

AC Copper Loss Modeling for Permanent Magnet Synchronous Motor Plant Model Based on Cauer Ladder Network Method

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This study proposes a novel AC copper loss modeling for a FEM-parametrized plant model of a permanent magnet synchronous motor (PMSM). In the proposed method, an equivalent circuit for the PMSM is combined with Cauer circuit derived from the Cauer ladder network (CLN) method to take account of frequency-dependent AC resistance due to armature windings composed of parallel round wires or flat wires. The effectiveness of the proposed plant model is validated though the loss analysis of PMSMs with full-pitch and short-pitch armature windings composed of parallel round wires.

Index Terms—AC copper loss, Cauer ladder network method, finite-element method, permanent magnet synchronous motor.

I. INTRODUCTION

IN the design of permanent magnet synchronous motor (PMSM) drive systems, a finite-element method (FEM)-parametrized plant model [1] is frequently used, in which the motor characteristics are represented by a nonlinear function of armature current and rotor position. To further improve the accuracy of the plant model, the equivalent circuit (EC) taking account of the iron loss due to carrier harmonics was proposed [2]. In addition, AC copper losses generated in the armature winding composed of flat wires were modeled using the Cauer circuit representation [3]. However, in the method proposed in [3], the equivalent Cauer circuit is derived from the analytical formula for rectangular conductors under the assumption of a locally uniform leakage flux distribution in the stator slots, which leads to the difficulty in applying the method to PMSMs with short-pitch armature winding and/or armature winding composed of many parallel wires.

In this paper, with this background, a novel AC copper loss modeling is proposed for a FEM-parametrized plant model of PMSMs. In the proposed method, the EC for the frequency-dependent armature resistance is derived from the Cauer ladder network (CLN) method [4]-[5], and it is combined with the PMSM plant model considering harmonic iron losses. Since the application scope of the proposed method is not limited by the shape of the conductors and the winding arrangement in the stator slots, it can be applied to PMSMs with the short-pitch windings as well as those with the full-pitch windings. Furthermore, it can take account of the circulating current loss generated in parallel round wires forming one turn of the armature winding. The effectiveness of the proposed plant model is validated though the loss analysis of PMSMs with armature windings composed of parallel round wires.

II. AC COPPER LOSS MODELING FOR PMSM PLANT MODEL

A. AC Copper Loss Modeling for Full-pitch Winding

Fig. 1 shows the proposed d- and q-axis ECs which take account of frequency-dependent armature resistance and harmonic iron losses due to carrier harmonics. The harmonic iron loss model consists of the iron loss resistor R_i and the inductor L_i which adjusts the influence of carrier harmonics [2].

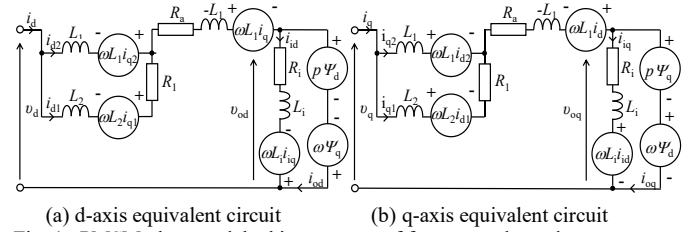


Fig. 1. PMSM plant model taking account of frequency-dependent armature resistance and harmonic iron losses.

In the case of the PMSM with the full-pitch winding, the Cauer circuit for the frequency-dependent armature resistance is derived from the single-port CLN method. Fig. 2 shows the concept of the proposed method when deriving the circuit parameters of the CLN. In this example, one turn is composed of three parallel conductors and three turns are installed in the slot, as shown in Fig. 2(a). Since the relative permeability of the stator and rotor cores is sufficiently large, it is assumed to be infinite in the proposed method. This situation is realized by applying appropriate Neumann boundary conditions (BCs). The CLN method based on the $A-\phi$ formulation [6]-[7] is applied to the simplified stator slot model shown in Fig. 2(b) to consider the circuit connections of wires between different turns. This approach, which is called EC with single-port CLN (ECSC), is compared with an EC with DC resistance (ECD).

B. AC Copper Loss Modeling for Short-pitch Winding

In the PMSM with the short-pitch winding, the influence of different phase current should be considered in a stator slot. The simplest approach is to take account of circulating currents in different phase armature windings, as shown in Fig. 2(c), by modeling them as parallel-connected conductors. In this case, the Cauer circuit for the frequency-dependent armature resistance is derived from the single-port CLN method. This method is called ECSC taking account of different phase winding (ECSCDP). Fig. 2(d) shows the simplified stator slot model for ECSCDP, where parallel-connected conductors in different phases are also taken into account. However, the influence of leakage flux due to the armature current flowing in a different phase cannot be considered, which may result in insufficient accuracy.

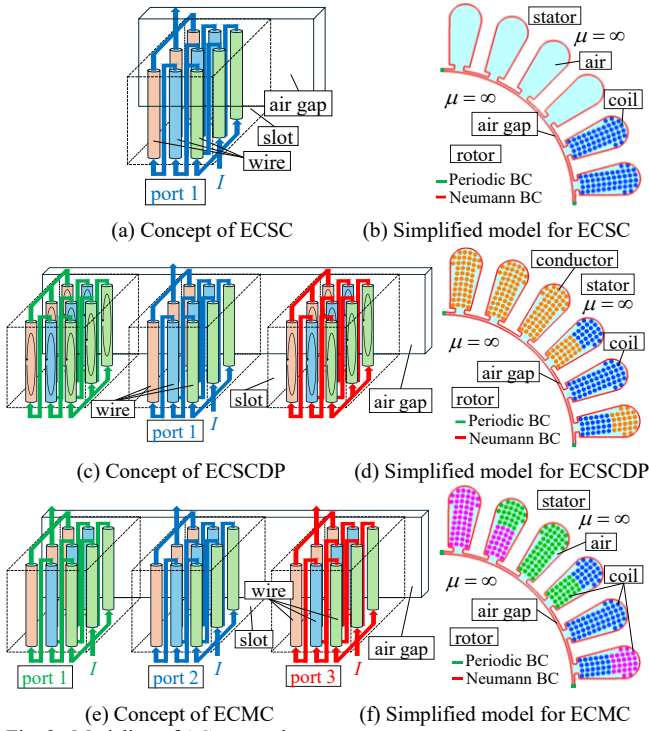


Fig. 2. Modeling of AC copper loss.

To overcome the difficulty, we propose the use of the multiport CLN method [8] in deriving the EC of frequency-dependent armature resistance. Figs. 2(e) and 2(f) illustrate the concept and the simplified stator slot model of this approach. By treating each phase winding as a separate port, the leakage flux caused by armature currents flowing in different phase windings within the same slot can be directly accounted for. This method is called EC with multiport CLN (ECMC).

III. NUMERICAL RESULTS

Fig. 3 illustrates the PMSM models with full-pitch and short-pitch windings composed of parallel round wires. The number of turns per slot is 4 in both models. Each turn of the winding is distinguished by a different colored number, and the wires with the same number are connected in series in Fig. 3. The pulse-width-modulation (PWM) waveform was generated using the sine-triangular modulation with a carrier frequency of $f_c = 5$ kHz and a DC voltage of $V_{DC} = 200$ V. The number of time steps per period is 3,600. The lookup tables for the plant model of the PMSMs are obtained from 8,869 FEMs.

Figs. 4 and 5 show the numerical results of copper and iron losses obtained from the plant models and FEM. By considering appropriate iron loss model [2] in the EC of a PMSM, the sufficiently good accuracy can be achieved, as shown in Figs 4(b) and 5(b). The copper loss obtained from the FEM differs significantly from that from ECD in the full-pitch model. This is because the circulating current loss of the PMSM shown in Fig. 3(a) is large, and therefore, the conventional DC resistance cannot evaluate the AC copper loss accurately. In contrast, since ECSC takes account of frequency-dependent AC resistance appropriately, it obtains almost the same copper loss as that from the FEM, as shown in Fig. 4(a). In the case of the short-

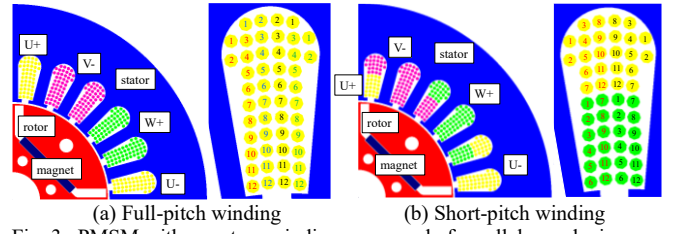


Fig. 3. PMSM with armature winding composed of parallel round wires.

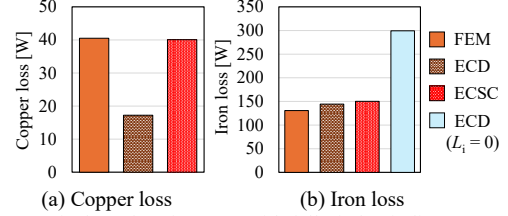


Fig. 4. Numerical results of PMSM with full-pitch winding.

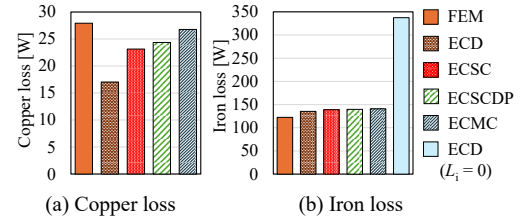


Fig. 5. Numerical results of PMSM with short-pitch winding.

pitch model, although ECSC improves the accuracy compared with ECD, the accuracy is further improved by the ECMC. This is because the ECMC considers the leakage flux caused by armature currents flowing in different phase windings directly. From the results, the effectiveness of the proposed methods can be confirmed. More numerical results on the PMSM with flat wires and the details of the proposed method will be included in the full paper.

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