Electric Power Systems Research 158 (2018) 219–227

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

A novel analysis of offset mho characteristic of memory-polarized and cross-polarized distance functions

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ARTICLE INFO

Article history:
Received 22 October 2017
Received in revised form 4 January 2018
Accepted 5 January 2018

Keywords:
Offset mho characteristic
Memory-polarized distance function
Cross-polarized distance function

ABSTRACT

This article shows a novel and detailed description of the offset mho characteristic of memory-polarized and cross-polarized distance functions. The exact expressions for offset impedances are found, analyzing by symmetrical components a power system taken as an example. The power system model is general, and it includes the effect of additional interconnections between both line ends. Single line-to-ground faults, line-to-line faults, and double-line-to-ground faults are rigorously analyzed. Memory-polarized and cross-polarized distance functions have variable characteristics in the R–X plane (i.e., offset values change, depending on power system conditions), and these variations are shown for the analyzed example. Under some circumstances, the directionality of these distance functions is not evident, and the possible use of an additional directionality restraint is analyzed.

1. Introduction

There are different methods to polarize distance functions, as well as there are different geometric shapes for distance characteristics in the R–X plane [1–18]. The offset mho characteristic (OMC) is a circle which does not pass through the origin of the R–X plane. This article particularly analyzes the OMC whose offset impedance (Z_{OF}) is only defined by its polarization method (e.g., cross-polarized or memory-polarized). This OMC is typically applied in protection of transmission lines. Diameter of this OMC is defined by Z_{OF} and by the characteristic impedance (Z_R) of distance function. Z_R is a relay setting, but Z_{OF} is not a relay setting. Z_{OF} is a variable quantity, which depends on the power system. In some cases, Z_{OF} also depends on time (e.g., memory-voltage for the polarization changes dynamically in some relays). Quadrature-polarization is detailedly analyzed here because it is the most common cross-polarization (other voltage combinations could be applied in cross-polarization [8], and they can be analyzed in a way similar to the shown one here).

Origin of R–X plane is inside of the OMC for forward faults. Thus, there is a region of third quadrant that is inside of this OMC, but third quadrant of the R–X plane is related to reverse faults. These functions do not operate for reverse faults because their behavior changes for reverse faults [6–18]. Some explanations in the literature are not very clear about this point (e.g., some documents only mention that the relay does not operate for reverse faults, without any additional information [6,7]). Some explanations are based on comparisons between polarizing and operating phasors for reverse faults, but without showing the effect on the OMC [8,9]. Some documents change the definition of apparent impedance for reverse faults [10–13], by changing the current taken as reference. Finally, some other documents clearly indicate that the sign of Z_{OF} changes for reverse faults [14–18], without changing the definition of apparent impedance, and the explanations of this article are in accordance with this last group of documents. From this perspective, Z_{OF} tends to be in the first quadrant for reverse faults, relatively far from the origin of the R–X plane.

There are documents (e.g., Refs. [2,6,8–11,14,15]) which indicate simplified values for Z_{OF}. This article shows detailed values of Z_{OF}, which were analytically obtained by applying symmetrical components for forward faults and reverse faults. This article also shows the variations of Z_{OF} for different conditions of a power system taken as an example. This power system is general enough in order to take into account other possible interconnections between both line ends. These other interconnections could be, or not, at the same voltage level because transmission systems usually are meshed networks.

Some OMC can be partially memory-polarized or partially cross-polarized, by including the self-polarizing voltage in the polarizing voltage (in a weighted sum with memory-voltage or cross-voltage, respectively). This case is also analyzed in this article. Dynamic

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https://doi.org/10.1016/j.epsr.2018.01.009
0378-7796/

changes of memory voltage can be qualitatively seen as special cases of partially memory-polarized OMC (where the memory-voltage dynamically changes, until its final expiration).

The OMC have been widely applied for memory-polarized and cross-polarized distance functions. Therefore, there is enough practical experience related to the validity of these polarization methods in real power systems. However, there are important differences among the protective functions from different manufacturers. For example, there are distance relays with a built-in directional restraint which is always active in conjunction with the OMC (e.g., Refs. [19,20]). This directional restraint can be shown in the same R–X plane of the distance function [19] or not (e.g., because it could be based on other concepts, such as negative-sequence impedances [20]). Other distance relays do not have any unavoidable additional built-in directional restraint (e.g., Refs. [21,22]). Thus, in this context, a discussion about the need of additional directional restraints for these OMC is appropriate, and this article explores this point by the analysis of the locus of Z_{OF} for the power system taken as an example.

The main contributions of this paper are: (a) summarize a complete description for the OMC of memory-polarized and cross-polarized distance functions; (b) show exact expressions for offset impedances of the OMC; (c) show the behavior of offset impedances for different conditions of a power system taken as an example; (d) discuss the need of an additional directional restraint under certain circumstances.

2. Offset mho characteristic in memory-polarized and cross-polarized distance functions

2.1. OMC from theory of phase comparators

From the theory of phase comparators, an OMC is obtained from the following conditions:

$$-90^\circ < \arg(S_1/S_2) < 90^\circ \quad (1)$$

$$S_1 = V_P \quad (2)$$

$$S_2 = I\, Z_R - V \quad (3)$$

V_P: polarizing voltage.

V, I: voltage and current for the apparent impedance Z (i.e., Z = V/I).

Z_R: characteristic impedance (a relay setting).

A novel way to explain this phase comparator is shown in the Appendix A. This novel explanation is much simpler than other explanations from the literature.

Mathematically, only the phase of V_P is relevant, because arg (S_1/S_2) = arg (S_1) – arg (S_2). In this article, the magnitude of V_P has been selected to facilitate the demonstrations. With this selection of V_P, the quotient V_P/I can be defined as Z-Z_{OF} (Z_{OF} is the offset impedance). Thus, S_1/S_2 is $(Z - Z_{OF})/(Z_R - Z)$. Z_{OF} is not a relay setting; Z_{OF} is simply the result of $(V - V_P)/I$.

It is assumed for this article that $V = V_{BC}$ and $I = I_B - I_C$ for double-line-to-ground faults and line-to-line faults, and $V = V_A$ and $I = I_A + 3 K_0 I_{R0}$ for single-line-to-ground faults. K_0 is the residual compensation factor (a relay setting). I_{R0} is the zero-sequence current, measured by the relay ($3I_{R0} = I_A + I_B + I_C$). V_{BC}, V_A, I_A, I_B, I_C are voltages and currents measured by the relay.

2.2. Power system representation

A reduced representation of a generic power system is shown in Fig. 1. This model has equivalent sources at both line ends (M and N), and the impedances can be obtained from the impedance matrix ($[Z_{BUS}]$) [23]. Z_I represents the other interconnections between line terminals M and N (these interconnections could be, or not, at the same voltage level). Z_I does not represent a parallel line for the analyzed line (i.e., magnetic coupling effect between parallel lines is not analyzed in this article). The use of more simplified network models (without Z_I) is frequent in the analysis of distance relays, but model of Fig. 1 is more realistic.

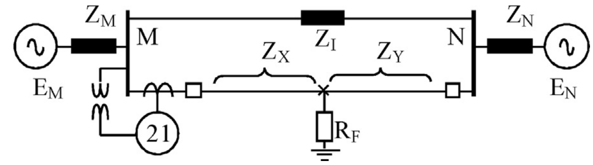

Fig. 1. Power system representation.

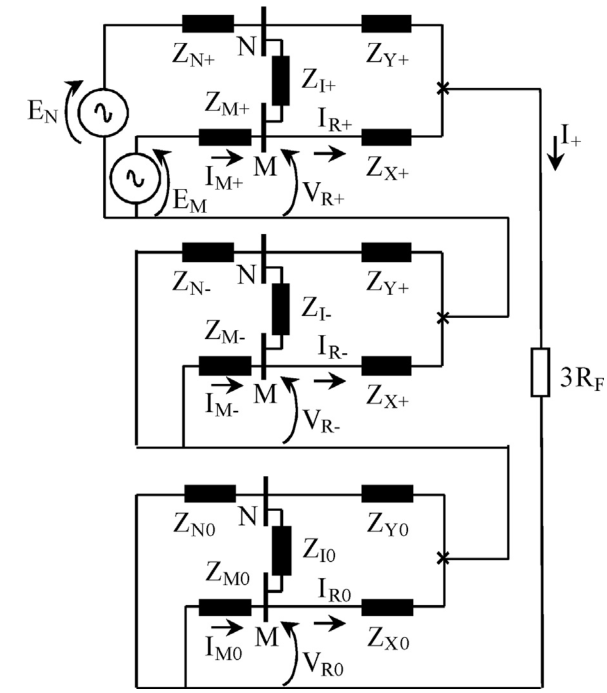

Fig. 2. Sequence networks for SLG faults in the line. Connection of sequence networks changes for DLG faults or LL faults.

Fig. 2 shows the sequence networks for single-line-to-ground (SLG) faults in the analyzed line (i.e., in forward direction). Fig. 3 shows the sequence networks for SLG faults at busbar M, behind the relay location (i.e., in reverse direction). For the sake of simplicity, reverse faults are only analyzed at this location in this article. Obviously, connection of sequence networks changes for double-line-to-ground (DLG) faults or line-to-line (LL) faults, but Figs. 2 and 3 are still useful for those who know the sequence networks in order to obtain a proper idea about the expressions that relate the internal variables of sequence networks for these cases.

2.3. OMC in cross-polarized distance functions

2.3.1. Single-line-to-ground faults

For this case, $V_P = jV_{BC}/\sqrt{3}$. Thus, $Z_{OF} = [V_A - (jV_{BC}/\sqrt{3})]/(I_A + K_0 I_R)$. Therefore:

$$Z_{OF} = \frac{2V_{R-} + V_{R0}}{I_A + K_0 I_R} \quad (4)$$

In case of forward faults, Z_{OF} can be found from Fig. 2:

$$Z_{OF} = -\frac{2Z_{M-}I_{M-} + Z_{M0}I_{M0}}{I_{R+} + I_{R-} + I_{R0}(1 + 3K_0)} \quad (5)$$