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Distance protection of block transformer units

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ABSTRACT

The main protection of block transformer units is usually realized with use of differential relays. For back-up protection distance relays are mostly employed. Their second and third zones provide also coverage of faults along the adjacent line connecting the power plant with the nearest substation. This paper deals with a challenge related to proper impedance measurement across the transformer for the configurations where the currents from the HV star terminals are not available. Commonly used algorithms of the distance relays may be prone to serious under-reaching in such situations, which calls for a new approach with correction of the measurement procedure. The inclusion of zero-sequence current is proposed, and the improved protection algorithm is analyzed theoretically and thoroughly tested with the signals obtained from EMTP-ATP simulations. Rules for new protection settings are also provided.

1. Introduction

In this paper problems related to protection of block units are discussed, where distance relay is usually a back-up for given transformer and adjacent lines [1]. Special attention is paid to the configurations when the distance relays are installed at the triangle side of a block transformer, as shown in Fig. 1. It is usually the case that the star side signals are not available or are not used, which may be a source of impedance measurement errors and relay maloperation [2,3]. It is even stated in [3] that the operation errors of the distance relays are unavoidable for behind located ground faults. Although the distance relay is meant as a back-up for faults along the adjacent line, its operation should be reliable and safe, which cannot be guaranteed with standard solutions and algorithms.

There exist a number of decent publications related to distance protection principle. Nevertheless, not many of them are related to block transformer or in-zone transformer applications. If any, they mostly deal with different aspects of distance protection, e.g. discussing the protection under-reach for in-zone phase shifting transformers [4] or the influence of power swings on block unit distance protection [5]. Some proposals to overcome the problems with transformer distance protection operation may be found, introducing e.g.:

- zero-sequence based compensation of the transformer tertiary winding influence (first zone is analyzed only) [6],
- employing a three-relay arrangement based on resistance elements [7],
- distance protection coordination with use of the IEC61850 GOOSE message-based scheme [8],

which do not solve the basic problem of wrong impedance calculation through the transformer for behind located faults.

Since none of the abovementioned approaches is 100% efficient or the ideas described require a lot of effort and costly installations, an efficient and comprehensive approach to the problems with distance relay under-reaching for single-phase faults behind the in-zone transformer is still to be developed. In this paper the following points have been addressed. First, present solution performance for d and Y transformer side faults is investigated. Then a proposal of improvements for correction of through-transformer impedance measurement errors as well as development of settings recommendation for the new protection is discussed.

It is shown that substantial improvement of the distance protection operation may be reached with introduction of the zero-sequence current and appropriate settings of the protection algorithms.

2. Distance measurement for ground and line faults at transformer star side

The following analyses have been done for a selected configuration of Yd11 transformer, presented in Fig. 2. Similar investigations and results may easily be provided for other transformer connection groups.

In relation to Fig. 2 one can introduce the winding turn ratio N_z and transformation ratio N defined as:

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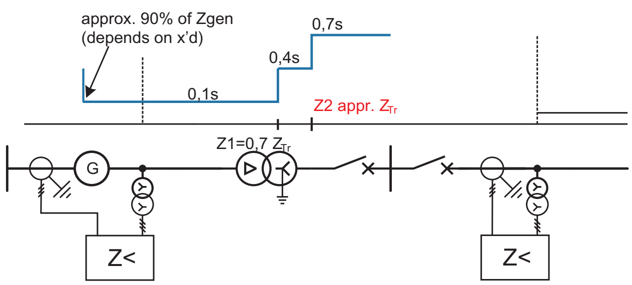

Fig. 1. Basic configuration of block unit with distance protection.

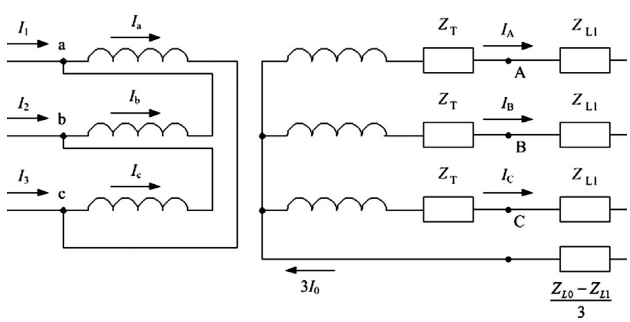

Fig. 2. Yd11 transformer and line configuration studied.

$$N_z = \frac{w_Y}{w_d} \tag{1a}$$

$$N = \sqrt{3} N_z \tag{1b}$$

With this in mind one can write the following relationships between triangle and star currents:

$$I_a = N_z I_A \tag{2a}$$

$$I_b = N_z I_B \tag{2b}$$

$$I_c = N_z I_C \tag{2c}$$

$$I_1 = I_a - I_b = N_z (I_A - I_B) \tag{3a}$$

$$I_2 = I_b - I_c = N_z (I_B - I_C) \tag{3b}$$

$$I_3 = I_c - I_a = N_z (I_C - I_A) \tag{3c}$$

For the voltage signals it holds:

$$U_{ab} = \frac{1}{N_z} U_B = \frac{\sqrt{3}}{N} U_B \tag{4a}$$

$$U_{bc} = \frac{1}{N_z} U_C = \frac{\sqrt{3}}{N} U_C \tag{4b}$$

$$U_{ca} = \frac{1}{N_z} U_A = \frac{\sqrt{3}}{N} U_A \tag{4c}$$

Measurement of impedance seen from the transformer delta side is further analyzed. For *ground faults at the star side* (at transformer terminals or along the adjacent line) the following relations for star side voltages are valid:

$$U_A = I_A Z_1 + 3I_0 \frac{Z_0 - Z_1}{3} \tag{5a}$$

$$U_B = I_B Z_1 + 3I_0 \frac{Z_0 - Z_1}{3} \tag{5b}$$

$$U_C = I_C Z_1 + 3I_0 \frac{Z_0 - Z_1}{3} \tag{5c}$$

where

Z_1 – impedance between the transformer delta terminals (measurement point) and the fault point (star side), $Z_1 = Z_{T1} + Z_{L1}$,
Z_0 – zero-sequence impedance to the fault point, $Z_0 = Z_{T0} + Z_{L0}$,
Z_{T1} – transformer short-circuit impedance (referred to the star side voltage level),
Z_{L1} – positive sequence impedance from the transformer star terminals to the fault point,
Z_{T0} – transformer zero-sequence impedance ($Z_{T0} = Z_{T1}$),
Z_{L0} – zero-sequence impedance between the transformer star terminals and the fault point.

Then the measurement of phase A loop impedance is done with the following equations:

$$Z_a = \frac{U_{ca}}{I_1 - I_3} = \frac{\sqrt{3}}{N} U_A \frac{1}{\frac{N}{\sqrt{3}}(3I_A - 3I_0)} = \frac{U_A}{N^2 (I_A - I_0)} \tag{6a}$$

This may be rewritten in the form:

$$Z_a = \frac{Z_1}{N^2} \frac{1 + \frac{I_0}{I_A}\left(\frac{Z_0}{Z_1} - 1\right)}{1 - \frac{I_0}{I_A}} \tag{6b}$$

which finally yields:

$$Z_a = \left(\frac{Z_1}{N^2}\right)\left[1 + \left(\frac{I_0}{I_A - I_0}\right)\left(\frac{Z_0}{Z_1}\right)\right] \tag{6c}$$

The formula (6c) shows the relative increase of the measured impedance caused by the current I_0 and impedance Z_0.

For the A-phase faults it holds $\frac{I_0}{I_A} = \frac{1}{3}$ (the most probable value), therefore:

$$Z_a = \frac{1}{N^2} \frac{\frac{2}{3} Z_1 + \frac{1}{3} Z_0}{\frac{2}{3}} = \frac{Z_1}{N^2}\left(1 + \frac{1}{2}\frac{Z_0}{Z_1}\right) \tag{7a}$$

If the ratio of impedances $\frac{Z_{L0}}{Z_{L1}} = 3$ (it is so just for the line impedance or for the case when the line is long and the transformer impedance can be neglected), then:

$$Z_a = \frac{Z_{L1}}{N^2}\left(1 + \frac{3}{2}\right) = 2.5 \frac{Z_{L1}}{N^2} = 2.5 \frac{Z_1}{N^2} \tag{7b}$$

One can see that the measured impedance (7b) is 2.5 times higher than in reality and thus the relay is prone to serious under-reaching. In reality this coefficient may change between 1.5 and 2.5 and depends on the fault place. For faults at transformer terminals one should replace the total impedances with the ones of block transformer, which yields:

$$Z_a = \frac{Z_{T1}}{N^2}\left(1 + \frac{1}{2}\frac{Z_{T0}}{Z_{T1}}\right) = 1.5 \frac{Z_{T1}}{N^2} = 1.5 \frac{Z_1}{N^2} \tag{7c}$$

One should of course understand that for the relay installed at the delta side the star side signals may not be available. Measurement of the phase current as well as more accurate impedance measurement during ground faults at Y side calls for "measurability" of the zero-sequence current $3I_0$. Then

$$3I_A = 3I_0 - \frac{\sqrt{3}}{N}(I_3 - I_1) \tag{8}$$

With introduction of the corrected current I_r:

$$I_r = \frac{N}{\sqrt{3}}[3I_A + 3I_0(n-1)] = I_1 - I_3 + \frac{N}{\sqrt{3}} n 3I_0 \tag{9}$$

one may derive the following relations for impedance measurement:

$$Z_a = \frac{\sqrt{3}}{N} \frac{I_A Z_1 + I_0 (Z_0 - Z_1)}{I_r} \tag{10a}$$