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Simplified modelling of an air-core reactor for lightning impulse transient studies

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ABSTRACT

This paper presents a methodology that can be used to model the electromagnetic behaviour of large disk type air-core reactors when excited by fast transient voltages having a frequency content ranging from 10 kHz to 500 kHz. The subject of transient voltages in complex winding structures has been extensively studied for more than a century resulting in increasingly complex model synthesis and parameter acquisition methods to increase accuracy. The novelty in this work however, lies in the study of a particular composition of simple well-known methodologies and an analysis of its suitability this context. A lumped parameter white-box model is generated using the design details of the reactor. The model parameters are calculated analytically and frequency dependency is mostly omitted for the sake of simplification in the methodology. The parameters are verified by measurements and finite element method simulations. The modelling methodology is applied to an actual case study and the simulation results are compared to the measured results. The model response varies in its performance. The results are good when evaluating the voltages to ground in the frequency domain. However with evaluation in the time domain it becomes clear than the methodology still needs improvement. Restrictions and limitations of the simplified model are discussed.

1. Introduction

The electromagnetic modelling of electrical equipment for the evaluation of fast transient voltage excitation is not a novel field of study. The non-linear voltage distribution in machine windings when subjected to steep fronted wave excitations has been observed more than a century ago [1,2]. The perils associated with this resonance behaviours of transformer windings are also well documented [3–5].

It is therefore important for design engineers of equipment manufacturers as well as utilities to be able to predict the response of the system equipment when subjected to fast-fronted excitation waves such as those typically encountered in lightning surges [2]. These surges may have frequency components ranging from 10 kHz to 500 kHz.

Steady state models commonly used in load flow studies are not appropriate for fast transient voltage studies. Since they lack the capacitive parameters that play a significant role at higher frequency excitations [6]. Thus the development of accurate wide band models are required to enable engineers to coordinate the insulation of the equipment and network to withstand high voltages caused by resonance [7].

Modelling methods where the exact geometrical design information are known are commonly referred to as white-box models and have been a covered in numerous studies [8–10]. The novelty in many of these studies lies in the unique permutation used with reference to the choice of model type and in the way in which the parameter values are determined.

This paper presents a particular permutation with reference to the choice of model type and parameter calculation methods. It is not the intent of this paper to claim novelty in any parameter calculation method or model synthesis. The novelty lies rather in the study of the viability of using a *particular* combination of simple well-known parameter calculation methods and its application in a specific well-known model composition.

A wide band electromagnetic model of an air-core reactor of disk winding type is constructed. The model is used to determine the voltage distribution throughout the winding when excited with a standard lightning impulse wave. The frequency dependence of the model parameters is crudely introduced by considering the effects at a fixed frequency of 255 kHz. Naturally, inaccuracies are anticipated as the frequency increases. However, in the context of its application, adequate accuracy is obtained that is suitable for certain design aspects.

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2. Reactor specification

The modelling methodology presented in this paper was applied to an air-core reactor. The reactor winding was wound as a disk winding, similar to that portrayed in Fig. 1. Multiple turns are wound radially on top of a former cylinder with circumferential spaced ribs to form a disk [11,12]. A transition from one disk to another is achieved by making a cross-over as seen in Fig. 2 [13]. The stray capacitances in disk windings are much more prevalent than those in normal layer windings [14] making it a suitable winding type to demonstrate the contribution of the stray capacitances in and around the winding.

Typically air-core reactors are placed in enclosures – and therefore the capacitance to earth is clearly an important consideration. In the experimental setup however, enclosing the winding with a ground plane creates difficulty in accessing the various places to measure. Thus to introduce the concept of a ground plane, an electrostatic shield was created by lining the former cylinder with aluminium foil. However, the presented methodology can me readily applied by modelling a ground plane on the outside which will be discussed in Section 4.2.

The dimensions and winding information of the actual reactor design are given in Table 1. The information pertaining to the conductor used for winding the reactor is given in Table 2 [13].

3. Model topology

3.1. Equivalent circuit model

The study discussed in this paper made use of the equivalent electrical circuit model method which entails the distinct representation of the inductance, resistance and stray capacitances in and around the machine windings. This modelling approach can be subdivided into two types namely a lumped parameter model (LPM) or a distributed parameter model (DPM) [2,3]. The LPM was used in this study due to its simplicity considering the mathematical formulation of the voltage behaviour.

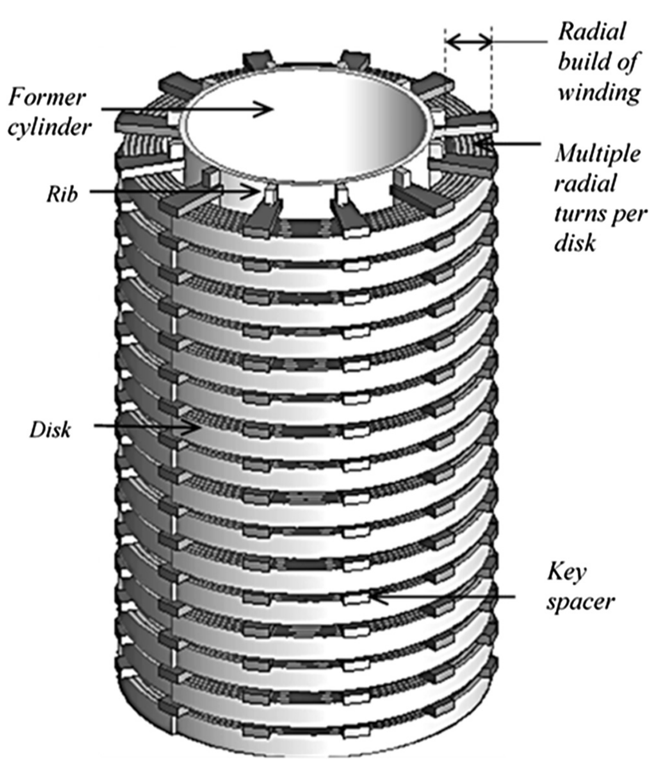

Fig. 1. Disk winding with spacers around circumference [13].

Lumped parameter models traditionally represent a turn or a group of turns in the winding as a discrete inductive branch as presented in Fig. 3. Each inductive branch has got a self-inductance L_{ii} and a mutual inductive coupling L_{ij} to all the other branches. Lumped capacitances C_{ij} represent the series capacitance of each turn and C_{ig} is the nodal representation of the capacitive coupling of a branch to a nearby ground plane. Dielectric conductance G was also be introduced in parallel with each lumped capacitance.

3.2. Model discretization

The application of a LPM requires the discretization of the actual winding into sections representing inductive branches. Careful consideration must be made in the discretization of the physical system. The frequency range over which the model should be valid, plays a significant role in the required length per section [15]. If the physical length l of a section exceeds the wave length λ of the highest required frequency, multiple reflections can occur which would not be noticed at the terminals of the section [16]. The physical length of the conductor represented by a lumped circuit should be much shorter than the shortest required wave length expected. Good results have been obtained when [17]:

$$l = 0.12\lambda \tag{1}$$

The highest frequency that this study is concerned with is 500 kHz. The wave length λ of the highest frequency f is given by the expression [18]:

$$\lambda = v/f \tag{2}$$

where v is the velocity of the traveling wave.

Assuming a vacuum medium where $v = 3 \cdot 10^8$ m/s, the wave length would be 600 m. Referring to Eq. (1), this means that the physical length of a discrete winding element should ideally not be longer than 72 m. Power reactors have windings where the length of a conductor in a disk winding can be up to 70 m [13]. Thus a suitable resolution would be to divide the winding into sections where each section represents a single turn of a conductor winding as shown in Fig. 4 [13]. The reactor in this study has got 2 cables wound parallel over 82 disks where each disk has 3 turns. Thus, cable 1 starts at node 1 and ends at node 247. Cable 2 starts at the bottom disk with node 248 and ends at node 494. Cable 1 and 2 is connected at the top and bottom.

4. Parameter calculation

4.1. Inductance

To calculate the self- and mutual-inductances of each section, a conductor is approximated by a current-filament at its centre as presented in Fig. 5. Each current carrying section is represented as a circuit branch with reference to Fig. 3. A multi-filament approach could very well be implemented, but the purpose of the methodology is to keep the modelling approach as simple as possible. Admittedly, accuracy is sacrificed due to simplicity. However, despite this crude simplification the accuracy was considered to be sufficient in similar studies [19]. It was also found to be reasonably accurate in the context of this application.

The self- and mutual-inductances between the sections are captured in a branch inductance matrix $[\boldsymbol{L_b}]$ where the diagonal entries represents the self-inductance of the inductive branches and off-diagonal entries represent the mutual-inductance between branches. For a model having a number of N nodes and $N-1$ branches, the inductance matrix is expressed as: