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Zero-sequence voltage trajectory analysis for unbalanced distribution networks on single-line-to-ground fault condition

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ABSTRACT

Faulty phase recognition under single-line-to-ground (SLG) fault condition is critical for some arc suppression methods in medium voltage (MV) networks. Traditional methods usually assume that the distributed parameters of the network are symmetrical, thus are unsuitable for the asymmetrical networks, especially when the ground-fault resistance is relatively high. In this paper, the trajectory of the zero-sequence voltage with the change of ground-fault conductance is analyzed in detail. The magnitude and phase angle variation rules of the voltage under different asymmetry ratios are presented. Then, the ranges of their unique variation rules on SLG fault for each phases are separately and strictly discussed both for the under-compensated and over-compensated grounding conditions. Furthermore, a faulty phase recognition method is proposed based on the variation rules of zero-sequence voltage on faulty condition. Simulation results verify the concluded variation rules and validate the effectiveness of the proposed fault phase recognition method, which ensures exact recognition of faulty phase in asymmetrical network and high-resistance ground fault condition.

1. Introduction

Power supply reliability is of great importance in distribution networks [1]. Most of the reliability problems originate from single-line-to-ground (SLG) faults. Arc suppression devices are designed for distinguishing the arcs caused by SLG faults. Their performance is critical to the safety of the power supply apparatus, and is strongly associated with the inherent parameters of the distribution network [2–5].

Traditional arc suppression coil (ASC) compensates the capacitive ground current by the principle of parallel resonance, encountering limited arc suppression performance as large harmonic contents can also maintain arcs at the ground point [6,7]. Besides, the possible overvoltage caused by the series resonance between ASC and inherent capacitance at the inception of ground fault may further result in cross-country faults and insulation failure [8–13]. Several methods have been presented to avoid overvoltage and achieve dynamic adjustment of ASC inductance. Zeng et al. [14] has presented a grounding method using a pre-adjusted Petersen coil paralleling with a reactor, which disconnects the coil in normal condition and connects it to the neutral at ground fault, to avoid overvoltage and extinguish fault arcs. This method avoids series resonance to some extent, but lacks of flexibility to the change of distributed parameters. Chen et al. [15] has proposed a two-stage magnetically controlled reactor to enhance the dynamic performance and mitigate the 3rd order harmonics caused by nonlinearity of saturated iron core. Although they are more flexible than the ASCs, these methods are still not able to compensate the active and harmonic components in ground current, thus have limited arc suppression performance.

Some active ways based on the technology of power electronics are proposed to meet this requirement. Janssen et al. [16] and Winter [17] has proposed a residual current compensation ground fault neutralizer (RCC-GFN) which is able to compensate harmonic ground current up to the 7th order. Tian et al. [18] has proposed an ASC based on transformer with controlled load, which has the ability of full ground-current compensation and rapid response. A hybrid flexible grounding system is proposed by Peng et al. [19], which combines the magnetic control reactor (MCR) providing large-capacity reactive power and the active power compensator (APC) realizing full ground current compensation. Besides, the voltage control method used in this device does not need capacitive current detection, which decreases the response time and residual

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current level. Wang et al. [20] has proposed a single-phase inverter based full ground current compensator with time-domain dual-loop zero-sequence voltage control method, which is able to realize fast and reliable ground-fault arc suppression.

The performance of the active methods depends on the precise detection of the faulty phase on SLG fault. A misjudgment may result in cross-country fault as the arc suppression device may short-circuit the sound line to the ground, which will cause the immediate operation of current protection to cut off the faulty feeder [21].

The faulty phase recognition is straightforward if the distribution network is symmetrical and the ground-fault resistance is low enough. That is, in under-compensated grounding system, e.g., ungrounded or resistance grounded system, the faulty phase is the phase with the system voltage lagging its counterpart whose line-to-ground voltage is most significant among the three line-to-ground voltages on SLG fault condition. In over-compensated grounding system, on the other hand, the faulty phase has the system voltage heading its counterpart whose line-to-ground voltage is most significant among three phases [22].

Nevertheless, the distribution network has the inherent feature of asymmetry and various ground-fault resistance. It means in some high ground-fault resistance conditions the criterion above goes invalid. As the zero-sequence voltage on SLG fault follows the particular rules that might indicate the faulty phase [23], it is useful to analyze the voltage trajectories with the change of ground-fault resistances. Xu et al. [22] has proposed a novel criterion by establishing and comparing three-phase voltage phasors, however, the three-phase asymmetry ratio is considered to be scalar which is impractical enough as the ratio is a vector in most cases. Liu et al. [21] has practically improved the zero-sequence voltage trajectory by introducing three-phase asymmetry ratio vector and proposed a faulty phase recognition method based on estimating and plotting the zero-sequence voltage under SLG fault in each phase. However, the boundaries of the sectors are ambiguous and complicated to calculate, which makes the method difficult to apply in practice.

In this paper, the magnitude and phase angle variation rules of the zero-sequence voltage are analyzed in detail. The change of the ground-fault resistance together with the distribution network parameters are taken into consideration. The invalid region of the traditional criterion above is discussed. A practical faulty phase recognition method based on the variation rules of zero-sequence voltage is proposed, which can be easily implemented in digital processors. Simulation results are presented for verification of the proposed method.

2. Zero-sequence voltage trajectory analysis

A typical medium voltage distribution network is shown in Fig. 1. Either a neutral grounding inductor (Peterson Coil), a resistor or their combination can be chosen to ground the neutral point of the distribution network. Some small-scale networks use non-grounded method as the distributed capacitive current is relatively low. Therefore, the detuning ratio differs with the grounding methods. Assume that the SLG fault occurs in phase A, the neutral voltage or the zero-sequence voltage can be described by the following expression.

$$\boldsymbol{U}_{0\mathrm{A}} = -\frac{\mathrm{j}\omega(C_\mathrm{A}\boldsymbol{E}_\mathrm{A} + C_\mathrm{B}\boldsymbol{E}_\mathrm{B} + C_\mathrm{C}\boldsymbol{E}_\mathrm{C}) + G_\mathrm{E}\boldsymbol{E}_\mathrm{A}}{\mathrm{j}\omega C_{\sum} + \frac{3}{R} + G_\mathrm{E} + \frac{1}{\mathrm{j}\omega L_\mathrm{N}} + \frac{1}{R_\mathrm{N}}} \quad (1)$$

$\boldsymbol{U}_0$ is the neutral voltage or zero-sequence voltage. $\boldsymbol{U}_{0X}$ is the Zero-sequence voltage when single-line-to-ground (SLG) fault occurs on phase X (X = A, B or C). $\boldsymbol{E}_X$, C_X and R_X are the line-to-neutral voltage, line-to-ground capacitance and resistance of phase X, respectively. The line-to-ground resistances on the three phases are assumed to be equal, as R, for simplicity. R_E and G_E are Ground-fault resistance and conductance, respectively. $C_{\sum}$ is the sum of the line-to-ground capacitances. L_N and R_N are the neutral grounding inductance and resistance, respectively. The expression is unified as it applies for all the grounding methods discussed previously. It can be simplified by using the rotating coefficient $a = e^{\mathrm{j}2\pi/3}$.

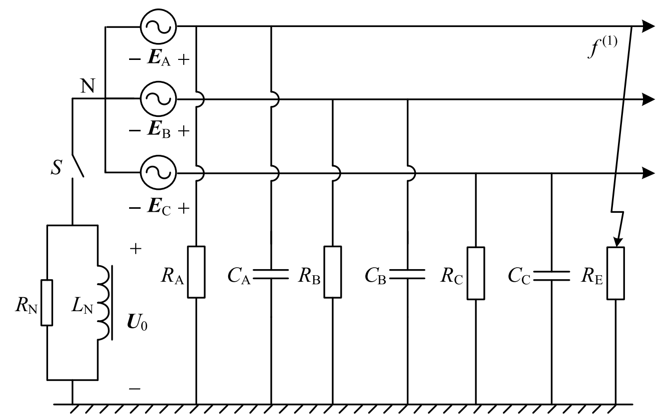

Fig. 1. Typical medium distribution network on SLG fault condition.

$$\boldsymbol{U}_{0\mathrm{A}} = -\boldsymbol{E}_\mathrm{A}\frac{\mathrm{j}\frac{C_\mathrm{A}+a^2C_\mathrm{B}+aC_\mathrm{C}}{C_{\sum}} + \frac{G_\mathrm{E}}{\omega C_{\sum}}}{\mathrm{j}\left(1-\frac{1}{\omega^2 L_\mathrm{N}C_{\sum}}\right) + \frac{1}{\omega C_{\sum}}\left(\frac{3}{R}+\frac{1}{R_\mathrm{N}}+G_\mathrm{E}\right)} \quad (2)$$

The three-phase asymmetry ratio $\boldsymbol{r}_\mathrm{a}$ is used to describe the unbalance ratio of the distribution network, which is defined as

$$\boldsymbol{r}_a = \frac{C_\mathrm{A}+a^2C_\mathrm{B}+aC_\mathrm{C}}{C_{\sum}} = r_a\angle\alpha \quad (3)$$

Theoretically, its magnitude r_a has the maximum values of 5% in distribution network with pure overhead line, 0.5% with pure cable line and 1.5% with mixed line. It should be noticed that the phase angle of $\boldsymbol{r}_\mathrm{a}$ (defined as α) changes with the distribution line, which makes great difference when considering the zero-sequence voltage trajectory. Meanwhile, if its magnitude is specified, the trace of $\boldsymbol{r}_\mathrm{a}$ as α changes from 0° to 360° is a circle with a circle center of the origin point.

The detuning ratio υ and damping ratio d mainly depend on the distributed capacitive current and system grounding methods.

$$\upsilon = 1 - \frac{1}{\omega^2 L_\mathrm{N} C_{\sum}} \quad (4)$$

$$d = \frac{1}{\omega C_{\sum}}\left(\frac{3}{R}+\frac{1}{R_\mathrm{N}}\right) \quad (5)$$

To avoid series resonance between the Peterson Coil and distributed capacitance, the detuning ratio should not be too small in resonant grounded systems. Typically, a negative detuning ratio of 10%–20% is set to over-compensate the capacitive current in case of overvoltage caused by series resonance when power system operation mode changes from the maximum one to the minimum one.

The damping ratio has the range of 1.5%–5% in ungrounded systems. A damping resistor is necessary to connect in parallel with the Peterson coil to damp the aforementioned series resonance, which consequently increases the system damping ratio. The damping