

Analytical Approach to Model a Saturated Interior Permanent Magnet Synchronous Motor for a Hybrid Electric Vehicle

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ABSTRACT

This paper presents an analytical approach to model an interior permanent magnet motor for a hybrid electric vehicle. Therefore, an analytical model for the calculation of parameters of an interior permanent magnet motor is presented. Furthermore, these parameter values are compared with good agreement to those from finite-element analysis and experimental data. An analytical model to simulate the behaviour of the motor and its control are developed and validated by comparison with experimental data. The thermal analysis of the motor prototype is also done. At the end, the presented model is embedded in the hybrid vehicle simulator and improvements are proposed, such as an analytical approach based on the finite element results to include the core saturation effect.

INTRODUCTION

Interior permanent magnet synchronous motors (IPMSMs) are considered as an attractive technology for hybrid electric vehicles (HEVs) because of their high efficiency and ability to operate in the field-weakening mode for extended speed range. In HEVs, during a driving cycle, the traction motor has to operate in both the constant-torque and constant-power regions, due to the wide speed range required by the driving cycle. IPMSMs are thus well adapted to these applications and the objective of this paper is to present an analytical method of modelling an IPMSM and its inverter to be embedded in a HEV simulator. The validation of the method is carried out on the PRIUS II motors, whose geometrical parameters are well-known. In a first section, an analytical model is developed to estimate the electromagnetic parameters of the V-IPMSM. The latter has been validated by using FEM analysis and the experimental results. The

following section of this paper consists of the modelling of the performance of the V-IPMSM using a steady state model in the Park frame. An ideal control algorithm which allows the motor to be driven with maximum-torque-per-ampere characteristic (MTPA) below the base speed has been integrated. This algorithm maintains also the maximum voltage limit of the motor under wide flux-weakening and the motor current limit under all conditions of operation accurately. The steady state model of the motor includes also the different losses of the motor such as iron losses and copper losses. The thermal model of the motor based on an equivalent lumped parameter circuit is presented also in this section. The final electric motor model is then used to generate the efficiency map of the electric motor using the calculated parameters. The simulated efficiency map is compared to the experimental one. In the third section, the developed model is integrated in the Toyota Prius II complete vehicle simulator. The latter is running on the New European Driving Cycle (NEDC) and some results of this simulation are given. Finally, in the last section an improvement of the analytical model to include the core saturation effect is proposed. This new model is used to generate the efficiency map of the motor and is compared to experimental data.

1. ANALYTICAL CHARACTERIZATION OF V-IPMSM

A picture of the rotor of the EM is presented in Figure 1. The rotor is structured with 8 poles. As it can be seen on the picture, each pole is constituted with two permanent magnets shaped in a V. A cross section of two half magnets and the associated stator and rotor back iron behind the magnet halves are well described on the Figure 2. An equivalent magnetic circuit based on the geometrical structure of this description is used to estimate the main electro-magnetic parameters used afterwards in the simulation model.

1.1. DESCRIPTION OF THE ANALYTICAL MODEL

A detailed magnetic equivalent circuit based on the geometrical structure of the motor (Figure 2) can be used to calculate the average air gap flux density as:

$$B_g = \frac{C_\Phi}{1 + \beta(1 + 2\eta + 4\lambda)} B_r \quad (1)$$

where B_r is the remanence of the magnet, $C_\Phi = A_m/A_g$ the flux concentration factor and A_g and A_m are the cross-sectional areas per pole of the air gap and magnet, respectively [2]. The magnetic reluctances of stator and rotor cores are ignored. The values of parameters in (1) are given by:

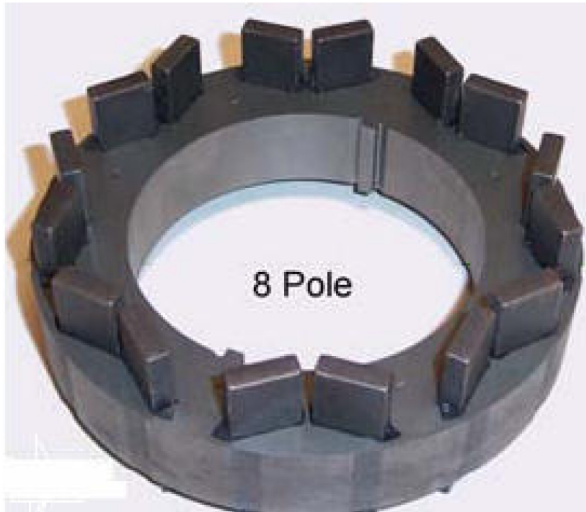


Figure 1. V-IPMSM motor rotor.

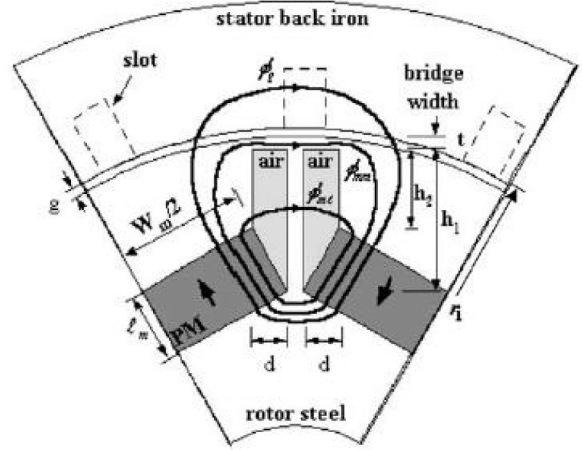


Figure 2. V-IPMSM motor structure.

$$\beta = \frac{\mu_{rec} K_c g}{w_m} C_\Phi \quad (2)$$

$$\eta = \frac{w_m (h_1 + h_2)}{4d\mu_{rec} l_m} \quad (3)$$

$$\lambda = \frac{1 + 1/\beta + 2\eta}{2(A_m / A_{mm})(B_r / B_s) - 4} \quad (4)$$

where g is the air gap length, K_c the carter coefficient, μ_{rec} the recoil permeability and $A_{mm} = tl$ represents the cross sectional area of the iron bridge above the nonmagnetic barriers with t and l being the bridge width and motor stack length, respectively. Also l_m and w_m denote the magnet length and width; and h_1 and h_2 represent the inner and the outer flux barrier heights, respectively. B_s is a limit of the leakage flux density in the bridge due to saturation. Using B_g from (1) in connection with (2) and (4), the maximum value of PM flux linkage is obtained as [2]:

$$\psi_m = \frac{4Dl}{\pi} \left(\frac{K_{w1} N_{ph}}{p} \right) B_g \sin\left(\frac{\pi}{2} \alpha\right) \quad (5)$$

where α is the pole-arc to pole-pitch ratio.

The d - and q -axis inductances can be expressed as [3]

$$L_d = \frac{3\mu_0 D l}{\pi p^2 g_d} k_{w1}^2 N_{ph}^2 + L_f \quad (6)$$

$$L_q = \frac{3\mu_0 D l}{\pi p^2 g_q} k_{wl}^2 N_{ph}^2 + L_f \quad (7)$$

where L_f is the per-phase leakage inductance [3] and

$$g_d = \frac{k_c g}{k_{lad} - (k_1 k_{ad} / (1 + \beta(1 + 2\eta + 4\lambda)))}$$

$$g_q = \frac{k_c g}{k_{lad}} \quad (8)$$

with

$$k_{lad} = \alpha + \frac{\sin \alpha \pi}{\pi}, \quad k_{laq} = \alpha + 0.1 + \frac{\sin 0.1\pi - \sin \alpha \pi}{\pi},$$

$$k_{ad} = \frac{\sin(\alpha \pi / 2)}{\alpha \pi / 2}$$

1.2. FEM MODEL

To validate the analytical methodology to calculate the electro-magnetic parameters of the motor, a FE model has been created and used on the described motor. 2D FE analysis allows the accurate determination of the inductances through magnet flux distribution solutions as it takes into account the actual distribution of the armature-winding, the details of cross section geometry and the nonlinearities of magnet materials.

1.2.1. Calculation of IPM Motor Parameters

The most effective approach to calculate saturated L_d , L_q and Ψ_{md} under rated load conditions and still preserve all the information about the saturation in the motor is to freeze the permeabilities in the nodes of the finite element mesh. Once the permeabilities are frozen the problem becomes linear and the parameters can be determined one at the time. Three linear magnetostatic simulations are needed to determine L_d , L_q and Ψ_{md} .

1.2.1.1. Saturated d - axis inductance

The first linear simulation is used to calculate L_d . The magnet flux is turned off by setting the magnet remanence B_r to zero. The current vector must be aligned with the d axis. Since the problem has become linear after freezing the permeabilities, the magnitude of the current vector can be chosen arbitrarily. If the magnitude is chosen to be I_R A and in order to align the current vector with the d axis, the instantaneous phase currents have to be defined as:

$$i_a = I_R \text{ A}, i_b = i_c = -\frac{I_R}{2} \quad (9)$$

The d and q components of the current vector are then

$$i_d = I_R \text{ A}, \quad i_q = 0 \quad (10)$$

The d- axis inductances can be calculated as:

$$L_d = \frac{\Psi_d}{i_d} \quad (11)$$

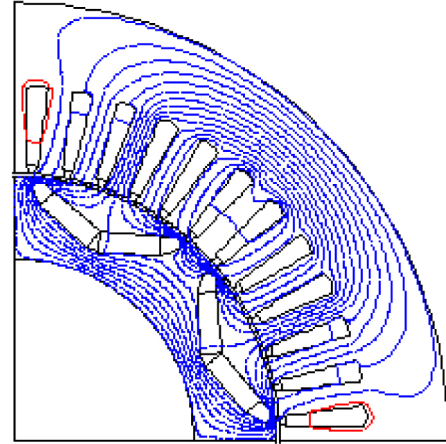


Figure 3. Flux distribution due to d - axis stator current.

Inductance L_d only takes into account the flux linkage in the core region. The 2-D FE simulation neglects the leakage flux in the end region. Hence, the end winding leakage inductance L_{ew} is calculated separately using the empirical formula [4] and added to L_d to calculate the total L_d .

1.2.1.2. Flux linkages Ψ_d

The flux linkages Ψ_d is determined from the flux linkages of phases a, b and c by Park transformation. For instance, the a-phase flux linkage is calculated as a sum of the flux linkages of all a-phase coils. The flux linkage of each individual coil is equal to the line integral of the magnetic vector potential A_z along the contour of the coil. In a 2-D FE model this integral is proportional to the difference between the average potentials in the meshed geometric regions occupied by the coil sides located in different pole regions. The a-phase flux linkage is then

$$\Psi_a = p \sum_{k=1}^{Q_{coil}} \Psi_{coilk} = p \sum_{k=1}^{Q_{coil}} \frac{1}{S} \left(\int_{S_1} A_z dS - \int_{S_2} A_z dS \right) N_c I_r \quad (12)$$

where Q_{coil} is the number of coil sides per phase in one pole region, p is the number of pole pairs, N_c is the number of turns of each coil, I_r is the length of the stator core and S is

the cross-section of the coil region. Subscripts 1 and 2 denote coil sides located in different pole regions.

1.2.1.3. Saturated q-axis inductance

The inductance L_q is calculated in a similar manner, only in this case the current vector needs to be aligned with the q axis as shows on [Figure 4](#). The phase currents are then

$$i_a = 0; i_b = -i_c = \frac{\sqrt{3}I_R}{2} \quad (13)$$

which in turns gives:

$$i_d = 0, \quad i_q = I_R \quad A \quad (14)$$

The q -axis inductances is estimated as

$$L_q = \frac{\psi_q}{i_q} \quad (15)$$

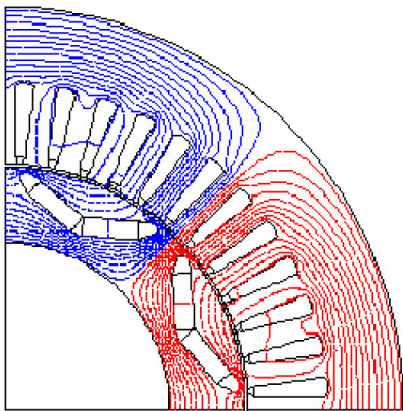


Figure 4. Flux distribution due to q - axis stator current.

1.2.1.4. Flux linkages Ψ_{md}

This simulation is used to calculate magnet flux linked by the armature winding. In this case the magnets are turned on by setting the magnet remanence B_r to the actual value while phase currents are equal to zero. The field solution is shown in [Figure 5](#). The flux linkages of the phase windings are calculated using the previously described procedure.

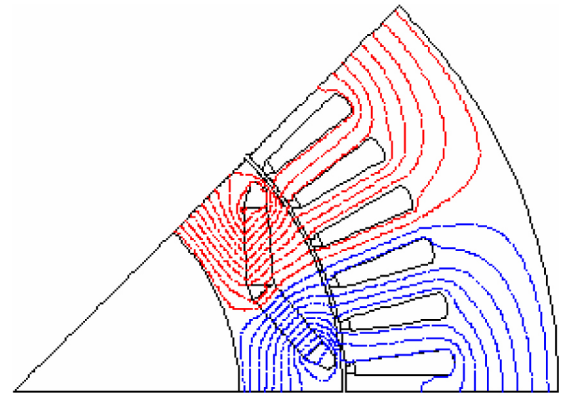


Figure 5. Flux distribution due to permanent magnet poles.

1.3. FINAL MODEL VALIDATION WITH EXPERIMENTAL RESULTS

The presented analytical and FE models have been used to estimate the electro-magnetic parameters of the electric motor of the Toyota Prius II vehicle, whose geometrical parameters are well-known [6] and [7]. These electro-magnetic parameters have also been identified with experimental tests. [Table 1](#) gives a comparison between the results of experimental tests, FE and analytical models. The analytical predictions of the unsaturated parameters are compared to those from FEA and measurement with good agreement (relative error inferior to 10%).

Table 1. Electro-magnetic parameter result comparison

	Analytical model	FE model	Experimental tests
Ψ_{md} (Wb)	0,185	0,198	-
L_d (mH)	1,90	2,00	2,10
L_q (mH)	4,90	5,20	5,00

2. SIMULATION MODEL OF THE V-IPMSM

The simulation model takes into account different aspects:

- Electric equations in the d/q axis reference frame
- First level of control strategy to determine d-q axis currents
- Equations to model the different losses occurring in the EM

These aspects are illustrated in the following sections.

2.1. EQUATIONS FOR ELECTRIC MODEL

In the rotor-fixed d/q reference frame, neglecting the ohmic voltage drop and assuming steady state operation, the voltage equations of the V-IPMSM are given by: