Modeling Surge Propagation in Machine Windings

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Abstract:- This paper describes a computer model for calculating the surge propagation in the winding of electrical machines. The model considers the winding as a combination of a multiconductor transmission line and a network of lumped parameters. The frequency dependence of the winding electrical parameters are calculated and incorporated into the analysis by means of Foster and Cauer circuits. Finally, this hybrid model is validated by a comparison of calculated and measured results inside a high voltage machine winding.

Key-Words:- Switching transients, surge distribution, winding electrical parameters, network synthesis.

1 Introduction

Switching operations on industrial installations give rise to steep fronted transient voltages which penetrates into the winding of electrical machines [1, 2]. Recently, the introduction of power electronic devices has increased the concern about the surge environment on industrial installations [3].

Several computer models for calculating the voltage distribution in the very short periods of time after the surge arrival to machine terminals have been developed [4, 5, 6]. Because of the very high frequencies involved they considerer the iron core as a flux barrier and no flux penetration is accounted for in the calculations. Hence, the analysis is restricted to a few coils during short periods of time (1-3 μs).

For representing a full winding during switching transients some authors have proposed lumped parameters [7]. However, this analysis is too simplified and they do not take into account important phenomena like the flux penetration into the iron core and the frequency dependence of the electrical parameters.

The calculation of the winding electrical parameters is always a problem to solve in surge propagation studies. Computer models in the frequency domain allow to include directly this frequency dependence, but they have difficulties for dealing with non linear phenomena and complex system arrangements. On the other hand, the use of time domain models is quite extended. They are suitable to assess the effect of switching transients in motor banks during sequential pole closure, the more severe conditions for the winding, but they have problem in dealing with the frequency dependence of the parameters.

This paper develops a three phase time domain model for the winding of electrical machines, suitable for calculating switching transient in motor banks. The computer model takes into account the machine winding design and construction specifications in order to calculate the winding electrical parameters at high frequencies. These parameters are calculated by using recursive formulations. Then, a synthesis network based on Foster and Cauer circuits is proposed to represent the frequency dependence of the winding electrical parameters. This lumped parameter network is used, together with a multiconductor transmission line representation, to calculate the surge propagation through the winding. The complete hybrid model is validated by a comparison of measured and calculated results.

2 Winding Electrical Parameters

Let us consider a single current carrying conductor located in the stator slot, as shown in Figure 1. For this simplified geometry, the current produces a magnetic field "H_o" and a flux density "B_o" in the slot walls. The flux penetration into the iron core laminations can be calculated approximately by using the one dimension diffusion equation:

$$\frac{d^2 B}{dx^2} - m^2 B = 0 \qquad (1)$$

where:

$$m = \sqrt{\frac{s\mu}{\rho}} \qquad (2)$$

"ρ" and "*μ"* are the iron resistivity and permeability respectively, and *"s"* is the complex frequency under consideration ($s = \alpha + j\omega$).

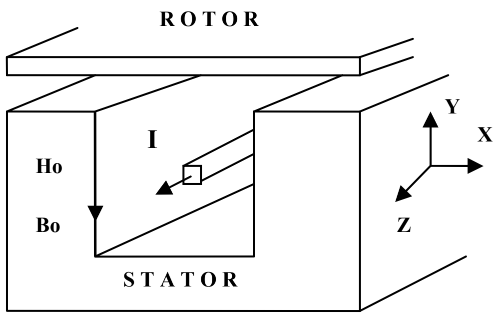

Fig. 1. Simplified representation for a current carrying conductor located in the slot

The solution for (1) in the complex frequency domain is given by:

$$B(x,s) = B_o \exp(-mx) \tag{3}$$

From (3), it is evident that the flux penetration into the iron core is dependant on the frequency and the electrical and magnetic properties of the material. Table 1 shows the values of the real part of $p = 1/m$ for several frequencies. It is evident that at high frequencies the iron behaves as a flux barrier.

Table 1. Depth of penetration for several frequencies

Frequency (kHz)	p (mm)
0.1	0.4358
1.0	0.1378
10	0.0435
100	0.0137
1000	0.0043
10000	0.0013

μ_r=4000 , ρ= 6.E-7 Ω-m

For calculating electrical parameters the total flux in the laminations in the "*x*" axis direction is needed. The total flux per unit length can be calculated as:

$$\Phi(s) = \int_0^\infty B_o \exp(-\frac{x}{p})dx = B_0 p \tag{4}$$

The approach used in this paper for calculating the winding electrical parameters is based on considering each winding as an element in a multiconductor transmission line system. Thus, the coil electrical parameters at high frequencies must be calculated, namely, the parallel admittance and series impedance.

The parallel admittance in the slot section is given by:

$$Y = j\omega C \tag{5}$$

The capacitance to ground in the slot section "*C*" can be calculated directly by approaching the walls of the coils to parallel plate capacitors. Therefore, from the insulation thickness "*d"*, insulation permittivity "ε" and coil geometry, the following general expression is obtained:

$$Y = j\omega \frac{\varepsilon \cdot l \cdot pe}{d} \tag{6}$$

where "*pe*" is the coil perimeter and "*l*" the total slot length.

The calculation of the series impedance is more complex and involves the flux penetration into the iron and skin effect. The general expression for the series impedance per unit length is:

$$Z_t = R_{iron} + R_{sk} + j\omega\left[L_{iron} + L_{sk} + L_{ins}\right] \tag{7}$$

In Figure 1, let us consider that the flux density "*Bo"* is produced by a current carrying conductor located in the center of the slot. Then:

$$\Phi(s) = \mu \cdot H_o \cdot p = \mu \cdot \frac{n \cdot I}{z} \cdot p \tag{8}$$

where "*n*" is the number of turns in the coil and "*z*" is the slot perimeter. Hence, the contributions to the coil self inductance due to the flux penetration into the iron core per unit length can be calculated approximately by:

$$L_{iron} = \frac{\mu \cdot n^2 \cdot p}{z} \tag{9}$$

The above analysis can also be extended to the current penetration into the iron, then:

$$I(s) = \int_0^\infty J(x,s)dx = J_o p \tag{10}$$

The approach used for calculating series losses in the iron is based in considering that return currents are limited to a narrow strip of width "*p*" and a current density "*Jo*". Under these conditions, the series resistance per unit length is approximated by:

$$R_{iron} = \rho \frac{l}{p \cdot z} \qquad (11)$$

where "*l*" is the coil length in the iron and "ρ" is the iron resistivity.

Finally, inductance and resistance contributions due to skin effect in the cooper conductors can be calculated by the well known expressions:

$$Z_{sk} = \frac{l}{A \cdot \xi \cdot \sigma} \qquad (12)$$

where "ξ" is the complex skin depth for copper conductors "σ" is the copper conductivity and "*A*" is the conductor cross section.

The inductance due to the flux in the insulation material between turns and the slot walls and wedges need to be calculated. The rectangular conductor used in machine windings can be substituted by a circular conductor with an equivalent geometric mean radius given by:

$$r = .2235(a + b) \qquad (13)$$

and by applying the method of the images in the slot:

$$L_{ins} = \frac{\mu_o \cdot n^2}{2 \cdot \pi} \ln\left(\frac{2h}{r}\right) \qquad (14)$$

where "*a*" and "*b*" are the height and width of the turns and "*h*" is half the slot width.

Measurements of coil electrical parameters were carried out in a 1690 kW, 6.6 kV machine winding, in order to assess the accuracy of the above formulations. Figures 2 shows a comparison of measured and calculated inductance in the 0 - 200 kHz frequency range. From these results it can be established that the formulations used show good agreement with measured results. The results presented are for one coil in the slot, but the analysis can be extended for a greater number of coils connected in cascade in the winding. In this case, mutual couplings are calculated using the techniques presented in references [8, 9]. Similar results were obtained for the series resistance.

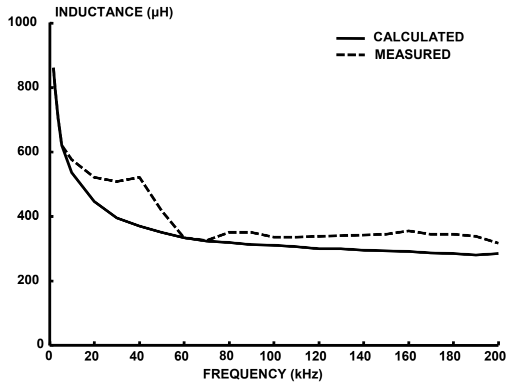

Fig. 2 Coil inductance measured and calculated

3 Synthesis of Electrical Parameters

The formulations presented in the previous section for calculating the coil electrical parameters are valid for the frequency domain. It is desirable to represent this frequency dependence of the electrical parameters in the time domain. The approach used in this paper to incorporate frequency dependence is based on Cauer and Foster networks. Thus, equations (9), (11) for the flux penetration and (12) for the skin effect are represented using this type of networks.

Equations (9) and (11) can be summarized as follows:

$$Z(\omega) = R_{iron} + j\omega L_{iron} \qquad (15)$$

The Cauer network is built up by shunt resistances and series inductances forming a ladder network, as shown in Figure 3. The synthesis process consist in obtaining a Cauer impedance Z_C as close as possible to *Z(ω)*:

$$Z(\omega) = R(\omega) + j\omega L(\omega) = Z_C = R_C + j\omega L_C \qquad (16)$$

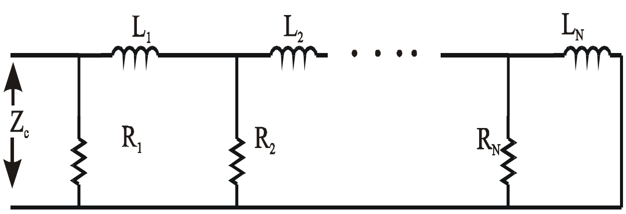

Fig. 3 Cauer Network

An exact match between $Z(\omega)$ and Z_C in the frequency domain requires an infinite number of blocks R-L. However, in order to maintain the model as small as possible, only a few frequency bands were selected and the frequency response is approximated with just six blocks. Thus, impedances $Z(\omega)$ and Z_C are of the same magnitude at the selected frequencies 10, 10^2, 10^3, 10^4,10^5, 10^6 Hz. From Figure 3, the Cauer network impedance is:

$$Z_C(\omega) = \cfrac{1}{G_N + \cfrac{1}{j\omega L_1 + \cfrac{1}{G_2 + \ldots \cfrac{1}{G_N + \cfrac{1}{j\omega L_N}}}}} \quad (17)$$

An iterative algorithm for calculating resistances and inductances in the Cauer network at discrete frequencies was implemented. The foundations for this analysis can be found in references [10, 11].

Figure 4 shows a comparison between the calculated phase inductance $L(\omega)$ and the Cauer network equivalent inductance L_C. On the other hand, Figure 5 shows a comparison between the calculated phase resistance $R(\omega)$ and the Cauer network equivalent resistance R_C. From Figures 4 and 5 it can be established that the Cauer network equivalent impedance Z_C is an adequate representation for the winding impedance $Z(\omega)$ in the frequency range of interest.

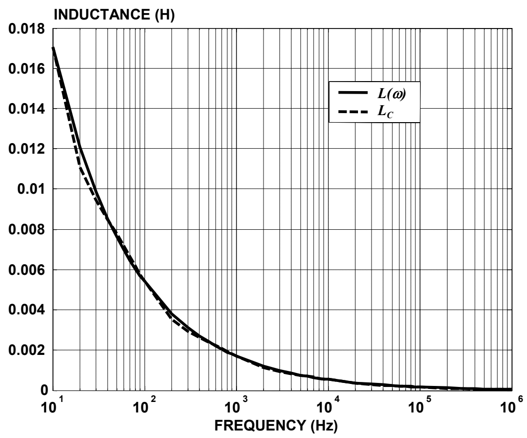

Fig. 4 Inductances $L(\omega)$ and L_C

Skin effect can be represented by using series and parallel Foster network. Both techniques were implemented and evaluated in this study with similar results. For illustrative purposes, let us consider the parallel Foster network shown in Figure 6. This circuit must fulfill the following conditions at discrete frequencies:

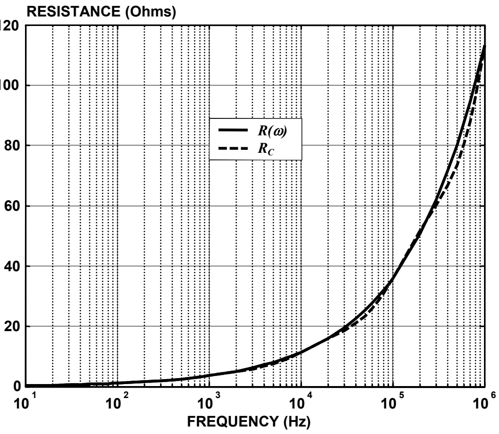

Fig. 5 Resistances $R(\omega)$ and R_C

$$Z_{sk} = R(\omega) + j\omega L(\omega) = Z_F = R_F + j\omega L_F \quad (18)$$

The terminal admittance for the network in Figure 6 is:

$$Y_F(\omega) = \frac{1}{Z_C} = \sum_{i=1}^{N} \frac{1}{R_i + j\omega L_i} \quad (19)$$

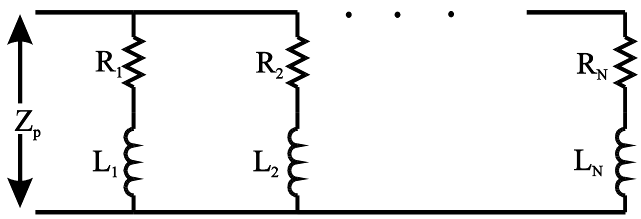

Fig. 6 Parallel Foster network

Again, computer programs were developed for calculating resistances and inductances in the parallel Foster network.

Figure 7 shows a comparison between the calculated phase resistance $R(\omega)$ due to skin effect and the Foster network resistance R_F. This figure show that the real part of the Foster network equivalent impedance, Z_F, is an adequate representation for the real part of the winding impedance $Z(\omega)$ in the frequency range of interest.

Similar results were obtained for the imaginary part of the circuit, L_F.

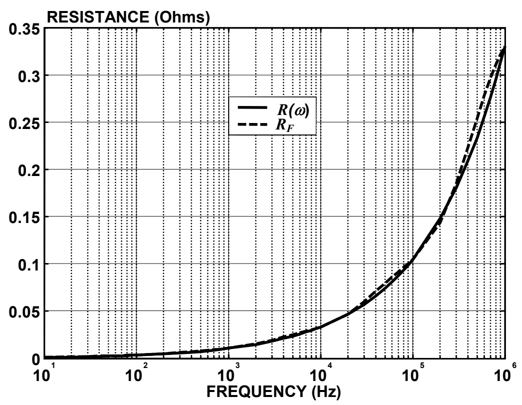

Fig. 7 Resistances R_F and $R(\omega)$

4 Machine Winding Model

The Alternative Transient Program (ATP) is used to calculate the surge propagation through the winding. The three phase winding model is based on two main blocks.

The first block is based on a multiconductor transmission line model which includes those parameters not dependant on frequency like the capacitance to ground C, self inductance due to the flux in the insulation L_{ins}, and mutual coupling between coils in the overhang region. The second block is based on Cauer and Foster networks representing the frequency dependence of the winding parameters due to the flux penetration into the iron core and skin effect in the copper conductors. In order to validate the model, low voltage steep fronted waves were applied to machine terminals by using a recurrent surge generator (RSG), see Figure 8.

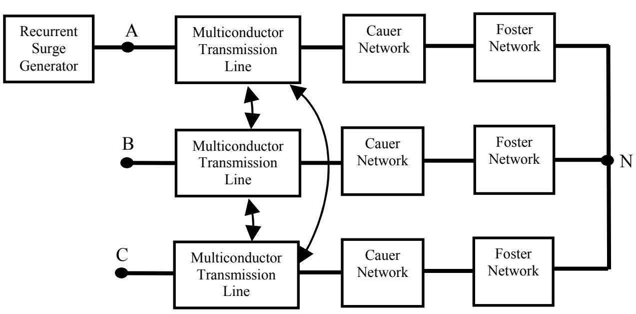

Fig. 8 Three phase model for the winding

Figures 9 and 10 show a comparison between measured and calculated results for a Y-connected, 1640 kW and 6.6 kV induction motor, whose electrical characteristics are given in reference [2]. A steep fronted wave 350 ns, 50V was applied in phase A with phases B and C in open circuit. Measurements were also made with the neutral grounded.

From Figures 9 and 10 it is clear that the winding model is capable of describing the surge propagation through the winding with a reasonably accuracy. It can also be seen that the surge propagation follows a pattern similar to overhead transmission lines with additional features such as mutual coupling between coils and flux penetration into the iron. The overall result when the surge reaches phases B and C is a damped oscillation at the natural frequency of the system. In this particular case, the peak value reach a magnitude of 1.5 p.u. and the natural oscillation frequency is 6-7 kHz. It should be mention that for smaller machines the natural oscillation frequency should be much higher. This is the reason why electrical parameters calculating techniques were validated up to a few hundreds of kilohertz.Given its modular construction, the computer model can also be used for representing individual machines in a motor bank.

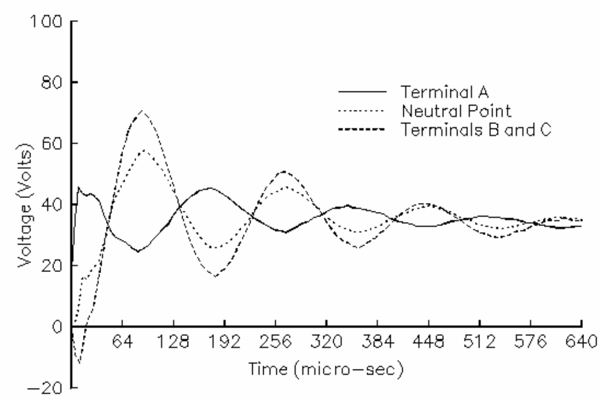

Fig. 10 Measured surge propagation

5 Conclusions

A three phase time domain model to assess the transient voltage propagation in machine windings has been presented. The model takes into account the frequency dependence of the electrical parameters due to the flux penetration into the iron core, skin effect and the mutual coupling between phases in the winding.

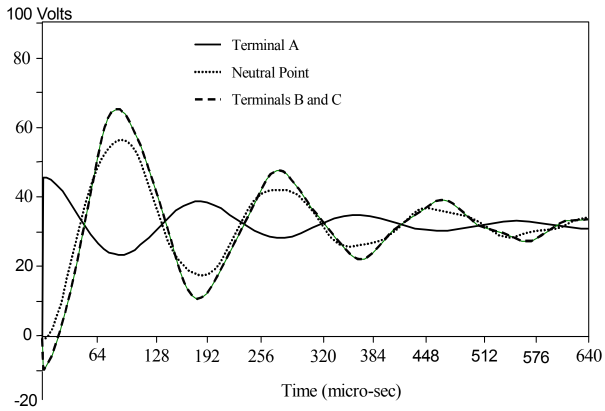

Fig. 11 Calculated surge propagation

In order to include in the analysis the frequency dependence of the electrical parameters in the time domain, a synthetized Cauer and Foster networks were obtained for the winding. The computer model was verified by a comparison of measured and calculated results in a high voltage machine.

Computer results give a reasonable degree of confidence in the model and its capability for predicting transient voltages on terminals in the range 0-800 μs. Since second and third pole closure occurs in this time range, the model can be used in the calculation of switching transient magnitudes in terminals and inside the winding during this kind of phenomena, which represents the more severe conditions for the insulation. The model is also suitable for switching transient analysis in motor banks.

Acknowledgments

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