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High-Frequency Modeling of Star-Connected Induction Motors Using Multilayer Perceptron

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Abstract—This letter presents an easy-to-use accurate high-frequency (HF) behavioral model of star-connected induction motors with a simple and straightforward parameterization process for conducted electromagnetic interference (EMI) analysis. The HF model contains nine circuit elements per phase with a simple structure. These circuit elements are determined using a multilayer perceptron (MLP) neural network, where only the individual phase-to-frame impedance is needed for training purposes. Compared with parameterization methods in conventional motor modeling, the MLP significantly simplifies the parameterization process. Using two different induction motors (1.5 hp and 7.5 hp) as case studies, experiments verify the capability and accuracy of the HF model to predict the motor common-mode (CM) and differential-mode (DM) impedances in the HF range of 150 kHz to 30 MHz.

Index Terms—Electromagnetic interference (EMI), high-frequency (HF) modeling, induction motor, multilayer perceptron (MLP), parameterization.

I. INTRODUCTION

VARIABLE frequency drive (VFD) systems have been widely used in many industrial applications because of their excellent power conversion efficiency [1]. With the advancement in power semiconductor technology, higher switching frequency has become norms in the designs of VFD systems, which also generates higher electromagnetic interference (EMI) due to fast edge rates [2]. EMI modeling and simulation serves as an effective means to predict system EMI behavior and optimize EMI mitigation strategies at the design stage before final product implementation. With the increasing switching frequencies in VFD systems, an accurate and reliable high-frequency (HF) model of induction motors is necessary to ensure good EMI prediction results [3]. This paper focuses on the HF range of 150 kHz – 30 MHz, which is the mandatory requirements by many EMI standards [4]–[6].

Conventionally, the HF models of induction motors are categorized into two main types, the finite element analysis (FEA)-based models and the behavioral models [7]. FEA-based models are created via 2-D or 3-D electromagnetic analysis using numerical methods [8]–[10]. Behavioral models are developed through impedance measurements and curve fitting techniques [3], [7], [11]–[14]. Numerous behavioral models have been proposed to represent the motor's common-mode (CM) and differential-mode (DM) impedance characteristics for conducted EMI analysis. High-accuracy behavioral models

Fig. 1. Proposed HF model of star-connected induction motor per phase.

usually require more circuit elements and complex parameterization process, which sacrifices model simplicity and practicability [7].

This letter proposes a simplified and accurate HF behavioral model of star-connected induction motors with a simple and straightforward parameterization process. The model consists of a simplified circuit with nine circuit elements per phase. These circuit elements can be easily determined using a multilayer perceptron (MLP) neural network, where only the individual phase-to-frame impedance is needed for training purposes. Compared with the parameterization methods in conventional motor modeling, the MLP simplifies the parameterization process. Among various neural networks, although the MLP is less competent in multi-scale feature extraction than more advanced deep neural networks, it is still preferred in this application for its adequate regression ability with less computational cost.

In this letter, two different induction motors (1.5 hp and 7.5 hp) are selected as case studies. Section II describes the proposed HF modeling and parameterization process. Section III demonstrates its accuracy to predict the motor CM and DM impedances in the HF range of 150 kHz to 30 MHz. Finally, Section IV concludes this letter.

II. HF MODELING OF MOTOR USING MLP

Fig. 1 shows the proposed HF model of star-connected induction motor per phase, which consists of nine physically meaningful circuit elements. L_c represents the combined inductance of the stator winding leakage inductance in the first few turns and the inductance of internal feed conductors connected to the stator winding. C_{sf1} and C_{sf2} account for the stator-to-frame capacitances. R_c denotes the combined resistance of the HF stator copper skin effect resistance and the frame resistance. L_{lk1} and L_{lk2} represent the stator winding leakage inductances. C_{it1} and C_{it2} account for the stator winding interturn capacitances. R_e denotes the HF stator eddy-

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Fig. 2. Parameterization process using a MLP neural network.

current losses. For the three-phase HF model, it is constructed using three per-phase HF models shown in Fig. 1 based on the motor winding connection. Due to manufacturing tolerances and layout differences [8], there may be slight differences in the values of these circuit elements for the three phases, namely phases A, B, and C.

To determine the values of these circuit elements of each phase, a MLP neural network is employed, where Fig. 2 shows the parametrization process. As illustrated in Fig. 2, the MLP neural network consists of five layers, namely one input layer, three hidden layers, and one output layer. The input of the MLP is a random constant value C , and the output of the MLP are the nine circuit elements (i.e., L_c , C_{sf1} , C_{sf2} , R_c , L_{lk1} , L_{lk2} , C_{it1} , C_{it2} , and R_e). The units of L_c , R_c , and R_e are set as microhenry (μH), ohm (Ω), and kilohm ($\text{k}\Omega$), respectively; the units of C_{sf1} , C_{sf2} , C_{it1} , and C_{it2} are set as nanofarad (nF); the units of L_{lk1} and L_{lk2} are set as millihenry (mH) [7], [12]. The number of neurons in the three hidden layers are set as 100, 500, and 100, respectively. The loss function ($\mathcal{g}_L$) is defined in terms of the motor's phase-to-frame impedance as follows:

$$\mathcal{g}_L = \frac{1}{2m} \left\{ \sum_{i=1}^m (|\mathbf{Z}_{PF}| - |\mathbf{Z}'_{PF}|)^2 + \sum_{i=1}^m (\angle \mathbf{Z}_{PF} - \angle \mathbf{Z}'_{PF})^2 \right\} \quad (1)$$

where m is the number of frequency points. $\mathbf{Z}'_{PF}$ represents the reference phase-to-frame impedance measured with an impedance analyzer. When measuring $\mathbf{Z}'_{PF}$ of one phase, the probe of the impedance analyzer connects between the phase and frame, and the neutral is disconnected. $\mathbf{Z}_{PF}$ represents the trained phase-to-frame impedance via the MLP. $\mathbf{Z}_{PF}$ is trained through substituting the results of the output layer into the per-phase HF model. By minimizing $\mathcal{g}_L$, the values of these circuit elements per phase can be determined, and finally, the HF model of induction motor can be constructed. It should be noted that $\mathcal{g}_L$ represents the sum of the impedance magnitude loss and phase loss, and both losses have the same weightage (i.e., 1/2).

For proof of concept, Figs. 3 and 4 show the measured and trained phase-to-frame impedances for phases A, B, and C of a 1.5 hp (TECO AESV38041R50FUN) and a 7.5 hp (TEOC AEEBKB067R50FM) induction motor, respectively. The

Fig. 3. Measured ($\mathbf{Z}_{PF}$) and trained ($\mathbf{Z}_{PF}$) phase-to-frame impedances for phases A, B, and C of the 1.5 hp induction motor.

Fig. 4. Measured ($\mathbf{Z}_{PF}$) and trained ($\mathbf{Z}_{PF}$) phase-to-frame impedances for phases A, B, and C of the 7.5 hp induction motor.

individual phase-to-frame impedance is measured with a Bode 100 impedance analyzer. The iteration number of the training process is 1000. As shown in Figs. 3 and 4, the trained phase-to-frame impedances have demonstrated good agreement with those of the measured ones for all three phases of the induction motors in the HF range of 150 kHz – 30 MHz. Based on the trained phase-to-frame impedances, the values of the circuit elements for the three phases of the induction motors are obtained, as given in Table I. Hence, the motors' HF models are constructed based on these circuit elements.

III. EXPERIMENTAL VALIDATION

For experimental validation, the same induction motors (1.5 hp and 7.5 hp) are selected as case studies. In order to verify the accuracy of the proposed HF model to predict motor CM ($\mathbf{Z}_{CM}$) and DM ($\mathbf{Z}_{DM}$) impedances in the HF range of interest, the

TABLE I
DETERMINED CIRCUIT ELEMENTS FOR PHASES A, B AND C OF THE TWO
INDUCTION MOTORS (1.5 HP AND 7.5 HP)

Element	1.5 hp induction motor			7.5 hp induction motor		
	A	B	C	A	B	C
L_c (μ H)	0.170	0.132	0.158	0.270	0.370	0.321
C_{sf1} (nF)	0.060	0.080	0.054	0.104	0.130	0.152
C_{sf2} (nF)	1.488	2.581	1.614	2.235	2.760	3.430
R_c (Ω)	10.358	14.524	10.890	7.807	5.828	7.737
L_{lk1} (mH)	4.547	5.808	5.771	3.991	2.913	3.878
L_{lk2} (mH)	4.547	5.808	5.771	3.991	2.913	3.878
C_{it1} (nF)	0.466	0.533	0.360	0.743	0.960	1.030
C_{it2} (nF)	0.466	0.533	0.360	0.743	0.960	1.030
R_e (k Ω)	5.202	4.700	4.038	0.832	0.873	0.974

Fig. 5. Configuration for measuring motor (a) Z_{CM} and (b) Z_{DM} .

actual measured Z_{CM} and Z_{DM} of the induction motors are used as references. Figs. 5(a) and (b) show the respective configuration for measuring the motor's Z_{CM} and Z_{DM} with a Bode 100 impedance analyzer [7].

Based on the obtained motors' three-phase circuit elements in Table 1, Figs. 6 and 7 show the simulated Z_{CM} and Z_{DM} in the HF range of 150 kHz – 30 MHz for the 1.5 hp and 7.5 hp induction motors, respectively. In addition, the actual measured Z_{CM} and Z_{DM} of the same induction motors are also shown in the figures for comparison purposes. As seen in Figs. 6 and 7, both magnitude and phase of the simulated Z_{CM} and Z_{DM} for the 1.5 hp induction motor show good agreement with the those of the actual measured from 150 kHz to 30 MHz. Although the simulated Z_{CM} and Z_{DM} for the 7.5 hp induction motor show some discrepancy from the measured results in certain frequency regions above 10 MHz, they still exhibit reasonably good consistency over most of the HF range from 150 kHz – 30 MHz. Based on these experimental results, the proposed HF model has shown its capability to predict the motor's CM and DM impedances with good accuracy.

IV. CONCLUSION

This letter proposes a simplified and accurate HF behavioral model of star-connected induction motors with a simple and straightforward MLP-based parameterization process for conducted EMI analysis. The motor's circuit elements can be determined by measuring individual phase-to-frame impedance for training purposes. It greatly simplifies the parameterization process as compared with the conventional HF modeling methods. Experimental results of two induction motors (1.5 hp and 7.5 hp) have demonstrated the accuracy of the proposed HF modeling approach to predict the motor's CM and DM impedances in the HF range of 150 kHz – 30 MHz.

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Fig. 6. Measured and simulated Z_{CM} and Z_{DM} of the 1.5 hp induction motor.

Fig. 7. Measured and simulated Z_{CM} and Z_{DM} of the 7.5 hp induction motor.

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