Design of Saliency-Based Sensorless Controlled IPMSM with Concentrated Winding for EV Traction

Myung-Seop Lim[1], Seung-Hee Chai[1], Byeong-Hwa Lee[1],
Jung-Pyo Hong[1], *Senior Member*, *IEEE,* and Jung-Ik Ha[2]
[1]Department of Automotive Engineering, Hanyang University, Seoul 133-791, Korea
[2]School of Electrical and Computer Engineering, Seoul National University, Seoul 151-742, Korea
E-mail Address: hongjp@hanyang.ac.kr

***Abstract*—This paper presents the design process of a sensorless-oriented interior permanent magnet synchronous motor (IPMSM), based on spatial saliency for traction in an electric vehicle. A prototype, sensorless controlled IPMSM, is proposed. However, it tends to have high cogging torque and torque ripple. The design method in the paper pursues fulfilling not only a stable sensorless drive capability, but low cogging torque and torque ripple. Therefore, some design factors are examined to figure out why the machine with concentrated winding has a result which is conflicting between sensorless drive and cogging torque/torque ripple. Furthermore, focusing on the examinations, improved model (16-pole, 24-slot, 115Nm-14kW IPMSM) for electric vehicle traction will be suggested. Lastly, the validity of the simulation results will be verified by comparing with experimental results of the prototype.**

***Index Terms*—cogging torque, high frequency injection, notch, sensorless control, space harmonic, spatial saliency, torque ripple.**

I. Introduction

Today an interior permanent magnet synchronous motor (IPMSM) is usually employed as electric vehicle (EV) traction because of its high torque density. Fulfilling the best performance of the machine, a position sensor is essentially needed for machine vector control. However, it increases the motor cost, volume and complexity, and decreases reliability of the machine. In addition, using the position sensor would be a latent critical defect of an IPMSM, especially, for a vehicle traction application. Because if the sensor is broke down, the driver cannot control the vehicle and the situation should make one shocked. For these reasons, nowadays, design method of an IPMSM for sensorless drive is getting important.

In an IPMSM, permanent magnets (PM) have an effect on not only induced back EMF, but spatial saliency distribution. Non-uniformly positioned PM in the rotor makes discrepancy between *d* and *q*-axis impedance. This is because *d*-axis flux path is saturated easily by the PM and high *d*-axis reluctance due to the fact that low permeability of the PM which is located on *d*-axis. This result brings about spatial saliency. Therefore, with high-frequency signal injection method, the position of rotor could be estimated based on the saliency [1]. As shown in Fig. 1, if voltage injection angle is 0 degree when the voltage injected on *d*-axis, the inductance should be the minimum value because of the impedance. However, it is not easy to estimate the rotor position under load conditions, since inductance profile is distorted by input currents [2].

In this paper, capability of sensorless drive is predicted as showing *d, q*-axis inductance pattern depending on the rotor position by fixed permeability method and *d*, *q*-axis

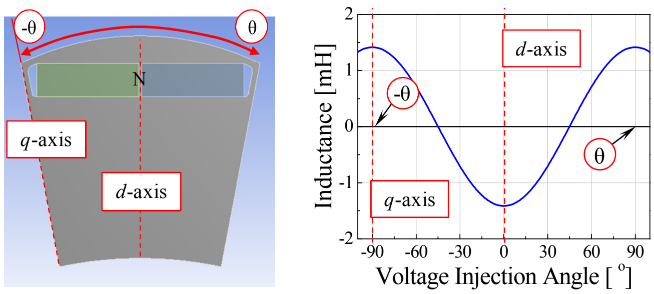


Fig. 1. Inductance profile depending on injection angle

transformation of inductances. The paper shows the simulation results of the sensorless-oriented prototype. However, to overcome the drawbacks of the prototype such as high cogging torque and torque ripple, some design factors (notch, chamfer, eccentricity and pole angle) will be analyzed with full factorial design (FFD). Through the design optimization of the factors, improved model fulfilling the requirements both sensorless drive and low cogging torque/torque ripple will be proposed. At last, the validity of simulation results will be verified by comparing with experimental results of the prototype.

II. Computing of Inductance for Saliency-Based Sensorless Drive

A. Fixed Permeability Method

Fixed permeability method is used for calculating the inductance profile mentioned above. Fig. 2 shows the process of this method to find a phase inductance. The first step is finite element analysis (FEA) including permanent magnets. At this time, nonlinear FEA has to be done, considering saturation of core. The second step is fixing the permeability of the each element. After then, linear FEA is conducted with eliminating the PM. At this point, by injecting 1-phase coil with unit current, self and mutual inductances can be obtained. This process should be iterated, changing the rotor position because *d*-*q* inductance's changing pattern according to the position of the rotor is important key to sensorless control.

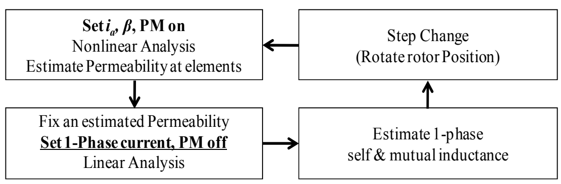
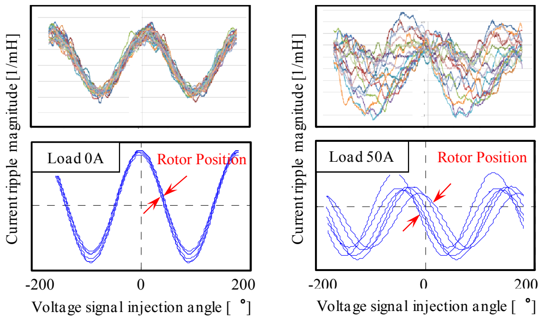


Fig. 2. Flow chart of fixed permeability method



(a) No-load condition (b) 50A load condition

Fig. 3. Estimated current ripple (lower) and experimental result (upper)

B. Matrix Transformation of Inductance

With (1), a 3-phase inductance matrix determined by fix permeability method can be transformed to *d*, *q* axis space harmonic profiles depending on a voltage injection angle.

$$L_{dq}^{r}=\frac{3}{2}T_{\theta_r}T_{dq}L_{AB}\left(T_{\theta_r}T_{dq}\right)^{T}. \qquad (1)$$

where L_{AB} is 3-phase inductances at stationary coordinate. T_{dq} and $T_{\theta r}$ are the *d*, *q* axis transform and rotational transform coefficient. Fig.3 illustrates pattern of *d*-axis current ripple (inverse values of inductances) as changed the rotor position under the no-load and load conditions.

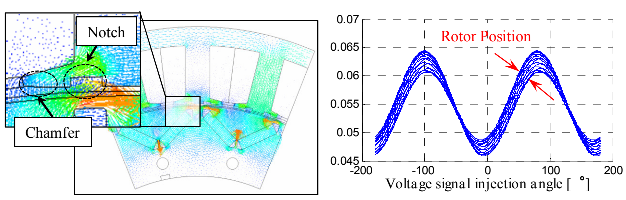
III. Analysis of Design Factors for an Sensorless-Oriented IPMSM

A. Magnetic Load and Electric Load

IPMSM for sensorless drive should have less-moving and less-changing *d-q* inductance profile as a rotor position under the load conditions. It requires sinusoidal flux distribution and minimum flux distortion by armature reaction at the air gap. This means that the machine has to be designed higher magnetic load than electric load as much as possible for taking advantages of sensorless drive. Eq. (2) and (3) describes magnitude of magnetic load and electric load. B, L_{stk}, N_{ph} and D_r mean flux density, stack length, number of turn phase and rotor diameter respectively. p and m are pole-pair number and number of phase.

$$\phi = B\times\frac{\pi D_r L_{stk}}{2p} \qquad [Wb]. \qquad (2)$$

$$A=\frac{2mN_{ph}I}{\pi D_r} \qquad [A/m]. \qquad (3)$$



(a) Prototype with chamfer and notch (b) *d*-axis inductance profiles

Fig. 4. Sensorless-oriented model (left), and the inductance profiles as changed the rotor position (electrical angle: 0~180 degree) (right)

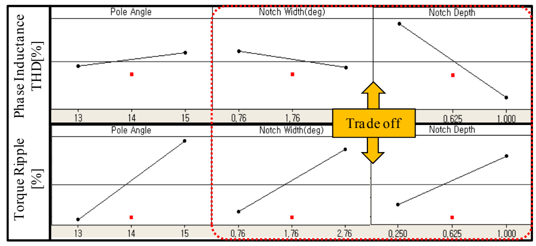


Fig. 5. Full factorial design

B. Design Factors in a Rotor and Stator

In this paper, some design factors are analyzed to find out their effects on the sensorless-oriented machine. As a result, eccentricity has a negative effect on sensorless drive. Pole angle is not considerably related to the sensorless control, but only affect cogging torque and torque ripple. On the other hand, chamfer and notch have a positive effect on sensorless drive. The reasons of the analysis results are discussed in the full paper. Fig.4 shows that the design of the prototype (115Nm-14kW) with chamfers and notches. It shows hardly moving *d-q* inductance profiles according to the rotor position under the maximum load condition. Given that the effects of the factors, it infers that saturating tooth-tip of the stator has a positive effect on saliency-based sensorless drive. However, it tends to bring about high cogging torque and torque ripple. Thus, optimized combination of notch size, chamfer and pole angle is required for achieving a better sensorless controlled and low cogging torque/torque ripple machine.

IV. Conclusion and Future Work

This paper presented calculating process of *d-q* inductance pattern depending on the rotor position. This process is needed to expect sensorless control capability. In addition, some factors were examined to clarify the design method of sensorless drive IPMSM. It infers that design concepts of machines for sensorless drive and EV traction are conflicted.

In the future, based on the FFD shown as Fig.5, optimization is going to be conducted. The design parameters and the objective functions are as follows. The design parameters: notch width and depth, and pole angle. The objective functions: phase inductance total harmonic distortion (THD), cogging torque and torque ripple. For quantification of sensorless control capability, phase inductance THD will be used. This is because the harmonics cause shaking of *d-q* inductance profiles as changed the rotor position. Furthermore, improved model which is fulfilling the requirements not only sensorless drive, but low cogging torque and torque ripple will be proposed. Lastly, the validity of the simulation results will be verified by comparing with experimental results of the prototype.

References

[1] Sungmin Kim, Jung-Ik Ha and Seung-Ki Sul, “PWM switching frequency signal injection sensorless method in IPMSM,” *IEEE Trans. on Ind. Applicat.*, vol.48, no.5, pp. 1576-1587, 2012.

[2] Y. Kano, T. Kosaka, N. Matsui and M. Fujitsuna, “Sensorless-oriented design of concentrated winding IPM motors for HEV drive application,” *in conf. Rec. of the 2012 IEEE ICEM*, pp. 2709-2715, 2012.