An adaptive three-phase reclosure scheme for shunt reactor-compensated transmission lines based on the change of current spectrum

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ABSTRACT

In this paper, a new three-phase adaptive reclosing scheme for transmission lines with shunt reactors is proposed to identify fault nature and determine the arc extinction time under the single and double-phase-to-ground faults. According to the fact that the faulted phase currents of shunt reactors contain only one oscillating frequency before the fault extinction and contain other two different oscillating frequencies when the fault is extinguished, this change of current frequency can be used to distinguish transient faults. When sampling rate is an integral multiple of the faulted phase current frequency of shunt reactors under permanent faults, an abrupt increase of currents even harmonics which is caused by spectral leakage of the DFT algorithm under non-synchronous sampling can lead to identify transient faults and three-phase reclosing. Electromagnetic Transient Program simulation results verify the correctness of the frequency spectrum characteristic analysis of the faulted currents of shunt reactor. The feasibility of the proposed scheme is also tested under different fault condition.

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1. Introduction

According to statistics, more than eighty percent of faults of overhead transmissions lines are transient faults. Auto-reclosure can provide a means for quickly clearing these faults to improving power system stability and synchronization. However, the conventional auto-reclosure adopts the fixed dead time strategy which could not give the optimal operating performance for the breaker. It may cause a second damage to the system when reclose before complete deionization of the arc path or even reclose on permanent faults. Therefore, adaptive reclose has been proposed which aims to not only distinguish a permanent fault from a transient fault but also be able to detect the secondary arc extinction time.

Since for more than 70% of transient faults are single-phase-to-earth faults (SPG), there have been a number of research papers to study adaptive single-phase reclose (ASPAR). Generally, they can be categorized according to their implementation time.

The time during fault duration is classified into the primary arc period [1]. In Refs. [2] and [3], the ASPAR start up their algorithm as soon as a fault occurring. The fundamental and third

harmonic of the terminal voltages and currents phasors are used for calculating the arc voltage amplitude and the fundamental arc resistance. Obviously, the result can only be used for blocking the permanent faults, but fails to detect arc extinction time for transient faults. The time after breaker single-phase tripping is classified into the secondary arc period which is maintained by both capacitive and inductive coupling from healthy phases. The nonlinear variation of arc causes the faulted voltage containing a large number of odd harmonics [4]. The high-frequency signal of the faulted phase voltage during secondary period is the basis for most ASPARs identify transient faults [5–10]. However, using the neutral point reactor may result in reduced arc extinction time and minor arc voltage [11], therefore, obtaining the high-frequency signal is restricted within the accuracy of the voltage transformer. After secondary arc extinction, there appears a recovery voltage which has different features under the different system configurations. In case of transmission line without shunt reactors, the recovery voltage waveform can be approximated with a sinusoidal signal with DC offset. The rms-value of voltage waveform within each data window will increase suddenly with the advent of DC component. Paper [12] uses the difference-value between present rms-value and previous rms-value at each time step to detect arc extinction time. For shunt-compensated lines, due to the oscillatory circuit formed by the capacitance of transmission line and the
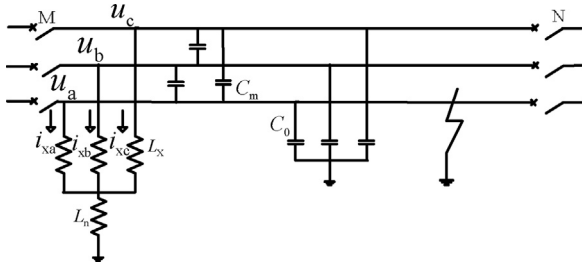
Fig. 1. Equivalent model for single-phase-ground fault of the transmission line with one shunt reactor after the breaker three-phase trip.

Fig. 2. The Karrenbauer modal circuits.

shunt compensator's inductance, the recovery voltage wave-form is characterized by a beat, so the derivative of the faulted phase voltage magnitude and angle will resonate around a certain value. Paper [13] employs this pattern to quickly detect the arc extinction for transient faults. Paper [14] proposes an integrated autoreclosure scheme which merged the function advantage of the adaptive reclosing technique and the optimal reclosing can not only identify faults nature but also enhance the transient stability.

On the other hand, there are few papers to study three-phase adaptive reclosure. Although the ratio of double-phase-to-earth faults (DPG) is relatively less, three-phase reclosing on permanent faults may cause more serious shock and switch overvoltage than single-phase reclosure. A new method to control the three-phase reclosing was proposed in Ref. [15] which detected the first minimum voltage region of the beating across the circuit breakers. However, the controller is able to reduce the switching overvoltage but can not identify permanent faults or determine the arc extinction time. In Ref. [16], the Karrenbauer matrix was used to transform phase domain voltage (v_a, v_b and v_c) in modal domain voltage (v_0, v_1, v_2). The signal $-v_0$ is equal to $v_1 + v_2$ when the fault remains. A statistical parameter is used to check the signals close to each other which can identify the extinction of SPG and DPG. However, for transmission lines with shunt reactors, the faulted phase voltage during secondary arc period or permanent fault is so minor that the error of voltage transformer limits the applications of voltage-based reclosure scheme. The current-based scheme has attracted [17,18] because shunt reactors normally have current transformer (CT) which has high measurement precision.

In this paper, an adaptive three-phase auto-reclosing scheme for shunt reactor-compensated transmission lines has been proposed based on the spectral leakage phenomenon caused by non-synchronous sampling. The expression of the faulted phase currents of shunt reactor has been derived in paper. As for permanent faults, the current expression contains only one frequency. As for transient faults before fault extinction, there is also only one frequency in current expression. But the other two different frequencies occur after transient fault extinction. When taking the oscillating frequency under permanent faults as the reference for sampling rate, the change of currents frequency will cause an abrupt increase in currents harmonics which can lead to three-phase reclosing. Simulation results verify the proposed method is insensitive to fault location and fault resister.

2. Proposed auto-reclosure principles

When the breakers at the two terminals of the transmission line three-phase tripping, the equivalent circuit of transmission line with one shunt reactor which has neglected the line impedance is shown as Fig. 1. In order to analyze the oscillating frequency of the line-terminal voltages, the inverse Karrenbauer transformation matrix was used in paper [16] to decouple the equivalent circuit into modal circuits as shown in Fig. 2. Where, C_0 and C_1 are
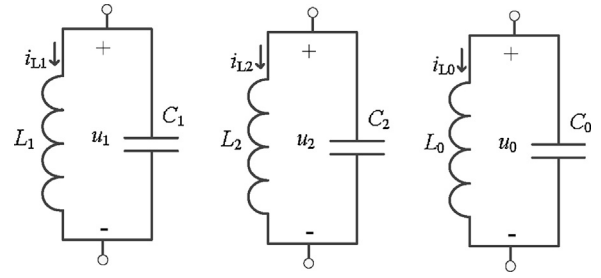
the line capacitance for zero sequence and positive sequence. L_0 and L_1 are equivalent inductance for zero sequence and positive sequence of shunt reactors after modal transformation. L_1 and L_0 can be acquired by the following formula:

$$L_1 = L_x \tag{1}$$

$$L_0 = L_x + 3L_n \tag{2}$$

where, L_x is the inductance of the shunt reactors, L_n is the inductance of the neutral reactor.

The voltages in modal domain (u_1, u_2, and u_0) as shown in Fig. 2 can be expressed by phase domain voltages (u_a, u_b and u_c) as follows:

$$u_1 = (u_a - u_b)/3 \tag{3}$$

$$u_2 = (u_a - u_c)/3 \tag{4}$$

$$u_0 = (u_a + u_b + u_c)/3 \tag{5}$$

where, u_a, u_b and u_c are line-side three-phase voltages at the M terminal as shown in Fig. 1.

2.1. The frequency of the faulted phase currents of shunt reactor under permanent faults

In order to discuss the relation between the faulted phase currents of shunt reactor and the modal voltages, the following equations can be obtained from Fig. 1.

$$u_a = L_x \frac{di_{xa}}{dt} + L_n \frac{d(i_{xa} + i_{xb} + i_{xc})}{dt} \tag{6}$$

$$u_b = L_x \frac{di_{xb}}{dt} + L_n \frac{d(i_{xa} + i_{xb} + i_{xc})}{dt} \tag{7}$$

$$u_c = L_x \frac{di_{xc}}{dt} + L_n \frac{d(i_{xa} + i_{xb} + i_{xc})}{dt} \tag{8}$$

where, i_{xa}, i_{xb}, i_{xc} are the currents of phase A–C in the shunt reactors as shown in Fig. 1.

By substituting Eqs. (6)–(8) into Eqs. (3)–(5), and using the inverse Karrenbauer matrix to transform the phase domain currents (i_{xa}, i_{xb} and i_{xc}) into modal currents (i_{x1}, i_{x2}, i_{x0}), the following three equations can be obtained:

$$u_1 = \frac{L_x}{3}\left(\frac{di_{xa}}{dt} - \frac{di_{xb}}{dt}\right) = L_x \frac{di_{x1}}{dt} \tag{9}$$

$$u_2 = \frac{L_x}{3}\left(\frac{di_{xa}}{dt} - \frac{di_{xc}}{dt}\right) = L_x \frac{di_{x2}}{dt} \tag{10}$$

$$u_0 = (L_x + 3L_n)\frac{di_{x0}}{dt} \tag{11}$$

For single-phase-to-ground faults, due to the modal circuits are connected in series, the relation between modal voltages is described as:

$$u_1 + u_2 + u_0 = 0 \tag{12}$$