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Methods for differential protection of Scott transformers

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ABSTRACT

This article describes different methods for the differential protection of Scott transformers, which are based on: (a) single-phase relays, (b) 3-phase relays for two-winding transformers, (c) 3-phase relays for multi-winding transformers, (d) specific relays for Scott transformers. Initially, a description about the currents in Scott transformers is shown, which is necessary to understand their differential protection. Afterwards, the different methods for the differential protection of Scott transformers are described. Some methods, based on single-phase relays and based on 3-phase relays for multi-winding transformers, are briefly described in literature, and the contribution of this article is to highlight important details about the matching of the currents in the differential protection. Other methods, based on 3-phase relays for two-winding transformers, are not described in the literature and they are shown here. Finally, two options for the design of specific relays for Scott transformers are proposed in this article. Thus, the result is a clear explanation about the options for the proper differential protection of Scott transformers.

1. Introduction

Scott transformers are mainly applied to feed two-phase systems from a three-phase power system, and they are an option to feed electric railways [1]. The main textbooks about power system protection do not describe the differential protection for Scott transformers (87T-Scott). An exception is the classical book written by Mason [2], which describes schemes with single-phase relays because it was the available technology at that moment. Some alternative options have been described by manufacturers, based on 3-phase relays for multi-winding transformers [3–7].

Conventional 3-phase numerical relays for two-winding transformers perform the matching of primary and secondary currents of these power transformers by taking into account the ratio of the power transformer and the ratios of the current transformers [8]. There is not a single ratio between primary and secondary currents in Scott transformers. Due to this fact, conventional 3-phase relays for two-winding transformers cannot be directly applied for the 87T-Scott, and the use of interposing current transformers (ICTs) is necessary in this case.

ICTs are not strictly necessary for the 87T-Scott in case of 3-phase relays for multi-winding transformers [3–7]. In general, 3-phase relays for four-winding transformers can be applied for the 87T-Scott [3,4]. Application of 3-phase relays for three-winding transformers is possible for the 87T-Scott, but only if the relay was designed to perform internal sums of input currents from different current transformers [5–7], or if these sums are performed at the secondary side of the current transformers [4].

For the substation to feed a Venezuelan electrical railway system, the original design for the 87T-Scott was based on conventional 3-phase numerical relays for two-winding transformers and the use of ICTs. During the commissioning of the substation, that initial scheme was considered unsuitable because the matching between relay currents is not possible, and some alternative methods were proposed (without change of relays) in order to solve this problem.

The previous articles directly related to the 87T-Scott were presented in international conferences [3,4,7,9]. The recent journal articles about the differential protection of transformers (87T) have been mainly related to new techniques to discriminate between internal faults and other conditions (e.g., Refs. [10–19]). An exception is a group of two papers [20,21], where the conventional numerical 87T for 3-phase transformers is adapted to the case of special phase-shifting transformers (which are typically applied in some industrial converters that need non-standard phase-shifts).

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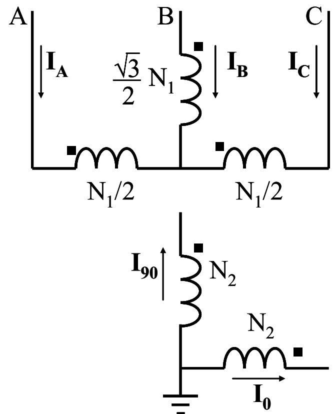

Fig. 1. Basic scheme for the Scott transformer.

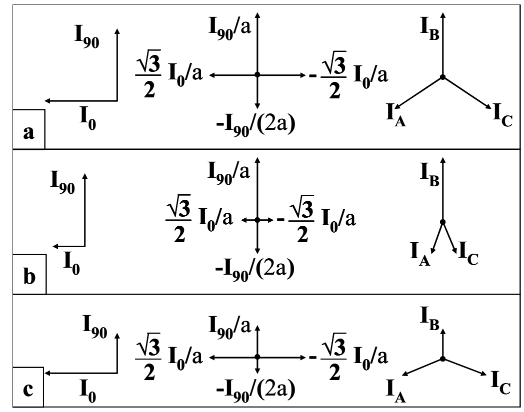

Fig. 2. Balanced (a) and unbalanced (b,c) operation of Scott transformer.

This article shows different proper methods for the 87T-Scott, based on a detailed description about the currents in Scott transformers. Some methods are based on conventional: (a) single-phase relays, (b) 3-phase relays for two-winding transformers, (c) 3-phase relays for multi-winding transformers. A clear explanation about all these methods was not available in the reviewed literature. On the other hand, two options for the design of specific relays for the 87T-Scott are proposed here. Thus, the main contribution of this article is to provide a systematic explanation about the available options for the proper application of the 87T-Scott, as well as to describe two proposed options for designing specific relays for the 87T-Scott.

Nowadays, the proposed options as specific relays for the 87T-Scott are not commercially available. Thus, the best available option for new projects probably is the use of 3-phase relays for multi-winding transformers, because their use avoids the need of ICTs (this option is simpler, and simplicity is a desired feature for the protective system). However, for existing installations, the need of using other options can be justified by different reasons (availability of relays, compatibility with existing devices, etc). Therefore, the content of this article can be very useful for different practical cases, related to the different possible methods for the proper application of the 87T-Scott.

2. Currents in Scott transformers

Fig. 1 is useful to explain the distribution of currents in Scott transformers. Here, secondary windings are named 0° winding and 90° winding (they are also named main winding and teaser winding, in the literature). N_2 and N_1 are numbers of turns. I_A, I_B and I_C are the currents in the 3-phase side. I_0 and I_{90} are the currents in the 2-phase side. Superposition method is useful for this explanation. If the current in the 90° winding is assumed to be null, then:

$$N_2\,I_0 = (N_1\,I_A - N_1\,I_C)/2 \tag{1}$$

$$I_C = -I_A \tag{2}$$

Therefore:

$$N_2\,I_0 = N_1\,I_A \tag{3}$$

$$I_A = -I_C = (N_2/N_1)I_0 \tag{4}$$

On the other hand, if the current in the 0° winding is assumed to be null, then:

$$N_2\,I_{90} = (\sqrt{3})(N_1\,I_B)/2 \tag{5}$$

$$I_B = 2(N_2/N_1)(I_{90}/\sqrt{3}) \tag{6}$$

In this condition, I_B returns by phases A and C in a balanced way (due to the equilibrium of magnetomotive forces):

$$I_A = I_C = -I_B/2 = -(N_2/N_1)(I_{90}/\sqrt{3}) \tag{7}$$

I_A, I_B and I_C are obtained as a function of I_0 and I_{90} by the sum of these partial results (superposition method). The following equations are shown as a function of the ratio (a) of the numbers of turns in the 90° winding, for the sake of simplicity.

$$a = (\sqrt{3}/2)N_1/N_2 = (\sqrt{3}/2)V_{HV}/V_{LV} \tag{8}$$

$$I_A = ((\sqrt{3})I_0 - I_{90})/(2a) \tag{9}$$

$$I_C = (-(\sqrt{3})I_0 - I_{90})/(2a) \tag{10}$$

$$I_B = I_{90}/a \tag{11}$$

V_{HV} is the rated phase–phase voltage at 3-phase side, and V_{LV} is the rated single-phase voltage at each secondary winding (2-phase side). Now, I_0 and I_{90} can be easily written as a function of I_A, I_B and I_C:

$$I_{90} = aI_B \tag{12}$$

$$I_0 = a(I_A - I_C)/\sqrt{3} \tag{13}$$

These relationships are equivalent to the ones shown in the literature [9,22]. In railway systems, I_0 and I_{90} feed different sectors. Fig. 2 shows examples of the results of currents in the 3-phase system, by assuming that I_0 and I_{90} are in quadrature (actually, the angle between I_0 and I_{90} depends mainly on the power factor of both loads).

3. 87T-Scott based on single-phase relays

Two single-phase relays can be used for the 87T-Scott [2,9], as shown in Fig. 3. If the current transformers of the 3-phase side have the same ratio (CTR_1), then the current transformers of the 2-phase side should have different ratios (r_1, r_2), because it is necessary to compensate the factor of $\sqrt{3}$. This problem had not been previously mentioned in the literature. Other option would be the use of a CTR_1 for phases A and C that is $\sqrt{3}$ times greater than the CTR for phase B. Actually, these differences in the required ratios for the current transformers can be compensated by interposing current transformers (ICTs). For the 87T with single-phase relays, ICTs are typically applied because the taps of ICTs allow improvements of the compensation between the currents to be compared (single-phase relays are not numerical). These ICTs can be external to the relays, or internal (taps in the relays).

Three single-phase relays can be also used for the 87T-Scott [2], as shown in Fig. 4. The main difference with the previous case is the