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Modeling of wind turbine transformers for the analysis of resonant overvoltages

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ABSTRACT

Switching transients and earth fault in a wind farm collection grid are two transient phenomena which can lead to resonant overvoltages at the LV terminal of the wind turbine transformers as well as inside HV and LV windings. The aim of this paper is to analyze the potential of the resonant overvoltage for various winding designs; disc, layer and pancake. In this way, the least vulnerable winding design can be recommended. For this aim, a 500 kVA transformer test object with the three aforementioned winding types has been designed and manufactured. Similar geometrical characteristics are used for all the three windings. By measuring the frequency response, the resonant frequencies can be found and the amplitude of the transferred voltage at these frequencies can be compared. The windings are also modeled in this paper in detail based on analytical functions. This RLC ladder model is verified by the measurements.

The measurements and modeling results show that all winding designs have a resonant frequency around 800 kHz for the transferred voltage to LV terminal. Disc winding shows the lowest amplitude of the transferred overvoltages (6 p.u.). The layer winding, also has a resonance at 1.6 MHz with an even higher transferred overvoltage (80 p.u.). The frequency response of the pancake winding has characteristics of both disc and layer windings. In spite of having the lowest transferred overvoltage peak, the disc winding has many additional resonant frequencies in the range of 100 kHz–1 MHz. This could excite resonances in other parts of the winding. Consequently, pancake winding designs might be the most promising to minimize resonance situations.

1. Introduction

Medium voltage transformers with ratings in the range of 300 kVA–8 MVA have been installed in both onshore and offshore wind farms. The energization of each wind turbine may result in cable-transformer resonant transients. This phenomenon has been studied in traditional medium voltage transmission and distribution networks [1–6]. The similar resonance condition can also happen in wind farms [7,8]. The length of the cables in wind turbines is in the range of 100–200 m. The quarter wave frequency of such cables can be in the vicinity of resonant frequencies of wind turbine transformers. Therefore, the energization may lead to resonant overvoltages on LV terminal of transformers and inside HV windings [9]. These overvoltages have higher amplitude and rate of rise (du/dt) compared to other overvoltages. They can lead to insulation failures in transformers. In [10], the voltage distribution due to energization of a 10 kV–200 kVA reactor with disc winding is analyzed. It was observed that energizations with short rise time (<100 ns) lead to the excitation of internal resonances. Resonant overvoltages can also occur due to earth fault in cables [11]. In this case, they can be harmful for the power converters as well. Thus, the investigation of them is necessary and appropriate protection devices such as resistive–capacitive (RC) filters are required [12].

The selection of less vulnerable winding design is a measure to prevent resonant overvoltages during wind turbine energizations. This means that knowing the cable lengths and their quarter wave frequency, a winding type can be chosen that does not have a resonant frequency in that vicinity. The aim of this paper is to compare the frequency responses of three winding types; disc, layer and pancake. A 500 kVA transformer with the three aforementioned winding types has been designed and manufactured. The transferred voltages to LV and HV input impedance of windings are measured based on frequency response analysis (FRA) technique [13–16].

An analytical model is also developed and introduced in this paper. The model assists us to draw general conclusions about

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the various characteristics of the three winding designs and their potential for resonant overvoltages. In literature, two main high frequency transformer modeling techniques are introduced as multi-transmission line (MTL) model and ladder RLC [17]. In [18], results from MTL and RLC ladder models of windings are compared with frequency domain measurements. It is concluded that the RLC model can give accurate results for fast transients (up to 1 MHz). However, for very fast transients (above 1 MHz) MTL model provides better results. In this paper, RLC ladder model is developed, since the maximum range of the quarter wave frequency of wind turbine cables are about 1 MHz.

In Section 2, the transformer test object and the setup for frequency response analysis are outlined. Section 3 describes the transformer model. In Section 4, the results of the analytical model for the different windings are compared. The characteristics of the three windings are also discussed. Section 5 discusses the challenges of transformer modeling.

2. Test setup

Fig. 1 shows the layout of the special 11/0.24 kV 500 kVA transformer which is designed and produced to enable comparison of the frequency response of the three different winding designs. The core and the windings are fully paper insulated and out of tank during the measurements. The LV and HV neutrals are grounded together and connected to the core with 2 cm wide braided aluminum wire.

As shown in Fig. 1, the transformer consists of a layer winding on the left limb, a pancake winding on the middle and a disc winding on the right limb. To compare the frequency response of the windings, design parameters are kept as identical as possible:

- The number of turns in HV and LV windings and rated voltage ratio are the same for the winding designs.
- The winding frame, i.e. axial winding height and radial width, is almost the same for the windings.
- The layer winding has aluminum wire and the others have copper wires. The conductors' cross-section is such that the DC resistance of the windings becomes similar.
- LV windings are all aluminum foil with the same geometrical designs and insulation materials.

In this way, the three windings have equal impedances at 50 Hz and similar steady state condition. The frequency response of the transferred voltages to LV terminals is measured from 1 kHz to 10 MHz with Agilent network analyzer E5061B and Tektronix P2220 probes. The voltage probes are used with *x10* attenuation which is appropriate for voltage measurement up to 200 MHz. Attenuation *X1* is appropriate up to 6 MHz and it may seem adequately accurate for our measurements. But, the input resistance/capacitance of attenuation *X1* is 1 MΩ/95 pF which may have loading effect on high frequency measurements compared to *X10* attenuation (10 MΩ/16 pF). Thus, *X10* attenuation is selected which has acceptable error (<5%). For measuring the input impedance of HV and LV windings, the current probe FLUKE PM6306 is used, which has low and acceptable error (<10%) in frequency range 1 kHz–1 MHz. Therefore, the results for input impedance will be shown in this frequency range in the next section.

3. Transformer model

The three winding types; disc, pancake and layer windings and the LV foil winding are represented by RLC ladder model in this paper in which windings are divided into units as shown in Fig. 2. Each unit has resistance and self inductance as well as series capacitance and insulation resistances. There are capacitances and conductances between units in adjacent layers. Mutual impedances between units of HV, LV and LV–HV are not shown in Fig. 2, but are considered. The capacitances between last layer LV and first layer in HV is not shown in Fig. 2. They are considered, though. The accuracy of the model mainly depends on the level of the discretization chosen for the windings. High discretization increases the calculation time. The procedure for the calculation of RLC parameters is explained here for layer winding. It is generally similar for the other windings with only topological adjustments. After that, input impedances of HV and LV windings and the transferred voltages to LV winding are calculated.

Let us consider nu number of units in each layer of HV layer winding. nH is the number of HV layers and therefore $nu \times nH$ is the total number of units. Besides, the LV foil winding has nL layers, and we take each layer as one unit. The total order of R, L, C and G matrices becomes $m = nL + nu \times nH$.

Performing the Kirchhoff's Voltage Law (KVL) and Kirchhoff's Current Law (KCL) for all units results in (1) and (2), respectively. In Appendix A.1, KCL and KVL for an arbitrary unit, i, is performed.

$$[A]_{m\times m}[V]_{m\times 1} = ([R]_{m\times m} + j2\pi f[L]_{m\times m})[I_b]_{m\times 1} \tag{1}$$

$$[I]_{m\times 1}[A]^t_{m\times m}[I_b]_{m\times 1} = ([G]_{m\times m} + j2\pi f[C]_{m\times m})[V]_{m\times 1} \tag{2}$$

Matrices V, I and I_b representing nodal voltages, injected nodal currents, the currents of inductive branches, respectively. A is a connectivity matrix describing the topology and linking branches and nodal quantities. The diagonal elements in A matrix are equal to 1 and sub-diagonal elements are equal to −1 and the rest is zero. Exceptionally, the first row and the row number $nL + 1$, which are for first units in LV and HV winding respectively, have only the diagonal element, since the other nodes of these units are grounded.

The nodal admittance matrix Y can be calculated by reforming (1) to obtain I_b based on V and inserting this in (2). This gives (3).

$$[I] = [Y][V], \qquad [Y] = [G] + j2\pi f[C] + [A]^t([R] + j2\pi f[L])^{-1}[A] \tag{3}$$

Since all of the R, L, C and G matrices are symmetrical, the admittance matrix also becomes symmetrical. To obtain the equation for the transferred voltage to LV, impedance matrix, Z, should be calculated from (3) by inverting Y. Since only the last element of I vector is none-zero due to the connection of last unit to the HV terminal, the last column of Z multiplies with the terminal current, I_m, and gives the nodal voltage in (4). Therefore, the transferred voltage to LV terminal is according to (5).

$$[Z(:, m)]I_m = [V] \tag{4}$$

$$\frac{V_{\mathrm{LV}}}{V_{\mathrm{HV}}} = \frac{Z(nL, m)}{z(m, m)} \tag{5}$$

In the following subsections, the process for the calculation of the R, L, C and G matrices are explained. It should be mentioned that these four matrices, Z matrix and equation (5) are coded and calculated in MATLAB. Inputs of this code are: (1) core and winding physical dimensions, (2) material properties of winding conductors, insulation and core. The main output of the code is input impedances of LV and HV windings as well as transferred voltage to LV.

3.1. Calculation of R and L matrices

The analytical method [19,20] for computing the self and mutual impedance is based on Eqs. (A-3)–(A-6) in Appendix A.2. In addition, the internal conductor resistance is added to the diagonal elements of R matrix, since Wilcox formulas only consider the core effect on the resistance matrix. In this paper, an analytical equation for the consideration of skin and proximity effects is applied for the calculation of the internal conductor resistances [21] in both LV