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Arrangements of transformer winding with respect to impulse stress

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ABSTRACT

Danger and stress posed to transformer winding through overvoltage still represent a hotly debated and hitherto unresolved technical issue the designers and operators of high-performance equipment have been grappling with. The actual impossibility of accepting all the real parameters of a transformer in its substitute model leaves considerable space for its constant improvement and modifications. Accepting the surrounding phenomena and properties of the transformers gives rise to complex situations and difficulties in the process of solving the model. Models tackling some of the issues pertaining to circuit models or electromagnetic field models have been developed on a long-term basis. Another issue in hand is the very complexity of the process of solving a model. This study introduces a model accepting solely the capacitance influences of transformer components, using the methods derived from the theory of Lax–Wendroff's and Lax–Friedrich's approximation of differential equations of the hyperbolic type for the solution of the respective equations. It does not represent solutions for all the parameters of a transformer, but provides an overview of the size of the initial impulse stress of transformer winding, doing so with adequate accuracy.

1. Introduction

Dynamic interactions in transformer winding follow either the distribution of the electric field and overvoltage phenomena in the winding, at the entry of the surge, or the distribution of the power field and the mechanical behaviour of transformer winding during various types of short-circuit. The first type is designated as fast, the other one as slow. The study deals with the first type of interactions. Examination of overvoltage relations in the transformer winding has been the subject of innumerable studies. Modern findings in the field of mathematical analysis and numerical mathematics have facilitated specification of the physical model under scrutiny.

The problems concerning a substitution transformer diagram cover its discrete model analogous, in circuit models, to electric wiring where longitudinal capacitance, eventually resistivity of the conductor used (that is, however, frequently ignored) operates between the turns. This fundamental model was published in 1915 by K. W. Wagner and all the subsequent theories proceed therefrom [1].

The first works stemmed from the model of a single-layer coil without iron, which made it possible to perform certain predictions analytically, further studies stemmed from the gradually more complex physical models, with numerical methods being incorporated into their behaviour step by step. In ref. [2] authors explained that the role played by the iron core in the response of an impulse-stressed winding is negligible. However, even modern studies proceed from a relatively heavily simplified configuration of the physical model.

In methodological terms, two approaches may be distinguished in the physical–mathematical description of the overvoltage phenomena. The first consists in the construction of the so called field model, i.e. in the formulation of the electromagnetic field in the sphere of winding as a marginal assignment for the partial differential equations of the type of wave equations in which the vector magnetic potential, less often the vector electric potential, figures most frequently as the unknown quantity. In numerical terms, the solution of this 3D, eventually 2D, assignment can be managed quite satisfactorily by applying a suitable commercial program (evidently based on FEM – Finite Element Method), but it is not easy to determine the appropriate boundary conditions. The other concept is based on the layout of the so called circuit model, i.e. formulation of a system of ordinary differential equations for a locally discretized circuit comprising elements R, L, C for the numerical solution of which one can use some standard numerical method. This type of solution poses the problem of precisely

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determining the parameter R, L, C, and also the process of setting up a 3D circuit model runs up against certain difficulties. However, in both types the numerical solution itself is accompanied by the necessity of coping with the reliability of the obtained results (especially stability, convergence etc.).

2. Justification of the choice of the problems under scrutiny and current status of solution

Considerable attention has been devoted to impulse stress of electric machines on a long-term basis. More precise, more computationally complex as well as less challenging and also less accurate mathematical models have been developed, based on the available mathematical theories (since the early 20th century). Owing to what is a frequently inaccurate and less credible way of stipulating the input parameters of the winding in the model there have emerged diverse simplified notions of voltage distribution in a transformer. Quite frequently, this issue is resolved on the basis of single-layer coil. The resulting solutions are then extended to cover the entire winding as well as multiple-winding transformers. In terms of voltage distribution, transformer's multiple-layer coil – without adequately thorough knowledge of its parameters – constitutes such a complex task that very small congruence may be anticipated if such parameters are neglected. Former Czechoslovakia (from the 1950s until 1989) figured among the leading countries generating valuable mathematical models of single- and multiple-layer coils – see works by A. Veverka, B. Heller, Š. Matěna. Since these studies could not be published abroad before 1989 they now represent a valuable biography for the topic that has not yet been reflected abroad. The most important specialist studies on the subject are as follows [3–5]: (in Czech). In addition, a large number of contributions was published in the journal Elektrotechnický obzor (active in 1910–1989) by A. Veverka and B. Heller. There are details that were not possible to publish in ref. [3].

However, both academic, business and manufacturing centres have been returning to the subject of impulse stress in the past decade. For their part, the major manufacturers of transformers and reactance coils strive to have the possibility of predicting computations through which they could declare – prior to designing a transformer – its resistance to impulse stress (most frequently an impulse of 1.2/50 μs). Up to now resistance has been verified solely by recording oscilloscopic response from the taps of the transformer winding when leading the impulse in to its input clamp. This gives rise to temporal–spatial behaviour of the voltage wave in which the spot of maximum coil stress is monitored. In view of the limitations of the possibility of calculating all the parameters of the winding, of reckoning precisely with own and mutual inductance in the model and of respecting the impact of the iron core, we have decided to verify the validity of the numerical solution solely while respecting the capacitance reserve model. With this particular model we want to single out the necessity of devoting great care when making conclusions from incomplete or very little valid circuits which represent only limited properties transferred to the entire winding, eventually to multiple-winding systems – three-phase transformer, while respecting the impact of all the interlinks involved.

As for the entry of voltage impulse to the transformer winding, we can state that voltage distribution along the winding is dependent solely on the winding's capacitance conditions since inductance in a time interval close to zero may be neglected. The design parameters of the coils of the transformer itself have a highly decisive influence on the initial voltage distribution. Assuming that we know initial and terminal voltage distribution on the transformer winding, it is quite easy to determine the free oscillations envelope, which represents a theoretical maximum voltage of the insulation in any point of the winding. Much smaller attention has been given to the calculations of the parameters of the longitudinal and earth capacitance themselves, and own and mutual inductance of the coils of transformers than, for instance, to the theories of calculation themselves, and to the proposed numerical solution of wave phenomena in the winding. Such a model yields more objective results than endeavours to capture simultaneously all the influences within a transformer. Among the key studies for the computation of C, K, L and M we can mention, for instance, the following refs. [6–12].

It is possible to trace in the literature two approaches to the studied issues of impulse voltage distribution in a transformer. One of them is the design of a model with concentric parameters; the other consists in observing the significance of distributed parameters. Authors in ref. [13] tend to distinguish models into Fast transient overvoltages (FTO) and Very fast transient overvoltage (VFTO). As for the FTO models, in which a frequency range from 10 kHz $\le f \le$ 1 MHz is assumed, many models have already been published, based on the theory of quadrupole [14,15] which are cascaded and calculated by means of the respective computational instruments. Subsequently, most [16,17] of other models are based on the solution of the telegraph equation, solved either analytically or numerically. For the VFTO models, hence models with a frequency over 1 MHz, it is no longer possible to neglect the wavelength of the input high-frequency impulse, and the circuits are resolved by means of distributed parameters – the most frequently used methods are then the hybrid calculation methods where parts of the winding are calculated as concentric – for instance for lower frequencies where the influence of conductivity prevails, and as distributed ones for moments when capacity is of explicit importance within a circuit. The models with concentric parameters reduce the calculation solely to predetermined points in the winding; it is impossible to monitor voltage behaviour in any random spot of the winding.

The types of the used windings themselves, too, have considerable impact on the design of the relevant models – the most frequently used is the simplified method via simple single-layer coils, but the transformer winding tends to be much more complex; multiple-layer disk and cylindrical windings are often used, or special adjustments, for instance interlaced windings, are utilized. Relevant studies dealing with these subjects may be found in: refs. [18,19]. The last approach to modelling resistant transformers is the application of various limiting elements, overvoltage arresters or the use of an older method involving voltage-dependent varnishes [20,21].

Transition from the transformer's real winding (single-layer) to its discrete model is described in Fig. 1.The classical theory of transformer model for the effects of overvoltage has been discussed in great detail, for instance, in refs. [3,4,22]. For the purpose of our study, we proceed from a simplified solution of the equation describing the overall diagram given in Fig. 2. This set of equations originated as a result of solving the Kirchhoff laws in the described Fig. 2.

$$\frac{\partial^2 u}{\partial x^2} + LK\frac{\partial^4 u}{\partial x^2 \partial t^2} - LC\frac{\partial^2 u}{\partial t^2} = 0 \tag{1}$$

$$\frac{\partial i}{\partial x} = -C\frac{\partial u}{\partial t} \tag{2}$$

$$i = -K\frac{\partial^2 u}{\partial x \partial t} \tag{3}$$

In case of initial voltage distribution at voltage impulse, a single-layer transformer winding may be approximated by means of