Eddy-Current Loss Modeling for Induction Motor with a Form-Wound Stator Winding

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Abstract —The eddy-current in the form-wound multi-conductor stator winding of a 1250-kW cage induction motor (form-wound IM) was modeled by using time-discretized finite-element analysis (FEA). The voltages and currents from the FEA simulation are used to estimate the equivalent circuit parameters instead of measuring those of the real motor. The traditional T-equivalent circuit is not enough to take the eddy-current effect of the motor with a form-wound multi-conductor stator winding into account. Additional circuit branches are necessary to obtain an appropriate circuit for the form-wound IM. The parameters of the circuit are estimated by using a numerical approach and used to determine the eddy-current losses of the motor. The losses and torque calculated from the circuit are compared to those of the time-discretized FEA to verify the feasibility of the circuit model.

I. INTRODUCTION

The eddy current loss prediction has a significant role during the design stage of a large induction motor, for instance, the method to reduce the losses is proposed after FEA simulation [1]. For end-users, the loss minimizing control of the motor is always based on the electric equivalent circuit model [2]. The suitable equivalent circuit with accurately-estimated parameters is very important to obtain an energy-efficiency electric drive.

In this paper, the time-discretized FEA was used to model the large IM. The equivalent circuit is proposed to represent the motor for control purpose. The parameters of the circuit are identified by a numerical approach from FEA data and used to predict the torque and loss of the motor. A good agreement between the circuit model and FEA is shown in the motor performance evaluation.

II. EDDY CURRENT LOSSES IN THE STATOR WINDINGS

The method to model eddy current losses in the form-wound multi-conductor stator winding of the IM was presented [1]. The eddy-current loss P_{eddy} is the difference between the total resistive loss P_{t} and DC resistive loss.

$$P_{\mathrm{eddy}} = P_{\mathrm{t}} - \sum_{j=1}^{m} R_{dc} i_j^2 \qquad (1)$$

where i_j – phase current in stator phase j, R_{dc} is the dc resistances of a phase.

The stator voltage and currents from the time-discretized FEA are used as the data for parameter estimation. The motor performance from FEA will be compared to that of circuit model. The details of motor structures and motor performance could be found in [1].

III. EQUIVALENT CIRCUIT MODELS

1. T- Equivalent circuit

The conventional circuit model for IM is shown in Fig. 1, in which the stator resistance is measured by a DC source and used in FEA simulation. Using the approach in [3], the stator voltage in the reference frame rotating at ω_{k} is written in space vector form due to the control purpose.

$$\underline{u}_{\mathrm{s}}^{\mathrm{k}} = R_{\mathrm{s}} \underline{i}_{\mathrm{s}}^{\mathrm{k}} + \frac{d\underline{\psi}_{\mathrm{s}}^{\mathrm{k}}}{dt} + \mathrm{j}\omega_{\mathrm{k}} \underline{\psi}_{\mathrm{s}}^{\mathrm{k}} \qquad (2)$$

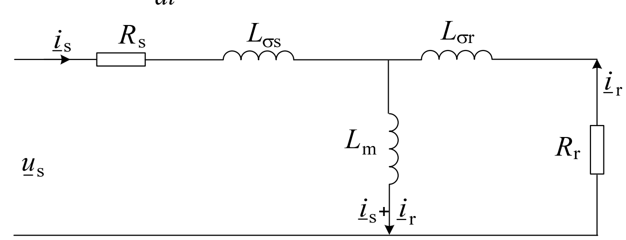

Fig. 1. traditional IM equivalent circuit.

The small-signal impedance of motor could be written in Laplace domain.

$$Z_e = \frac{\underline{z}_{\mathrm{s}}(\underline{z}_{\mathrm{m}} + \underline{z}_{\mathrm{r}}) + \underline{z}_{\mathrm{m}}' \underline{z}_{\mathrm{r}}}{\underline{z}_{\mathrm{m}} + \underline{z}_{\mathrm{r}}} = \frac{\Delta \underline{u}_{\mathrm{s}}}{\Delta \underline{i}_{\mathrm{s}}} \qquad (3)$$

$$\underline{z}_{\mathrm{s}}(s) = sL_{\sigma\mathrm{s}} + R_{\mathrm{s}} \qquad (4)$$

$$\underline{z}_{\mathrm{m}}(s) = sL_{\mathrm{m}} - j\omega_0 L_{\mathrm{m}} + j\omega_{\mathrm{k}} L_{\mathrm{m}} \qquad (5)$$

$$\underline{z}_{\mathrm{m}}'(s) = sL_{\mathrm{m}} + j\omega_{\mathrm{k}} L_{\mathrm{m}} \qquad (6)$$

$$\underline{z}_{\mathrm{r}}(s) = R_{\mathrm{r}} + sL_{\sigma\mathrm{r}} - j\omega_0 L_{\sigma\mathrm{r}} + j\omega_{\mathrm{k}} L_{\sigma\mathrm{r}} \qquad (7)$$

The parameters are estimated by minimizing the error between simulated frequency response function (FRF) and FRF given by model ($s = \mathrm{j}\omega$). The cost function is defined

$$I = \sum_{n=1}^{N} \left[\left(\mathrm{Re}\left\{Z_{\mathrm{m}}^{n}\right\} - \mathrm{Re}\left\{Z_{\mathrm{e}}^{n}\right\} \right)^2 + \left(\mathrm{Im}\left\{Z_{\mathrm{m}}^{n}\right\} - \mathrm{Im}\left\{Z_{\mathrm{e}}^{n}\right\} \right)^2 \right] \qquad (8)$$

N - the length of vector data, n – the index, Z_{m}- the FRF obtained from the impulse method [3], Z_{e}- the FRF from the model (3). All small-signal data are obtained from two time-stepping FEA simulations. The first one implements the fundamental signal and impulse signal. The latter applies the only fundamental signal only.

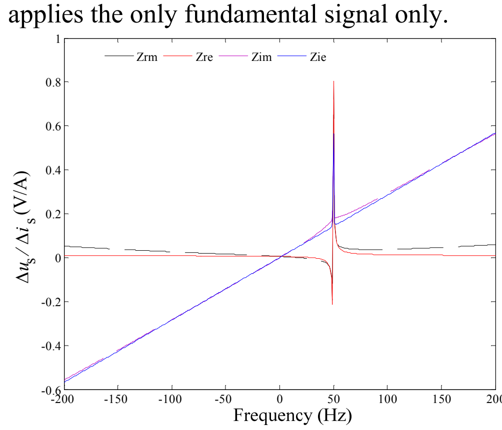

Fig. 2. Frequency response of T model.

The best fit from the data of FEA and circuit in (3) is shown in Fig. 2. There is a large deviation between those

FRFs. It is clear that the T-circuit model could not be enough to identify the motor.

2. Proposed circuit

The motor with a semi-open slot rotor and multi-conductor stator is modeled by the additional branches as shown in Fig. 3. R_e and L_{se} stand for the eddy-current effect of motor, and R_{r2} and L_{r2} are added due to the skin effect of the semi-open slot rotor.

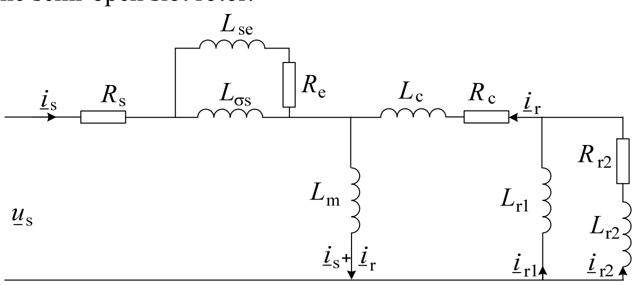

Fig. 3. Equivalent circuit for the form-wound IM.

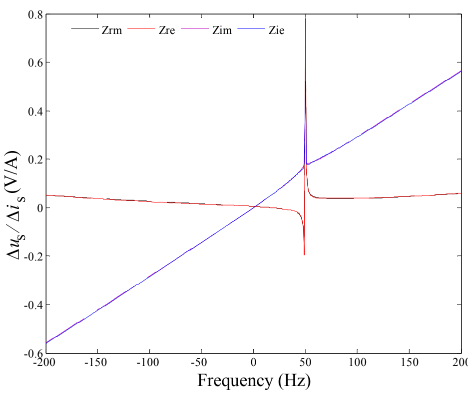

Fig. 4. Frequency response of proposed model.

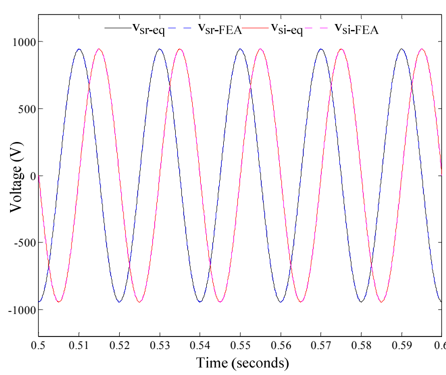

Fig. 5. Space vector components of voltage supply.

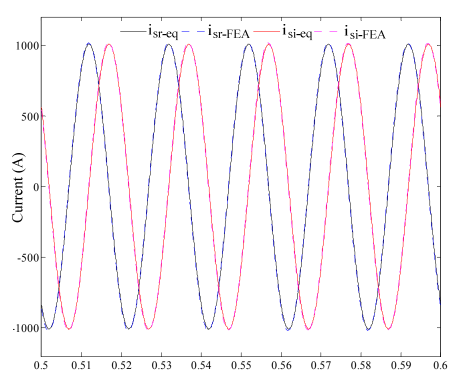

Fig. 6. Space vector components of stator current response.

The best fit of the data from FEA and from the proposed circuit is shown in Fig. 4. The parameters are listed in Table I. The circuit is supplied by the same stator voltage like FEA as shown in Fig. 5. Fig. 6 shows the current response of FEA and circuit model at rated load.

3. Performance evaluation

The parameters of the circuit are used to predict the torque and total resistive loss in the motor as follows.

$$T_{eq} = \frac{3}{2} p \mathrm{Im}\left\{ \underline{\psi}_s^* \underline{i}_s \right\} \quad (9)$$

$$P_{eq} = \frac{3}{2} k_s (R_s I_s^2 + R_e I_e^2 + R_c I_r^2 + R_{r2} I_{r2}^2) \quad (10)$$

Table II shows the total loss and torque calculated from the circuit in Section III and the time-discretized FEA as presented in Section II. The eddy-current loss in the motor is well modeled by a circuit. The error of the total stator loss or toque between the circuit and FEA is less than 3%.

TABLE I. ESTIMATED PARAMETERS OF CIRCUIT MODEL

	Linear		Nonlinear	
	without stator eddy current	including stator eddy current	without stator eddy current	include stator eddy current
R_s (Ω)	5.53E-03	5.53E-03	5.53E-03	5.53E-03
$L_{\sigma s}$ (H)	1.64E-04	1.84E-04	1.79E-04	1.49E-04
R_e (Ω)	1.328E+0	1.382E+0	1.595E+0	0.925E+0
L_{se} (H)	1.50E-04	1.05E-04	1.90E-04	3.42E-05
L_m (H)	6.61E-03	6.77E-03	6.22E-03	6.83E-03
R_c (Ω)	3.82E-03	3.75E-03	3.82E-03	3.83E-03
L_c (H)	5.78E-06	1.32E-05	2.87E-05	1.32E-05
L_{r1} (H)	3.75E-04	3.54E-04	3.32E-04	3.91E-04
R_{r2} (Ω)	2.17E-01	1.92E-01	1.77E-01	2.40E-01
L_{r2} (H)	1.26E-03	1.10E-03	1.10E-03	1.37E-03

TABLE II. TORQUE AND LOSS FROM FEA AND CIRCUIT MODEL

	Linear		Nonlinear	
	without stator eddy current	including stator eddy current	without stator eddy current	include stator eddy current
T_{eq} (N.m)	11237	11366	11158	11244
T_{FEA}(N.m)	11381	11382	11432	11429
error (%)	-1.27	-0.14	-2.40	-1.62
P_{eq} (W)	15817	16626	15934	16284
P_{FEA}(W)	15427	16195	15579	16059
error (%)	2.53	2.66	2.28	1.4

IV. CONCLUSIONS

A circuit model presented for the form-wound IM in electric drives is proposed and well identified by using a numerical approach from FEA data. The performance of the motor can be evaluated either from the time-discretized FEA or the appropriate circuit. The proposed circuit can take the eddy-current effect into account and well predict the resistive loss of motor for control purpose.

V. REFERENCES

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