NE-Map Based Design of IPM Synchronous Motor for Traction of EV

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***Abstract*—This study proposes a new coordinate system called NE-Map that has two axes presented by the no-load EMF and the number of windings per slot and investigates a design of IPMSM using this proposed coordinate system. Here, a design of rotor is implemented using a magnetic equivalent circuit. Also, currents and current phase angles are estimated through considering MTPA and a flux weakening control method and a design of stator is performed using this estimation. As these processes are presented by all EMFs and the number of windings per slot, it makes possible to verify the tendency in motor parameters and determine the final model by reflecting design constraints. Then, this process is applied to the design of a traction motor in Hybrid EVs and its validity is verified by comparing it with FEM and test data.**

***Index Terms*—Permanent magnet motors, Traction motors**

I. Rotor Design

In general most spatial constraints are included in such a traction motor. In this study it is assumed that the stack length is fixed and the outer diameter of the stator includes constraints.

Fig. 1 shows the magnetic equivalent circuit of IPMSM. In the calculation of the air-gap, air-gap flux density, and fundamental wave scale by simplifying it, it can be presented as Eq. (1), (2), and (3), respectively [1]. By assuming the no-load EMF and the number of windings per slot (the value given to the NE-Map), the series turns per phase and flux linkage caused by permanent magnets can be obtained using Eq. (4). Then, the rotor diameter and permanent magnet length presented by Eq. (5) can be obtained using an iterative algorithm that reduces error rates.

$$\phi_g = \frac{2k_{kb}k_{ls}}{1 + k_r \dfrac{g'\mu_R}{T_m}\dfrac{A_m}{A_g}}\left(\frac{\phi_r}{2} - \phi_{rib}\right) \tag{1}$$

$$B_g = \frac{k_{kb}k_{ls}}{1 + k_r \dfrac{g'\mu_R}{T_m}}\left(B_r - \frac{2B_{sat}T_{rib}}{W_m}\right) \tag{2}$$

$$\widehat{B}_{g1} = \frac{1}{\pi}\int_{-\pi}^{\pi} B_g(\theta)\cos(\theta)d\theta = \frac{4}{\pi}B_g \sin\frac{\theta_m}{2} \tag{3}$$

$$N_{ph} = \left(\frac{Q}{a \cdot m}\right)N_{tps}\ ,\ \lambda_{PM} = \frac{E_0}{\omega_{em}} \tag{4}$$

$$D_g = \frac{L_{stk}\widehat{B}_{g1}}{p\phi_{g1}}\ ,\ W_m = 2\left(\frac{D_g - g}{2} - T_{rib}\right)\sin\left(\alpha_m \frac{\pi}{2p}\right) \tag{5}$$

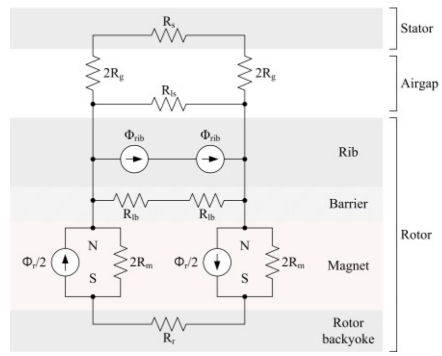


Fig. 1. Magnetic Equivalent Circuit of IPMSM

II. Stator Design

It is necessary to first determine the phase current for calculating a slot area in the design of a stator. It can be presented as Eq. (6) using the torque equation of IPMSM.

For obtaining the current that satisfies the target torque in Eq. (6), the flux linkage, d & q-axis inductance, and current phase angle are to be calculated. The flux linkage can be calculated using Eq. (4) shown in Section I. Then, d & q-axis inductance can be calculated using proposed method in [2].

$$T = \frac{3}{2}p\left(\lambda_{PM}I_a\cos\beta + \frac{1}{2}\left(L_q - L_d\right)I_a^{\,2}\sin 2\beta\right) \tag{6}$$

A. Currents and phase angles in the base speed

The phase angle in the MTPA control is given by Eq. (7). However, the current is first obtained for determining it. For solving it, the current and phase angle that satisfy the torque are to be simultaneously obtained using an iterative method under assuming its initial current. The initial current is determined for the condition of i_d=0, which generates magnetic torque only.

$$\beta = \sin^{-1}\left(\frac{-\lambda_{PM} + \sqrt{-\lambda_{PM}^{\,2} + 8\left(L_q - L_d\right)^2 I_a^{\,2}}}{4\left(L_d - L_q\right)I_a}\right) \tag{7}$$

B. Phase angles in the maximum speed

Because inductance values can be varied by the phase angle, an iterative routine is to be implemented while the phase angle in the base speed is determined by the initial value. Here, the d-axis current is the same as presented in Eq. (8). Then, it is necessary to verify the torque whether it satisfies the target specification in the final phase angle.

$$i_d = \frac{\lambda_{PM}L_d - \sqrt{\left(\lambda_{PM}L_q\right)^2 + \left(L_q^{\,2} - L_d^{\,2}\right)\left(\left(L_q I_a\right)^2 - \left(\dfrac{V_{om}}{\omega}\right)^2\right)}}{L_q^{\,2} - L_d^{\,2}} \tag{8}$$

The detailed process algorithm and the parameter design shown in Fig. 2 are to be described in the final manuscript.

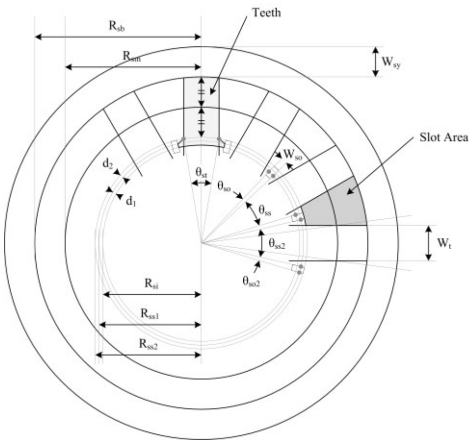
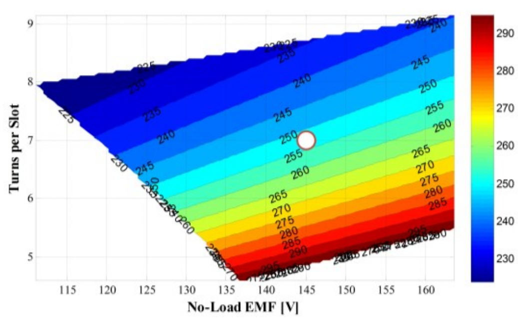


Fig. 2. Parameters for Stator Design

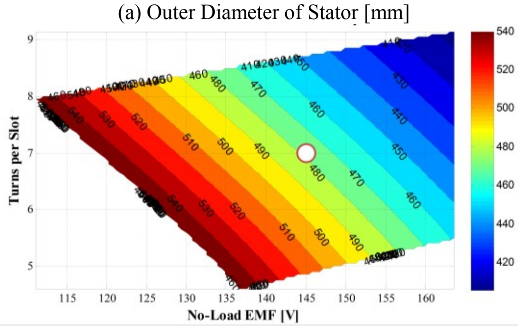
III. NE-Map Based Parameter Design

The final dimension and performance parameters obtained through the basic design process presented in Section I and II represent a single value only for the no-load EMF (E_0) and the number of windings per slot (N_{tps}) under the condition with the same stack length. By dividing a plan with x and y axes for E_0 and N_{tps} into grids, respectively, all parameters for each grid point can be calculated. These values presented at a coordinate plane as contours are called as Ne-Map. Also, the results calculated using the target specification and design coefficients are presented in Fig. 3.

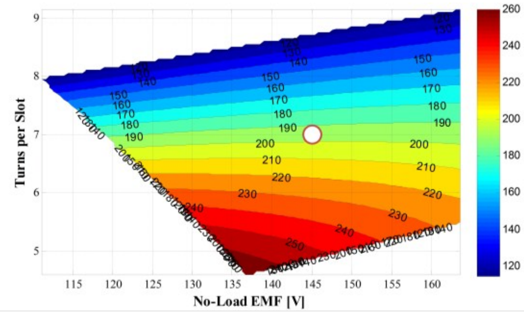
In the results, the bottom left side represents current constraint, the top left side represents torque constraint and the bottom right side shows a section that cannot be designed due to the limitation of the outer size of the stator. White dots exhibit the finally determined points and more parameters will be added to the final manuscript.



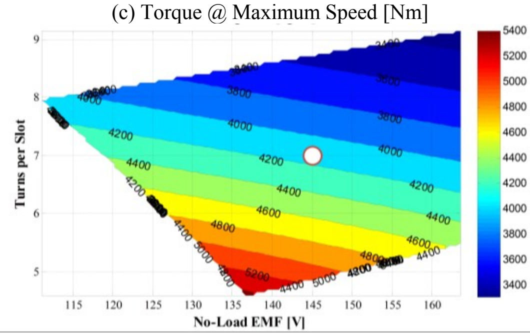
(a) Outer Diameter of Stator [mm]



(b) Phase Current @ Rated Speed [A_{peak}]



(c) Torque @ Maximum Speed [Nm]



(d) Base Speed [rpm]

Fig. 3. NE-Map Results

IV. FEM & Test

The final model presented by the proposed design process is presented in Fig. 4 and its verification is performed through FEM and tests. TABLE I shows the final results. It is verified that the NE-Map based design proposed in this study is valid.

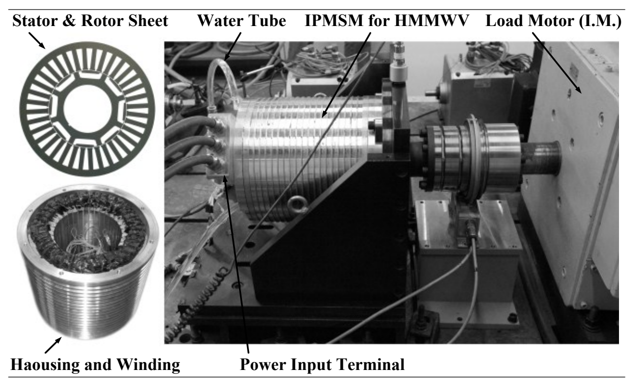


Fig. 4. Final Model and Test Dynamometer

TABLE I
COMPARISON OF FINAL RESULTS

Item		Proposed Method	FEA	Test
Rated Speed	Torque	403Nm	406Nm	402Nm
	Phase Voltage	242V_{peak}	241V_{peak}	235V_{peak}
Maximum Speed	Torque	196Nm	211Nm	202Nm
	Phase Voltage	347V_{peak}	353V_{peak}	355V_{peak}

References

[1] E. S. Hamdi, *Design of small electrical machines,* Wiley, 1994.

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