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Cite as: AIP Advances **10**, 015024 (2020); https://doi.org/10.1063/1.5130034
Submitted: 03 October 2019 . Accepted: 23 December 2019 . Published Online: 10 January 2020

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Accepted: 23 December 2019 • Published Online: 10 January 2020

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Note: This paper was presented at the 64th Annual Conference on Magnetism and Magnetic Materials.
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ABSTRACT

The potential distribution of windings under impulse voltage is very important for the design of transformer inter-turn insulation especially for large capacity transformers such as ultra-high voltage direct current (UHVDC) converter transformer. Quite a lot of equivalent circuit models for transformer winding have been proposed for the potential distribution calculation assuming that the influence of magnetic core is negligible at frequencies higher than 10 kHz. However, lightning impulse or VFTO waveforms usually contain abundant frequency components higher than 10 kHz. At above situations the magnetic core plays an important role during the transient procedure. To obtain a more comprehensive model and also to provide a more accurate potential distribution of transformer winding, in this paper, a wide frequency magnetic properties of silicon steel sheet were measured and the relationship between relative permeability of lamination stack and frequency is studied and implemented in the calculation of frequency-dependent parameters such as resistance, self- and mutual-inductances. Then the equivalent circuit model of UHVDC converter transformer is established considering the properties of core lamination stack. Coding the program in MATLAB to solve the matrix equation and the potential distribution properties are extracted from the calculation results under lightning situation. The inter-turn potential distribution is also analyzed and the results may provide more accurate information for transformer inter-turn insulation design.

I. INTRODUCTION

The rapid development of ultra-high voltage power grid, the popularity of gas insulated substations, the large-scale wind farm grid connection and the realization of AC/DC interconnection network, justifies the continuing trend toward higher transmission voltages and lager capacity of power transformers with increased complexity. In addition to the low-frequency operating voltage, the power transformer will also suffer from high frequency impulse overvoltage.

The potential distribution of windings under impulse voltage is very important for the design of transformer inter-turn insulation especially for large capacity transformers such as UHVDC converter transformer. People were eager to determine the overvoltage of transformer winding in operation at the design stage, and to calculate the distribution of impulse voltage in transformer, so as to arrange insulation reasonably and select the best coil structure to ensure the safe operation of transformer.

There have been some attempts to study the potential distribution on transformer winding by means of equivalent circuits since 1934, and experiments on scale models of convenient size were widespread in the fields of civil and mechanical engineering. Then some geometrical models of transformer has been made to determine the transient voltages in transformers. Then the appearance of electromagnetic model makes up for the shortcomings of the geometrical model and the equivalent circuit model.[1]

The transient voltages on the winding of the electromagnetic model of a certain type of transformer were measured, but the measurement results were not applicable to other types of transformer, and the researchers had to make the electromagnetic model of every type of transformers. With the continuous improvement of computer performance and the vigorous development of simulation software, the accuracy of modelling and calculation is constantly improved. For simple winding structures such as continuous winding and helical winding, the calculation result using multi-conductor transmission line (MTL) model[2,3] is more accurate and efficient. For complex winding structures such as inserted capacitance continuous winding and interleaved winding, the capacitances between regular turns and screen tapes have great influence on electromagnetic wave transmission and should be considered. Therefore researchers prefer to use the equivalent circuit model which can represent all the capacitances between any two conductors instead of MTL model which takes the coil section pair as a unit to solve the problem. Since the parameters are calculated directly from the design parameters of the transformer winding, for equivalent circuit models, the unit is able to be subdivided further to analyse higher frequency phenomena.

Quite a lot of equivalent circuit models[4–7] for analysis of the voltage oscillation caused by various excitations such as lightning impulse overvoltage and very fast transient overvoltage (VFTO) have been proposed. However the effects of the magnetic core have been simplified or ignored when calculating the parameters of resistances and inductances. In practice, even up to 1 MHz, the iron core have significant influence on the frequency transients, and it was demonstrated by measurement of transformer impedance frequency characteristic for a short-circuited transformer and a transformer under no load.[8,9]

To obtain a more comprehensive model and also to provide a more accurate potential distribution of transformer winding, the present paper deals with the problem of evaluation of the effect of core lamination stack on transient potential distribution on transformer winding. Therefore an UHVDC converter transformer was taken as the object of study and the broadband magnetic properties of silicon steel sheet were measured and applied to calculate the parameters of the equivalent circuit. In this paper, a comprehensive equivalent circuit of the transformer winding and the magnetic core was established, then a solving program was coded in MATLAB and the node voltage values are calculated. As a study case, the initial potential distribution and inter-turn potential gradient distribution under lightning situation are extracted from the calculation results. The research results indicate the effects of the magnetic core on the transient oscillation and provide a more accuracy potential distribution prediction for transformer inter-turn insulation design.

II. MEASUREMENT OF BROADBAND MAGNETIC PROPERTIES OF SILICON STEEL SHEET

Grain-oriented silicon steel sheet has been widely used in the manufacture of iron core of large power transformer, due to its excellent magnetization properties with high magnetic permeability and low losses. However, its linear magnetization characteristics supplied by the manufacturer are only applicable to the case of power frequency (50 Hz or 60 Hz). For broadband modelling of the transformer considering the effects of iron core, the broadband magnetic properties of the silicon steel sheet should be measured and modeled.

The measurement system consists of an Epstein frame and an AMH-1M permeameter.[10] A software feedback control is designed to drive the arbitrary function generator to provide the appropriate voltage to generate a satisfied sinusoidal V_2 (i.e. B(t)) waveform.

Dynamic properties of the grain-oriented silicon steel sheet (sample of B27RK100 which is usually used for the UHVDC converter transformer core manufacture) at different frequencies from DC to 1M Hz were measured, including hysteresis loops and normal magnetization curves which was defined as the loci of the crossover points of the up-going and down-going parts of the minor loops.[11] The normal magnetization curves of samples at different frequencies (f) are show in Fig. 1, and the relative permeability (μ) derived from the curves is shown in Fig. 2(a). Because of the skin effect, the permeability decreases sharply with an increasing frequency.[12] After fitting, there is a linear relationship between $\lg(f)$ and $\lg(\mu)$ below 1 kHz, but the error is unacceptable beyond 1 kHz. After processing the data with natural logarithm base and exponential fitting the relative permeability, the relationship between $\ln(\mu)$ and $\ln(f)$ is shown in Fig. 2(b). It is obvious that the fitting error of the exponential fit is significantly smaller than the linear fit. However this non-linear relationship is hard to implement in the software to calculate the parameters of the equivalent circuit, but it can be used for theoretical analysis in future research.

The relationship between relative permeability and frequency can be described as

$$\lg(\mu) = 5.495 - 0.81\lg(f) \quad (1)$$

Eq. (1) will be implemented in the material properties of the transformer model in the finite element calculation software to calculate the inductances and resistances of the equivalent circuit.

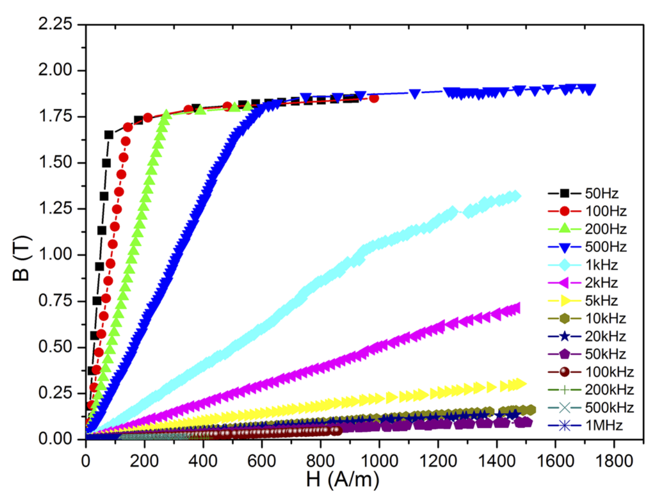

FIG. 1. Normal magnetization curves at different frequencies.

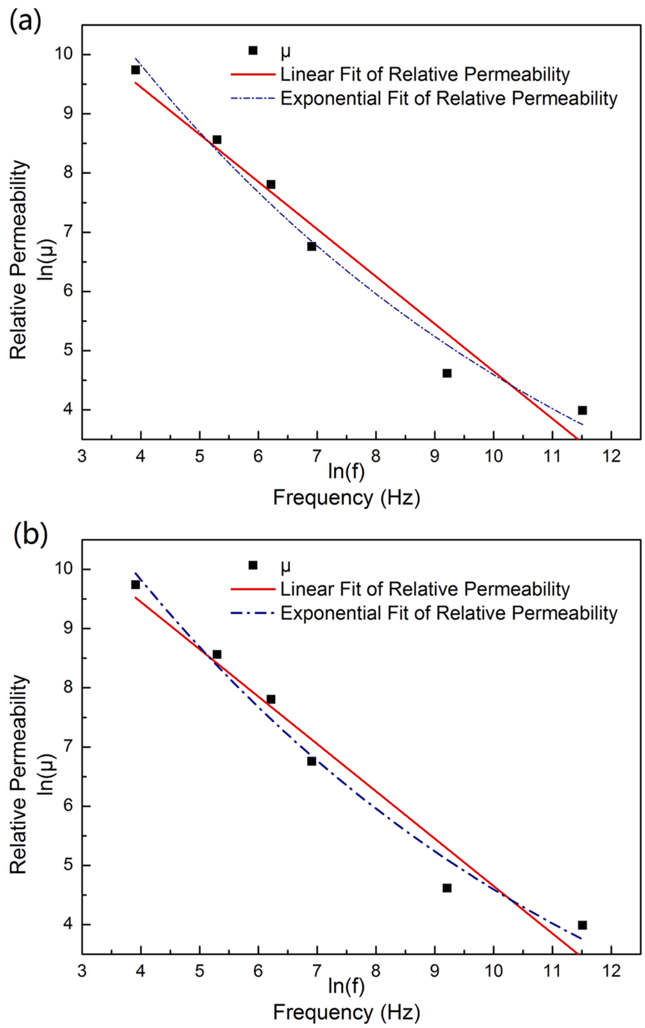

FIG. 2. Relationship between relative permeability and frequency (a) After linear fitting and (b) After exponential fitting.

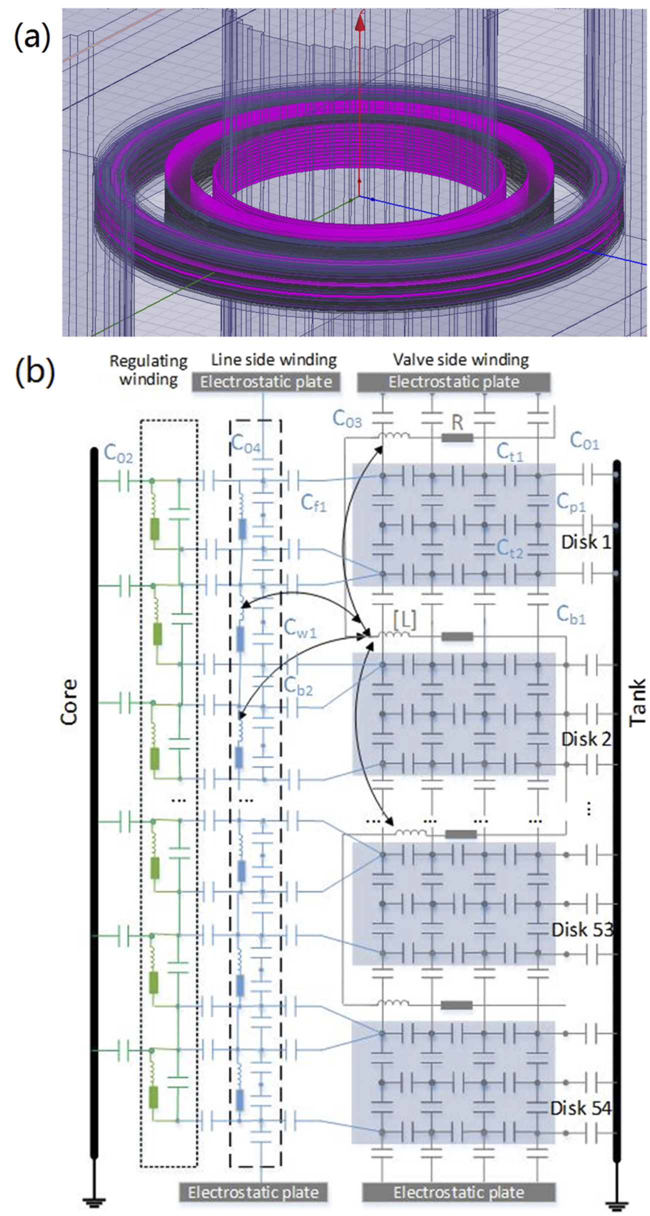

FIG. 3. Transformer winding model (a) 3D three-winding transformer model for parameter calculation (b) Equivalent circuit model of three-winding transformer.

III. EQUIVALENT CIRCUIT MODEL AND PARAMETERS CALCULATION

At high frequency range, the length of the transformer winding (which is 1728m for the modelled transformer winding) is comparable to the length of the electromagnetic wave (which is 1440m for lightning wave), and the distribution characteristics of the transformer should be considered. For three-wind transformer (shown in Fig. 3), the equivalent circuit model includes the capacitance between any two conductors and the inductance between any two coils and the resistance of every coil. It is the most detailed model to date.

The calculation of the capacitance and inductance parameters is the basis of the establishment of the equivalent circuit model. According to the structure parameters (shown in Table I) of the modelled UHVDC converter transformer, the equivalent circuit of the winding is established by using the calculated resistance, inductance and capacitance parameters. Both the mathematical analytical method and finite element method are capable to calculate the parameters of the equivalent circuit, considering the accuracy and the efficiency of the modelling procedure, we prefer the finite element method.

A detailed three-winding model was established in the finite element calculation software (Ansoft Maxwell[13]) to calculate the capacitance parameters of the equivalent circuit model. The computation results are listed in Table II.

TABLE I. The structure parameters of the modelled transformer.

Item	Data
V Winding structure	Axial innershield-continuous
Outer diameter of V winding	2546mm
Turn number of one disk of the outer winding	4
Inter-turn insulation thickness	9mm
Spacer thickness of the outer winding	6.4mm
Conductor parameter of the outer winding	30mm×28mm
Number of disk of the outer winding	54
Diameter of the iron core	1320mm

When computing the resistance and inductance parameters of the equivalent circuit, the material properties of the 3D model are reset with the previous measurement results of the silicon steel sheet. As a result, the matrix [L] contains all the mutual inductances between any two disks and because of hysteresis the values of the matrix are different at different frequency. Due to the skin effect the matrix [R] is also a function of frequency.

To realize the mutual inductances and the frequency-dependent parameters in the equivalent circuit, the mathematical software (MATLAB) is superior to the electromagnetic transients program (EMTP), because of its powerful matrix computing function.

IV. CALCULATION RESULTS AND DISCUSSION

According to the equivalent circuit established with the computed parameters above, the branch admittance matrix Y was achieved. Using the incidence matrix A to represent the relationship of the node and the branch, therefore the node voltage U_n can be acquired by equation

$$\mathrm{A} \cdot \mathrm{Y} \cdot \mathrm{A}^{\mathrm{T}} \cdot U_n = -\mathrm{A} \cdot \mathrm{Y} \cdot U_s \tag{2}$$

where U_s is the voltage source and should be treated by Fourier transform. At frequency domain, solve the equation (2) and add up the response voltage values to achieve the final value of the U_n.

Coding a program to solve the matrix equation above in MATLAB and the potential distribution properties are extracted from the calculation result.

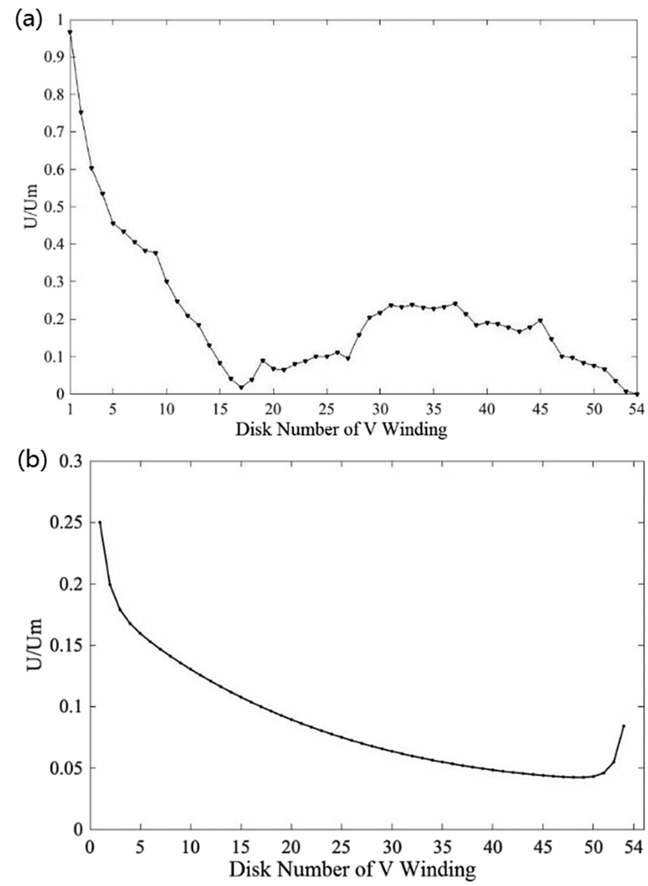

FIG. 4. Calculation results (a) Initial potential distribution on V winding (b) Inter-turn potential gradient distribution on V winding.

Taking lightning voltage as a case study, a standard lightning of 1.2/50 μs with peak voltage of 10 kV is provided as voltage source, after calculation the extracted initial potential distribution and the inter-turn potential gradient distribution on the Valve side winding are shown in Fig. 4.

TABLE II. Computation results of the capacitance parameters.

Capacitance parameter	Typical Value/pF	Description
C01	25	Capacitance between tank and conductor of V winding
Ct1	318	Radial capacitance between two conductors of V winding
Ct2	14	Radial capacitance between two shielding conductor of V winding
Cp1	3035.6	Axial capacitance between the shielding conductor and the conductor of V winding
Cb1	351	Axial capacitance between two conductors of adjacent disk of V winding
C03	273	Axial capacitance between electrostatic plate and conductor at end of V winding
Cf1	2	Radial capacitance between conductors of V winding and L winding, respectively
C04	193	Axial capacitance between electrostatic plate and conductor at end of L winding
Cw1	240	Axial capacitance between two conductors of adjacent disk of L winding

Fig. 4(a) shows that the voltage decreases to almost 0 at the 17^{th} disk and then increases to almost 30% of the amplitude of the voltage source and then decreases to zero again. The tendency is different from the results of previous work which ignoring the effect of the core lamination stack, and the maximum inter-turn potential gradient appears at the position between the first two disks, which agrees with the results of theoretical analysis.

V. CONCLUSION

This paper has technically measured the magnetic properties of electrical steel sheet under different frequencies, and implement the material properties into the 3D model for computing the parameters of the equivalent circuit. Then the nodal voltage equation is solved by MATLAB programming using the matrix parameters. From a case of lightning surge overvoltage, the potential distribution on the winding is calculated and the effects of the magnetic core is discussed. Therefore, when electromagnetic equipment such as transformer is designed, the effect of magnetic core should be quantitative considered.

ACKNOWLEDGMENTS

This work was supported by the National Key Research and Development Program of China (2017YFB0902701).

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