to increase and after about 20 milliseconds will reach to its maximum value. This delay occurs since the length of averaging window used to calculate DC value is assumed 1 power cycle, i.e. 20 milliseconds in a 50 Hz power system. Considering this delay, in the simulated system, the DC value will be a long-lasting DC after t=380 millisecond. Therefore, secondary arc extinction can be detected by the relays after t=380 millisecond (20 millisecond after secondary arc extinction).

To investigate whether or not the DC term depends on line length, we simulated the same single-circuit system with line length of 200 km and 50 km. Fig. 7 and Fig. 8 show the arc current and voltage and its DC component measured by relay R_1 during the whole process of fault, i.e. primary and secondary faults for the line of 200 km length. The same signals are shown in Fig. 9 and Fig. 10 for a line of 50 km. As can be seen, although the line length has been twice and half, the magnitude of DC term is still about 25 kV. This shows that

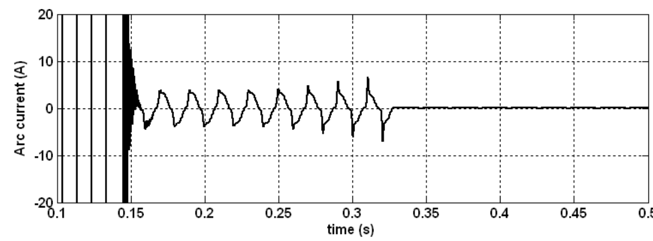

Fig. 9 Arc current at the fault branch for the 50 km-length single-circuit line

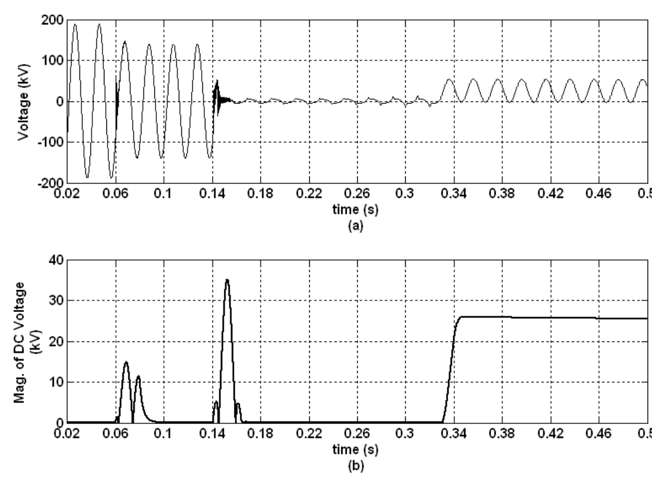

Fig. 10 Instantaneous voltage and its DC component measured by relay R_1 for the 50 km-length single-circuit line

the line length effect on the DC voltage term can be ignored.

For the second case, the system shown in Fig. 3 was considered with a double-circuit transmission line. The same fault scenario was simulated on one of the two lines. The arc current and the voltage and its DC component measured by the relay are shown in Fig. 11 and Fig. 12 respectively. As can be seen, for this case there is also a long-lasting DC voltage after secondary arc extinction.

Here, it is worthwhile to comment about the sign of DC voltage. As shown in Fig. 6 and Fig. 8 the DC voltage is negative while in Fig. 10 it is positive. The sign that the DC term will have depends on when the secondary arc is extinguished. If the secondary arc is extinguished at natural current zero with negative derivative (i.e. the current is positive at the last half period) then the DC will be negative and if the current is negative before going to natural current zero, then the DC offset will be positive. However, in our detection methodology since the magnitude of the DC voltage has been used, there is no matter what its sign is.

IV. The Feasibility of the Proposed Method

As illustrated, the proposed method is based on the measurement of DC voltage. Although it is easy to implement and to set, the main challenge of the proposed method is how to measure the DC voltage. This question arises since it is clear that CVTs and PTs will be saturated when a DC voltage is applied to them. This statement needs to be demonstrated in depth when we apply our proposed method. It means that it takes a specified time for CVT core to be saturated by a DC voltage. The time depends on the amount of DC voltage and the saturation flux of the CVT core. Since the DC voltage is about 20 kV that is about 10 percentages of rated voltage, typical CVTs or PTs used in the voltage level of 230 kV and 400 kV will not be saturated until about 10 power cycles (200 milliseconds). It means that CVTs and PTs can properly transform this amount of DC term to the secondary side for 200 milliseconds from arc extinction instant. This time is enough for the relay to detect secondary arc extinction and there is no concern regarding the saturation due to the DC voltage.

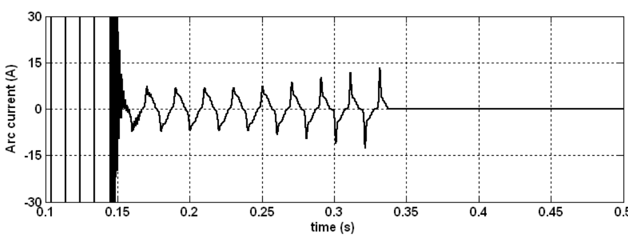

Fig. 11 Arc current at the fault branch for the 100 km-length double-circuit line

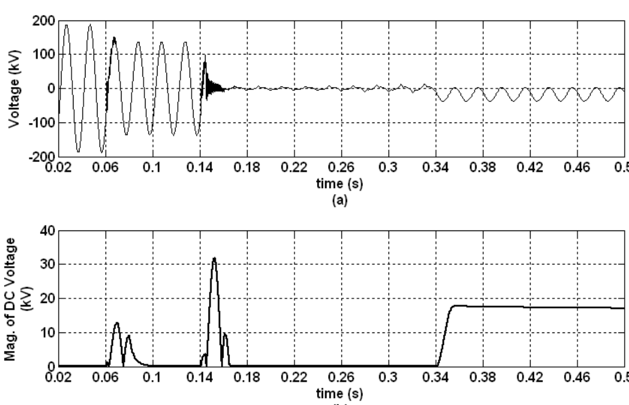

Fig. 12 Instantaneous voltage and its DC component measured by relay R_1 for the 100 km-length double-circuit line

As can be seen in Fig. 6, Fig. 8, Fig. 10 and Fig. 12, following primary fault inception and at the opening time of CBs (secondary fault inception), a DC voltage is also measured by the relay. However, in these cases the DC value is quickly damped whereas after secondary arc extinction a relatively constant DC voltage will be created. Therefore, to detect secondary arc extinction, the DC voltage should be included in a predefined threshold for a predefined duration. Duration of 0.1 second is plausible.

V. Conclusion

A new method for adaptive reclosing function was proposed and its validity was tested. It was demonstrated that during primary arc and secondary arc there was no constant DC voltage whereas after the secondary arc extinction, a long-lasting DC voltage that can be considered constant within a few seconds from the extinction will be superimposed on the fundamental frequency of the voltage of the phase that suffered from fault and is going to be reclosed. Therefore, this DC voltage can be a suitable criterion to determine the secondary arc extinction. The main concern for applying this function is whether or not the relay measures this DC voltage in spite of CVT core saturation. As can be illustrated, since the DC voltage is about 10 percentage of nominal voltage it takes enough time (about 200 milliseconds) for CVTs to be saturated and up to this time the DC voltage will be properly measured by the relay. Therefore, the DC voltage has been measured and the relay can reliably distinguish secondary arc extinction before the CVT is saturated. The main advantage of the proposed method over the existing adaptive ones is that it is easy to implement and to set it in numerical relays. We need to set only a threshold for DC voltage and as shown it has a low sensitivity to system parameters including line length.

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