

Design Optimization of Interior Permanent Magnet Synchronous Motors for HEV & EV

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ABSTRACT

This paper proposes a new motor design procedure for reducing motor loss in hybrid vehicles (HEV) and electric vehicles (EV). To find an optimum design in a short time, a non-linear magnetic circuit model was developed for interior permanent magnet synchronous motors (IPMSM). Speed-torque curves and motor losses were calculated based on this model. Combined with Energy Management Simulation, this model makes it possible to find an optimum motor design with minimum loss.

INTRODUCTION

Recently, achieving reductions in automobile CO₂ emissions are growing in importance because of environmental changes due to global warming and the depletion of oil resources. Automakers are actively developing HEVs and EVs that will contribute greatly to the reduction of CO₂ emissions through deceleration energy recovery and highly efficient driving operations.

Motors for HEVs and EVs are required to be small in size, lightweight, low cost, and have high efficiency. Permanent magnet synchronous motors (PMSM) are widely used to meet these needs, and PMSM design methods have been reported in a number of papers [1,2,3]. With HEV and EV motors, it is difficult to predict operation points, such as rotational speed and torque, at the design stage because they vary depending on energy management control methods and driving conditions. The operation points are also dispersed, so a new approach is needed to optimize motor design for fuel-economy. This paper proposes a design search method for fuel-economy optimization of HEV and EV motors.

Prediction of motor loss is essential in motor design for fuel-economy optimization. Motor loss can be divided into copper

loss and iron loss. Iron loss is difficult to predict because it is affected by numerous parameters, such as dimensions, material, frequency, and current. Thus, 3-D calculation and much know-how are required in finite element analysis (FEA) of iron loss [7]. The motor design process consists of two stages-the initial stage for examining rough specifications and the detailed design stage. In the initial examination there is a need to study specifications quickly at a level of accuracy that allows for relative comparison. In this regard, FEA has a disadvantage in that computations take a long time with limited current CPU capacity; FEA therefore cannot be applied in the initial design stage. To address this problem, we focused on the primary frequency component of the stator, which is the dominant cause of iron loss. We assumed that the primary frequency component of flux density waveforms in the teeth and the back yoke, if calculated in a short time, would be useful for examining motor design in the initial stage. Some papers reported that the permeance method, with consideration for magnetic saturation, was used to calculate torque with an accuracy equivalent to FEA [4,5,6]. This means that flux density can be predicted using this method, and it was therefore examined.

This paper proposes a method to search for a motor design that will realize fuel-economy optimization. It also reports the results of searching for optimum motor dimensions using the genetic algorithm (GA).

TEST MOTOR

Studies were made on an interior permanent magnet motor, concentrated winding, slot/pole/phase = 0.5, shown in Fig.1. Table 1 lists the typical motor parameters. Design for fuel-economy optimization was searched for by combining these parameters within target ranges.

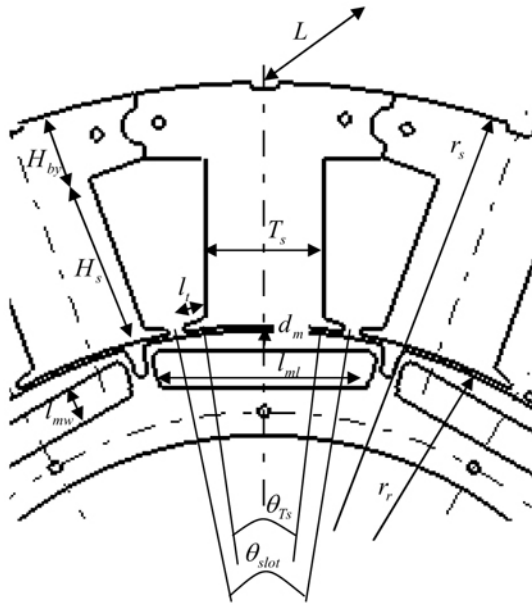


Fig.1. Cross-section of the IPMSM

Table 1. Dimensions of the motor

Number of Poles	P
Number of Turns	N_t
Stator outer radius	r_s
Rotor outer radius	r_r
Axial length	L
Stator teeth width	T_s
Stator teeth length	H_s
Stator Back Yoke Width	H_{by}
Stator teeth tip length	l_t
Magnet width	l_{mw}
Magnet length	l_{ml}
Depth of buried magnet	d_m

MOTOR POWER AND LOSS PREDICTION BY HIGH-SPEED MAGNETIC FIELD CALCULATIONS

Permeance method

In the permeance method, an equivalent magnetic circuit is used to represent a simplified motor configuration as shown in Fig.2. This method solves the determinant Eq. (1) to obtain magnetic flux, which is assigned in Eq. (3) to calculate torque and other magnetic characteristics. Reluctance in Eq. (1) is given by cross-sectional area, length, and permeability, as shown in Fig.3. This means that Eq. (1) can be solved once motor dimensions are set. However, magnetic saturation of the core causes relative permeability to change, which in turn causes reluctance to change (Eq. (2)). In this case,

calculations of flux linkage, or torque, become less accurate. Hence, the permeance method was regarded as unsuitable for studies of EV and HEV motors.

Regarding this issue, a paper discussed the fact that electromagnetic characteristics can be analyzed as accurately as FEA by considering magnetic saturation through iterative calculations and modeling a magnetic circuit for each stator-rotor positional relation [5]. This study takes magnetic saturation into account, but because the principal target is to seek a fuel-economy optimized design, more emphasis is placed on the computation speed and simplicity of models than on the accuracy of absolute values. Accordingly, a simplified equation has been adopted to determine permeance based only on stator dimensions, regardless of the rotor phase. Relative permeability in the presence of saturation can be obtained by iterative calculations of flux density given by Eq. (1) and the characteristic data (B - μ curve) of the electrical steel sheet used for the core. For the iterative calculations, Eq. (4) is used to prevent the divergence of relative permeability [5].

$$[R] \cdot [\phi] + [F_{winding}] + [F_{magnet}] = 0 \quad (1)$$

$$P = \frac{1}{R} = \frac{\mu_0 \cdot \mu_r \cdot S}{l} \quad (2)$$

$$Trq = \frac{3}{2} \frac{P}{2} (\phi_d \cdot I_q - \phi_q \cdot I_d) \quad (3)$$

$$\mu_r[i+1] = \mu_r[B(i)]^{(1-K_{damp})} \cdot \mu_r[i]^{K_{damp}} \quad (4)$$

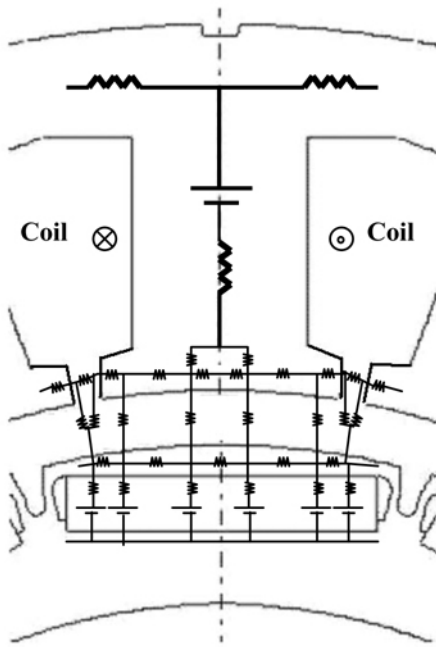


Fig.2. Magnetic Circuit

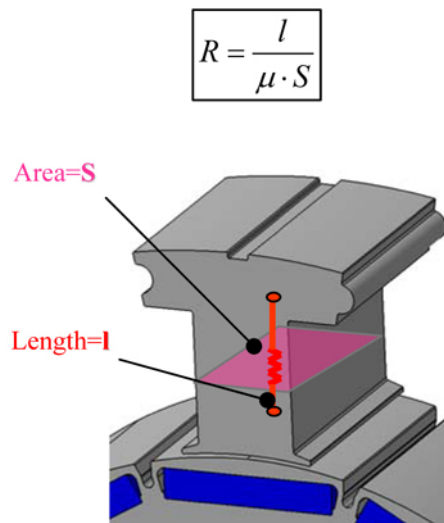


Fig.3. Permeance

Torque, flux and inductance calculations

No-load flux is given by Eq. (1) under the 0 current condition. Inductance is obtained from Eq. (5) two-dimensionally for each phase current amplitude and phase, giving consideration to non-linearity. To verify the computation accuracy of the proposed method, torque and inductance of the motor shown in Table 2 were calculated using the proposed method and FEA, and the results were compared. Fig.4 compares the torque values calculated with the proposed method and FEA, and Fig.5 compares the inductance values of the two methods. Because of the simplification of the equivalent magnetic circuit, the

calculated torque values deviate by 15% from the FEA values, and the inductance by a maximum of 25%. The calculated torque was corrected by multiplying by a correlation coefficient of 0.85. Discrepancies in the inductance values were tolerated as initial design errors, although inductance influences maximum power. For this verification, JMAG made by JSOL, Co., Ltd. was used as the FEA tool.

$$\begin{cases} L_d(I_{amp}, \beta) = \frac{\psi_d - \psi_{d-NL}}{I_d} \\ L_q(I_{amp}, \beta) = \frac{\psi_q}{I_q} \end{cases} \quad (5)$$

Table 2. Dimensions of the motor.

Number of Poles	P	12
Number of Turns	Nt	56
Stator outer radius	r_s	127[mm]
Rotor outer radius	r_r	84.9[mm]
Axial length	L	45.5[mm]
Stator teeth width	T_s	20[mm]
Stator teeth length	H_s	27.3[mm]
Stator Back Yoke Width	H_{by}	12.8[mm]
Stator teeth tip length	l_t	7[mm]
Magnet width	l_{mw}	6.2[mm]
Magnet length	l_{ml}	35[mm]

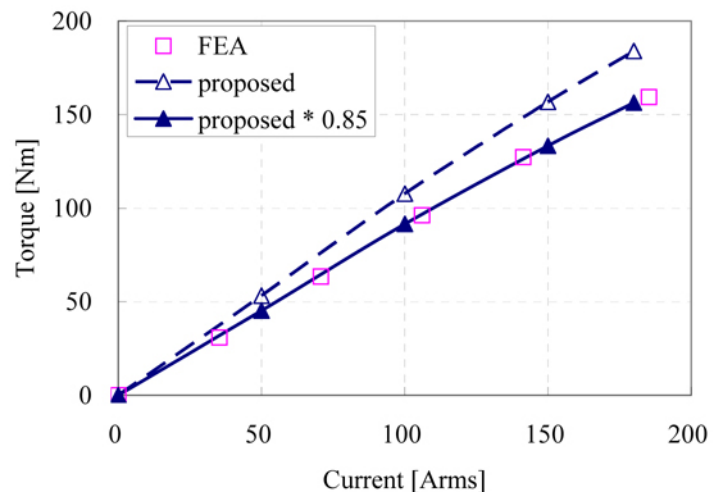


Fig.4. Comparison of Torque