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Calculation of the lowest currents caused by turn-to-turn short-circuits in power transformers

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ABSTRACT

Among all internal faults in transformers the most difficult to detect are turn-to-turn short-circuits with few turns involved. In such cases the short-circuit currents flowing in the affected turns are high, but at the terminals they are very low, thus making operation of the differential relays doubtful. If large number of turns are short-circuited, the currents are not that low and are mainly determined by the reactance, which is a consequence of the leakage flux. However, when very few turns are affected, the influence of the winding resistance may become dominant, reducing the terminal currents to a small fraction of the rated current. Since those are critical cases from the point of view of protection operation, calculation of the resistance and fault currents in such cases is important. The paper presents a simple equivalent circuit applicable for small number of short-circuited turns, along with the method of calculation the equivalent resistance for the turn-to-turn short-circuits between the parallel conductors.

1. Introduction

Power transformers are very reliable devices. Their failure rate for old units may be at the level of 0.5% up to 0.95%, but for the ones manufactured recently decreases to some 0.15% [1–3]. However, consequences of the faults are very grave. They mostly cause disconnection of the unit what may be detrimental for security of the power system operation. The short-circuits at the terminals – single-phase or inter-phase – may affect the stability of the power system operation and to avoid the developing faults they ought to be disconnected within a very short time, sometimes less than 0.05 s. However, their detection and operation of protective relays – differential and/or distance, do not cause problems. It is otherwise with the internal short-circuits, which are very dangerous for the unit itself, since they cause serious damage to the transformer windings (and sometimes cores as well) and drastic increase of the internal pressure in the tank. If the unit is not disconnected within some 0.5 s – the tank may explode.

Post-fault examination of the transformer which was disconnected due to a winding fault may not clearly indicate what was the initiation of the short circuit. However, most of the specialists believe that the faults start with a turn-to-turn short-circuit, very often between the adjacent turns, involving very few of them. Therefore, in order to limit the range of damage it is more than advisable to trip the transformer before the short-circuit develops and involves more turns. However, detectability of such short-circuits is difficult, since although the current in the faulted turns is very high, the currents at the terminals are low, often at the level of a small fraction of the rated transformer current [4]. Thus, the differential protective relays ought to be very sensitive in order to detect such faults and release the tripping command when needed. It becomes quite important to calculate the level of smallest expected differential currents for which the relay should operate.

In the literature one can find some results of investigations related to transformer turn-to-turn faults. The model of power transformer, which allows to simulate turn-to-turn faults, is presented in [5]. The extended/modified method of simulating turn-to-turn faults is described in [6]. The model presented in [7] is based on incremental values of currents after fault inception and analysis of symmetrical components observed during the fault.

After analysis of the cited literature it has been concluded that the presented methods for simulating turn-to-turn faults in power transformers are quite complex. Moreover, they do not take into account well enough the importance of the effect of winding resistances. It is true, that for the large number of faulted turns, the short-circuit reactance dominates. However, if very few turns are short-circuited – particularly if it is a short-circuit between the

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parallel conductors – it is otherwise, i.e. the winding resistances become dominant. Thus, since the detection of the short-circuits involving very few turns pose the greatest challenge for the protective relaying, the analysis of short-circuit resistances becomes important.

The ultimate aim of the transformer protection is to cause its tripping even in cases of a single-turn short-circuit also if it occurred between the parallel conductors. In such cases the short-circuit current level is determined by the fault resistances. In this paper the calculation of resistances is presented for the turn-to-turn short-circuits, which involve very few turns.

2. Fault representation by a fictitious winding

One of the problems of turn-to-turn fault analysis is caused by the fact that there is a number of possible locations of a short-circuit, and because of that a single general equivalent circuit does not exist. To mitigate the problem an idea of the fictitious winding is here introduced, which is illustrated in Fig. 1 for a single-phase circuit. The circuit which represents the short-circuit itself (Fig. 1a) is replaced by the circuit utilizing the fictitious winding (Fig. 2b). As a result the current I_1 is smaller than the current I:

$$I_1 = I\left(\frac{w_1 - w_z}{w_1}\right)^2 \quad (1)$$

while the equivalent circuit impedance is equal:

$$Z_1 = Z\left(\frac{w_1}{w_1 - w_z}\right)^2 \quad (2)$$

where: w_1 and w_z are numbers of turns of the winding and those being short-circuited, respectively.

Eqs. (1) and (2) show the scale of difference, which for a small number of faulted turns is acceptable. It is certainly so for 1 or even 2 short-circuited turns. As a compensation, usage of such an equivalent approach with a fictitious winding makes possible to develop the standard equivalent circuit, which may represent all the locations of turn-to-turn faults with small number of turns involved, whether the fault is located at star side or at delta side.

In the following sections of this paper the equivalent circuit and fault impedance due to various kinds of turn-to-turn faults as well as the resulting fault currents are calculated, which is followed by a discussion of such faults detectability by standard transformer differential protective devices and final conclusions.

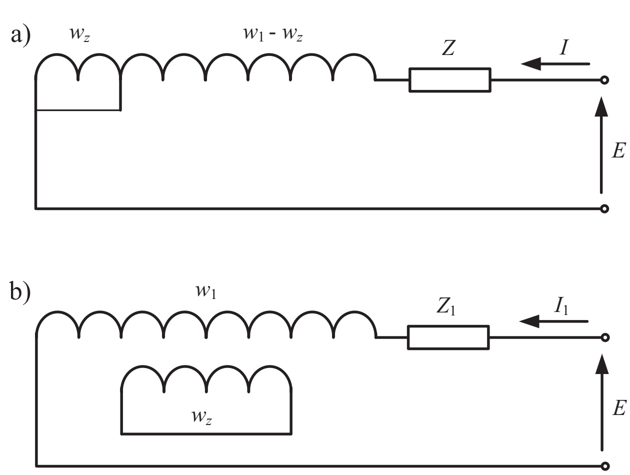

Fig. 1. Representation of the turn-to-turn short-circuit by the fictitious winding: (a) general circuit, (b) equivalent circuit with the fictitious winding.

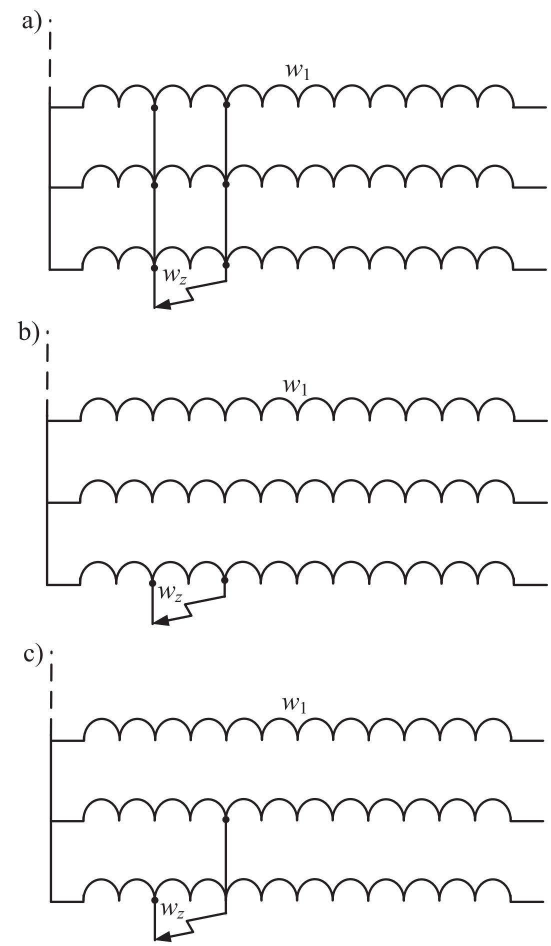

Fig. 2. Kinds of turn-to-turn short-circuits in the same phase: (a) turn-to-turn short-circuit of all parallel conductors, (b) turn-to-turn short-circuit in one conductor, (c) turn-to-turn short-circuit between the parallel conductors.

3. Equivalent circuit for turn-to-turn faults

Modern power transformers have windings composed of parallel conductors, to reduce the eddy current losses. Therefore there are three possible types of the turn-to-turn short-circuits (Fig. 2).

The first one is a short-circuit which involves all the parallel conductors (Fig. 2a). The second case is a turn-to-turn short-circuit in only one of the parallel conductors (Fig. 2b). The third (and most difficult to detect) - is a turn-to-turn short-circuit between the parallel conductors (Fig. 2c). In the latter case the short-circuit currents depend on the number of affected turns and on the their location in the coil.

The easiest and the most universal way to calculate the currents during the turn-to-turn short-circuits is not only to utilize the fictitious winding (applicable only for small number of faulted turns, up to some 5% of the winding), but also to use an equivalent Thevenin's circuit. Such an equivalent circuit for the turn-to-turn faults is presented in Fig. 3. One may note that all windings, including the fictitious one which represents the faulted section, have the same number of turns, equal to the star side number of turns, what is assumed for the ease of further considerations. The value w_1 used in the circuit is the number of turns in the star side transformer windings.

The circuit representing the faulted phase makes a three winding single-phase transformer, with the impedances between the three windings: Z_{Ad},-impedance between the star side and delta side windings, Z_{ZA}-impedance between the fictitious winding and