Extraction of High-Frequency Phase-to-Phase Coupling in AC Machine Using Mixed-Mode Network Parameters

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This paper proposes a method that can extract phase-to-phase transfer impedance of three-phase winding of an AC motor stator for high frequency characteristic. The phase-to-phase coupling parameters are obtained by calculating the relations between the terminal voltages and currents from single phase, common mode and differential mode. To verify the proposed method, the calculated input impedance is compared with the measurement result. By observation of the extracted phase-to-phase transfer impedance, a RLC equivalent circuit is constructed to estimate the components of phase-to-phase coupling noise.

***Index Terms*—AC Motors, electromagnetic compatibility, equivalent circuit model, parameter estimation.**

I. Introduction

SINCE AC machines involve high-frequency (HF) switch-mode inverters, the integrated driver design requires more attention to EMI issues. To understand the noise coupling mechanism, HF behavior of AC machines has been studied [1]-[2]. However, in the previous researches, the phase-to-phase coupling is not considered in the equivalent model of AC machine, or it is not distinguished from the stator-to-frame coupling component. Since the phase-to-phase coupling may conduct a significant amount of noise between the layers in a slot or long end-winding structures, it needs to be investigated carefully and added to the equivalent circuit properly.

To estimate the effect of phase-to-phase coupling, this paper proposes a method which can calculate the multi-port impedance parameters of AC motor by using the conversion of terminal voltages and currents from the common mode (CM) and differential mode (DM) voltages and currents. For verification, the calculated result is compared with the measurement result for single phase input impedance. By the observation of the extracted result, the phase-to-phase coupling noise is estimated with an RLC equivalent circuit.

II. Extraction of phase-to-phase coupling impedance

To observe the effect of phase-to-phase parasitic coupling, the stator winding of a 3.7kW induction machine is measured with different terminal conditions. Two measured input impedances through terminals 1 and 4 for the 'Phase U' line in Fig. 2 are compared in Fig. 1, where one is measured with the other terminals open and the other is measured with the other terminals connected to the reference impedance. As shown in Fig. 1, the input impedances of single phase line are different up to mid-frequency region since the phase-to-phase coupling effect is altered by terminal conditions. Therefore, the effect of phase-to-phase coupling should be considered for the accurate estimation of the frequency dependent behavior of the multiphase structure of AC machine.

The AC machines having three phase windings can be constructed by various methods according to the number of layers in a slot and coil pitch. For any winding structure, we can define the following relation of matrices with the 6 by 6 impedance matrix:

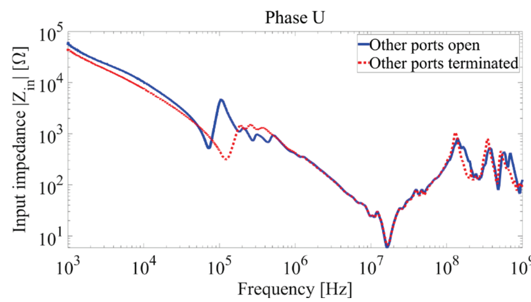

Fig. 1. Comparison of input impedances of single phase line measured with open and terminated ports for other phase lines.

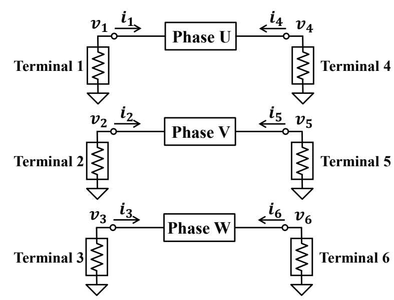

Fig. 2. Multi-port network model of a three-phase winding.

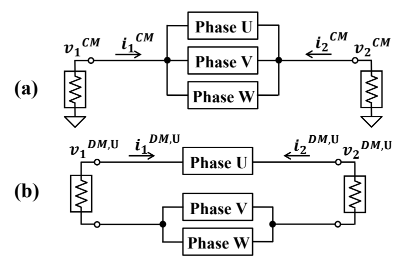

Fig. 3. (a) Voltages and currents for CM connection. (b) Voltages and currents for DM connection.

$$\begin{pmatrix} \mathbf{V_L} \\ \mathbf{V_R} \end{pmatrix} = \begin{pmatrix} \mathbf{Z_X} & \mathbf{Z_Y} \\ \mathbf{Z_Y} & \mathbf{Z_X} \end{pmatrix} \begin{pmatrix} \mathbf{I_L} \\ \mathbf{I_R} \end{pmatrix}, \tag{1}$$

where V_L is a 3 by 1 matrix of v_1, v_2 and v_3 that are indicated in Fig. 2. Similarly, V_R includes the terminal voltages which are right side in the figure. If we assume that the three phase winding structure is balanced, the elements of Z_X and Z_Y can be simplified as follows:

$$\mathbf{Z_X}=\begin{pmatrix} x & u & u \\ u & x & u \\ u & u & x \end{pmatrix},\quad \mathbf{Z_Y}=\begin{pmatrix} y & w & w \\ w & y & w \\ w & w & y \end{pmatrix} \tag{2}$$

In order to find the values of the unknown x, y, u and w, the relations of voltages and currents of CM and DM, which are shown in Fig. 3, can be used. Since all of the terminals in Fig. 2 are defined by same amount of input voltage and current, the relations of voltages and currents between CM, DM and single phase are obtained as follows:

$$\begin{pmatrix} v_1^{CM} \\ v_1^{DM,U} \\ v_1^{DM,V} \end{pmatrix}=\begin{pmatrix} \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \\ 1 & \frac{-1}{2} & \frac{-1}{2} \\ \frac{-1}{2} & 1 & \frac{-1}{2} \end{pmatrix}\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} \Rightarrow \mathbf{V_{M,L}}=\mathbf{M_V V_L} \tag{3}$$

$$\begin{pmatrix} i_1^{CM} \\ i_1^{DM,U} \\ i_1^{DM,V} \end{pmatrix}=\begin{pmatrix} 1 & 1 & 1 \\ \frac{1}{2} & \frac{-1}{4} & \frac{-1}{4} \\ \frac{-1}{4} & \frac{1}{2} & \frac{-1}{4} \end{pmatrix}\begin{pmatrix} i_1 \\ i_2 \\ i_3 \end{pmatrix} \Rightarrow \mathbf{I_{M,L}}=\mathbf{M_I I_L}, \tag{4}$$

where M_V and M_I represent transfer matrices between modal and terminal (phase) variables. By using the relation between the matrices M_V, M_I, Z_X and Z_Y, we can get the relation of voltages and currents for CM and DM as follows:

$$\begin{pmatrix} \mathbf{V_{M,L}} \\ \mathbf{V_{M,R}} \end{pmatrix}=\begin{pmatrix} \mathbf{M_V} & \mathbf{0} \\ \mathbf{0} & \mathbf{M_V} \end{pmatrix}\begin{pmatrix} \mathbf{Z_X} & \mathbf{Z_Y} \\ \mathbf{Z_Y} & \mathbf{Z_X} \end{pmatrix}\begin{pmatrix} \mathbf{M_I^{-1}} & \mathbf{0} \\ \mathbf{0} & \mathbf{M_I^{-1}} \end{pmatrix}\begin{pmatrix} \mathbf{I_{M,L}} \\ \mathbf{I_{M,R}} \end{pmatrix} \tag{5}$$

$$=\begin{pmatrix} \mathbf{M_V Z_X M_I^{-1}} & \mathbf{M_V Z_Y M_I^{-1}} \\ \mathbf{M_V Z_Y M_I^{-1}} & \mathbf{M_V Z_X M_I^{-1}} \end{pmatrix}\begin{pmatrix} \mathbf{I_{M,L}} \\ \mathbf{I_{M,R}} \end{pmatrix}=\mathbf{Z_{CM,DM}}\begin{pmatrix} \mathbf{I_{M,L}} \\ \mathbf{I_{M,R}} \end{pmatrix}$$

By calculating the matrix $Z_{CM,DM}$ with the unknown parameters, we can extract the elements related to CM and DM from (5) as follows:

$$\begin{pmatrix} v_1^{CM} \\ v_2^{CM} \end{pmatrix}=\frac{1}{3}\begin{pmatrix} x+2u & y+2w \\ y+2w & x+2u \end{pmatrix}\begin{pmatrix} i_1^{CM} \\ i_2^{CM} \end{pmatrix}, \tag{6}$$

$$\begin{pmatrix} v_1^{DM,U} \\ v_2^{DM,U} \end{pmatrix}=2\begin{pmatrix} x-u & y-w \\ y-w & x-u \end{pmatrix}\begin{pmatrix} i_1^{DM,U} \\ i_2^{DM,U} \end{pmatrix}$$

Under the balanced condition, off-diagonal terms of $Z_{CM,DM}$ become zero. Finally, we can obtain the unknown elements for the impedance matrix as follows:

$$x=z_{11}^{CM}+\frac{1}{3}z_{11}^{DM},\quad u=z_{11}^{CM}-\frac{1}{6}z_{11}^{DM} \tag{7}$$

$$y=z_{12}^{CM}+\frac{1}{3}z_{12}^{DM},\quad w=z_{12}^{CM}-\frac{1}{6}z_{12}^{DM}$$

Note that x and y can be the input impedance for each terminal of the phase line. On the other hand, u and w represent the transfer impedances which are involved the effect of the phase-to-phase coupling.

To verify the calculated results, the calculated input impedance for the single phase line is compared with the measurement as shown in Fig. 4. As can be seen in the results, the calculated input impedance shows a close match with the measured one because it includes the effect of phase-to-phase coupling by the transformation of terminal voltages and currents from the CM and DM voltages and currents.

By using the proposed method, we can extract the phase-to-phase coupling as impedance parameters and investigate its effect. The calculated result of the transfer impedance between phases is shown in Fig. 5. From the result, we can estimate the components of the phase-to-phase coupling by modeling a *RLC* series circuit. The value of L and C can be estimated by the slope of the calculated magnitude of u before and after the antiresonance frequency. R is the value of the impedance at the antiresonance frequency. The estimated values of R, L and C are 0.4Ω, 0.12uH and 2.5pF, respectively.

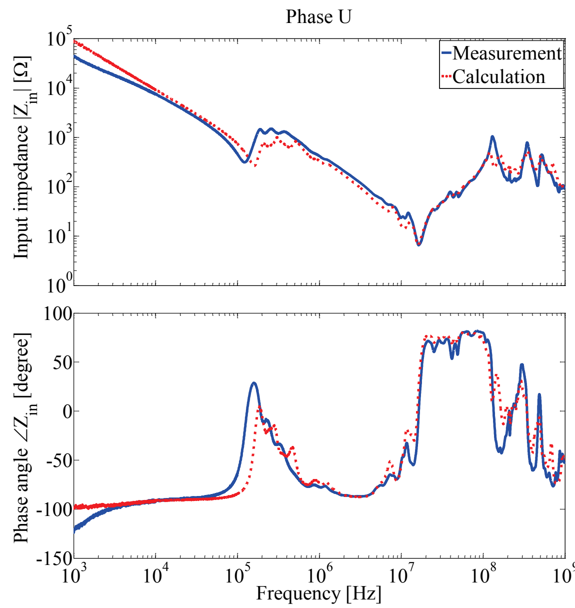

Fig. 4. Comparison between measured and calculated input impedance Z_{in} for the single phase line.

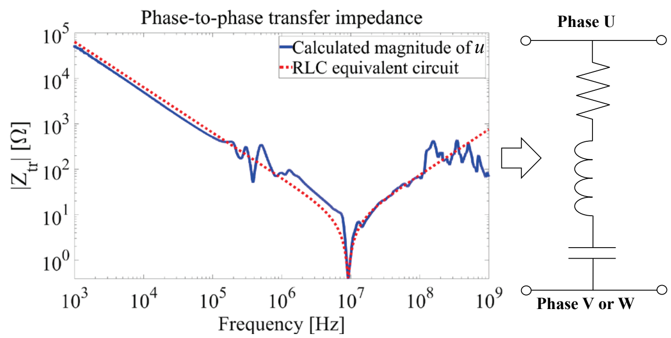

Fig. 5. Calculated phase-to-phase coupling parameter and constructed RLC circuit model.

III. Conclusion

In this paper, a method to extract the parameters for the phase-to-phase coupling is proposed. This method can be used to construct a proper PUL equivalent circuit model for the three phase winding structure of AC machine by applying the method of transmission line model [3].

IV. References

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