Design of IPMSM having High Power Density for Position Sensorless Operation with High-frequency Signal Injection And the Method of Calculating Inductance profile

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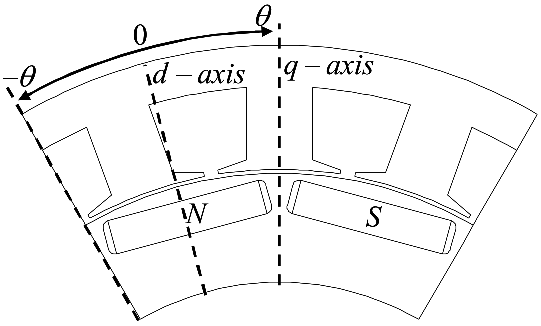
Abstract — This paper estimates inductance profile well adapted to position sensorless control method based on the high frequency signal injection and proposes a direction to design for sensorless control in interior permanent magnet synchronous motor(IPMSM) having a high power density. In sensorless control, controller calculates the position of rotor at smallest d-axis inductance from high frequency injection. In order to satisfy this characteristic, this paper designs a motor having a large magnetic loading and a small electric loading. Inductance is calculated by the FEM using frozen permeability method and voltage equations of d-q axis are used to analyze characteristics of IPMSM such as torque, output power, current angle and efficiency.

I. INTRODUCTION

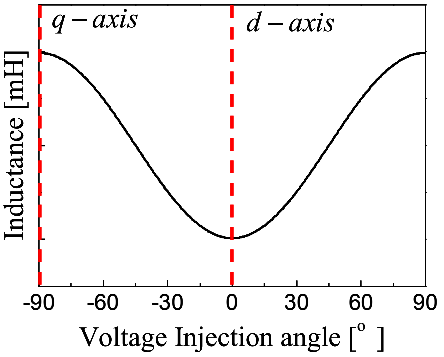
An IPMSM(Interior Permanent Magnet Synchronous Motor) having high out power is widely applied to industries at the appropriate range for high speed and mechanical stability. But, the problem has been brought up about the position sensor attached IPMSM for position estimating, because the position sensor is expensive and occupy much places. During last decade, position sensorless operation of IPMSM has been investigated extensively. When the rotating speed of IPMSM is high enough, the rotor's position information can be calculated from voltage equations of IPMSM [1],[2]. However, at standstill and low rotating speed, the voltage equations have severe error due to nonlinearity of PWM inverter, and rotor's position information can not be estimated from Back-EMF because it is very low level. Therefore, in that case, rotor's position information is detected from the inductance having minimum value as a high-frequency injection angle. Thus, it is necessary to design motor possessing minimum inductance value at d-axis according to high-frequency injection angle regardless of current, current angle and rotor position.

In Fig. 1, the inductance profile acted on high frequency injection angle is shown up. It is high-frequency injection angle 0° that the position is located on the center of permanent magnet d-axis, as shown in Fig. 1(a), then inductance carries the minimum value, as shown in Fig. 1(b). At q-axis, on the contrary to this, the inductance has the maximum value.

Generally, when rotor is rotated, it is hard to get minimum inductance value at d-axis in IPMSM because flux weakening control is used to reduce field flux. Therefore, this paper estimates inductance profile well adapted to position sensorless control method based on the high frequency signal injection and proposes a direction to design for sensorless control in interior permanent magnet synchronous motor(IPMSM) having a high power density.



(a) An example shape of the IPMSM



(b) An inductance profile as voltage injection angle for sensorless control

Fig. 1. A qualification of the inductance for sensorless control

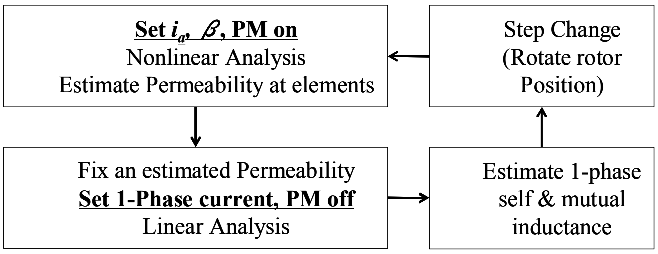


Fig. 2. The flow chart of frozen permeability method

II. METHOD OF ESTIMATING INDUCTANCE PROFILE

A. *Frozen Permeability Method*

Inductance is calculated by the FEM using frozen permeability method for estimating minimum d-axis inductance as high-frequency injection angle. In Fig. 2, A flow chart is presented to summarize the method used to calculate the flux linkages into components which is contributed by the stator currents and rotor magnets based on frozen permeability[4]. First, set exciting 3-phase current i_a with current angle β at specific load condition, and remain permanent magnet 'on' state. Then nonlinear analysis estimates permeability on all Finite elements at that load condition. And, fix the permeability of elements which is estimated with analysis. Second, set a 1-phase unit current and eliminates permanent magnet 'off' state. Then linear analysis with fixed permeability calculates linkage flux at phase. That is, from this linkage flux by only armature reaction, phase inductance about rotor position is estimated by dividing linkage flux with phase current, as shown in equation (1).

$$L = \frac{\Psi_{ar}}{I_a} \tag{1}$$

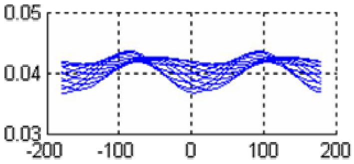
Where, L is a phase inductance, I_a is a phase current, Ψ_{ar} is a linkage flux of armature reactions.

This technique can be used in combination with either the magnetic circuit model described in the preceding section or the Finite Elements Analysis. After estimating the phase inductance about rotor position, 3-phase inductances matrix, according to the high-frequency injection angle, depending on rotor position, can be composed.

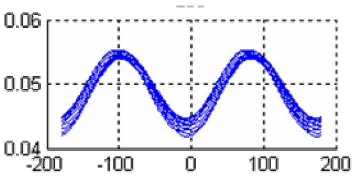
B. *Matrix Transformation*

From (2) ~ (10), the inductance matrix in the stationary 3-phase coordinate system is transformed the inductance matrix in the rotationary d-q axis coordinate system.

$$L_{AB} = \begin{bmatrix} L_A + L_B\cos 2\theta_r & -\frac{1}{2}L_A + L_B\cos 2\left(\theta_r - \frac{\pi}{3}\right) & -\frac{1}{2}L_A + L_B\cos 2\left(\theta_r + \frac{\pi}{3}\right) \\ -\frac{1}{2}L_A + L_B\cos 2\left(\theta_r - \frac{\pi}{3}\right) & L_A + L_B\cos 2\left(\theta_r + \frac{\pi}{3}\right) & -\frac{1}{2}L_A + L_B\cos 2\theta_r \\ -\frac{1}{2}L_A + L_B\cos 2\left(\theta_r + \frac{\pi}{3}\right) & -\frac{1}{2}L_A + L_B\cos 2\theta_r & L_A + L_B\cos 2\left(\theta_r - \frac{\pi}{3}\right) \end{bmatrix} \tag{2}$$



(a) Inductance profile in general In-Wheel type IPMSM



(b) Inductance profile in improved In-Wheel type IPMSM

Fig. 3. Inductance profile as voltage injection angle
(x : Voltage injection angle [°], y : Inductance [mH/30])

$$\lambda_{abcs} = L_{AB} i_{abcs} \tag{3}$$

$$\lambda^r_{dqs} = L^r_{dq} i^r_{dqs} = T_{\theta_r} T_{dq} \lambda^r_{abcs} = T_{\theta_r} T_{dq} L_{AB} i_{abcs} \tag{4}$$

$$L^r_{dq} i^r_{dqs} = L^r_{dq} T_{\theta_r} T_{dq} i_{abcs} = T_{\theta_r} T_{dq} L_{AB} i_{abcs} \tag{5}$$

$$L^r_{dq} T_{\theta_r} T_{dq} = T_{\theta_r} T_{dq} L_{AB} \tag{6}$$

$$L^r_{dq} T_{\theta_r} = \frac{3}{2} T_{\theta_r} T_{dq} L_{AB} T^T_{dq} \quad \left(\because T_{dq} T^T_{dq} = \frac{2}{3} I\right) \tag{7}$$

$$L^r_{dq} = \frac{3}{2} T_{\theta_r} T_{dq} L_{AB} T^T_{dq} T^T_{\theta_r} \quad \left(\because T_{\theta_r} T^T_{\theta_r} = I\right) \tag{8}$$

$$L^r_{dq} = \frac{3}{2} T_{\theta_r} T_{dq} L_{AB} \left(T_{\theta_r} T_{dq}\right)^T \tag{9}$$

$$T_{\theta_r} = \begin{bmatrix} \cos\theta_r & \sin\theta_r \\ -\sin\theta_r & \cos\theta_r \end{bmatrix}, T_{dq} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{10}$$

Where, L_{AB} is the inductance matrix in the stationary 3-phase coordinate system, L_A is a mean value of the inductance, L_B is the amplitude of the inductance, $L^r{}_{dq}$ is the inductance matrix in the rotationary d-q axis coordinate system, $T_{\theta r}$ and T_{dq} is transformation matrix of high-frequency injection angle and d-q axis.

C. *Review of Inductance calculating Method*

In Fig. 3, the inductance profile is calculated from general and improved In-Wheel type high power density IPMSM model with frozen permeability method and d-q axis matrix transformation. A number of profiles of each graph are the inductance profile calculated by different rotor position. As shown in Fig. 3(a), as rotor position rotates, the inductance profile shift right direction. It means, the inductance does not have minimum value at the center of permanent magnet, d-axis. Therefore, rotor position cannot be estimated by inductance profile and it cannot use a sensorless control. On the other hand, as shown in Fig. 3(b), the inductance profile does not shift. It means, the inductance has minimum value at the center of permanent magnet, d-axis. Therefore, rotor position can be estimated by inductance profile and it uses a sensorless control.

III. DESIGN OF MOTOR FOR SENSORLESS CONTROL

A. *Sensorless control for In-Wheel type IPMSM*

IPMSM is applied to industrial engineering widely due to the mechanical hardness at high speed range and the high power density. Fig. 4 shows In-Wheel type IPMSM for vehicle traction. Such as IPMSM has a high power density. Because of the strong armature reaction, it is difficult to have the minimum value of inductance at the center of permanent magnet, d-axis, as any rotor positions. So, this chapter proposes a direction to design for sensorless control in IPMSM having a high power density.

In sensorless control, controller estimates the position of rotor at smallest d-axis inductance from high frequency injection. Thus, the motor using this sensorless control method is designed to have inductance profile taking the smallest value at d-axis. In order to satisfy this characteristic, this paper designs a motor having a large magnetic loading and a small electric loading:

$$A = \frac{Total\ ampere-conductors}{Airgap\, circumference} = \frac{2mN_{ph}I}{\pi D_r} \quad [A/m] \tag{1}$$

$$\phi = B \times \frac{\pi D_r L_{stk}}{2p} \quad [Wb] \tag{2}$$

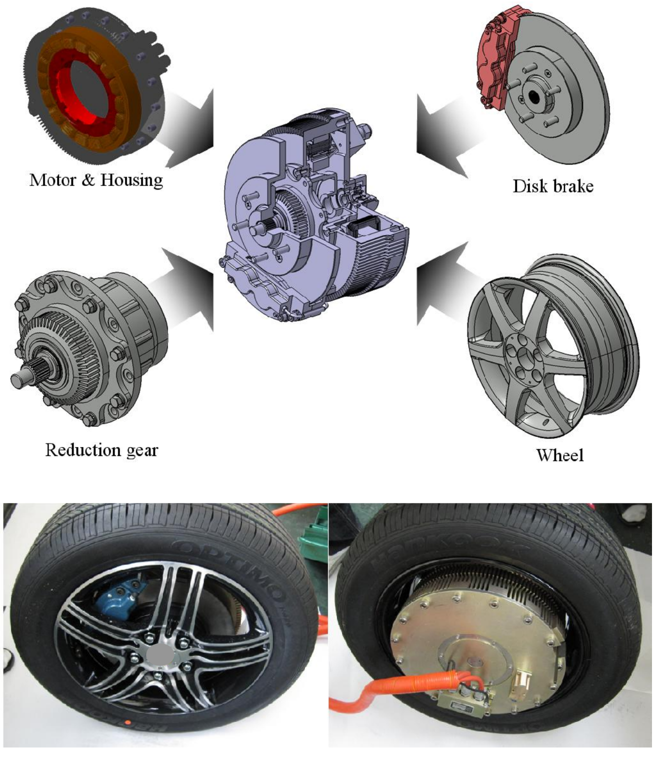
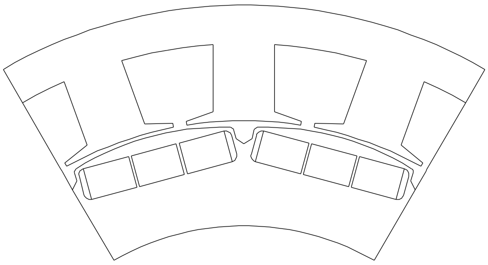
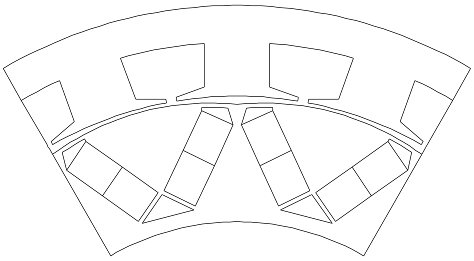


Fig. 4. In-Wheel type IPMSM for vehicle traction



(a) Prototype In-Wheel motor



(b) Improved In-Wheel motor

Fig. 5. Two models of In-Wheel type IPMSM

Where, m is the number of phase, I is the phase current, N_{ph} is series turns per phase, B is the mean flux density on rotor surface.

In Fig. 5, one of the improved In-Wheel type IPMSM is designed for sensorless control and compare it with prototype In-Wheel type IPMSM. Table 1. is the motor parameters and main dimension of two motors. In order to increase the effect of magnetic loading, it is not appropriate that using only strong residual magnetic flux density of permanent magnet, because of demagnetization in high temperature and a price problem. As shown in Fig. 5, an improved In-Wheel type model is applied V-shape to increase the amount of the magnet used. And it has a large rotor diameters and proper residual magnetic flux density of permanent magnet. These are effective to increase the magnetic loading and to decrease the electric loading.

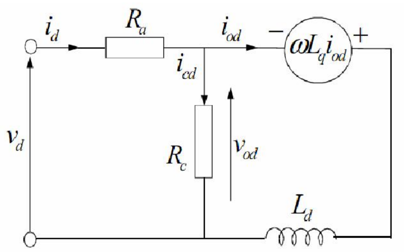
TABLE I
MOTOR PARAMETERS AND MAIN DIMENSIONS

	Prototype motor	Improved motor
Pole / slot number	12/18	12/18
DC link Voltage [V_{DC}]	320	320
Max. current [A_{rms}]	200	200
Max./rated Power [kW]	25/10	25/10
Max./rated speed[rpm]	8000/1900	8000/1900
Max. torque[Nm]	125	125
Stator outer dia.[mm]	270	270
Rotor outer dia.[mm]	203	216
Stack length[mm]	35.5	35.5
Current density[A/mm^2]	About 15	About 15
Coil fill factor[%]	55	55
Remanence flux density[T]	1.126 @100°C	1.267 @100°C

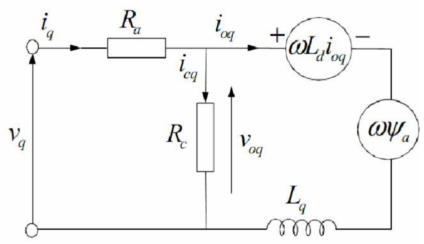
TABLE II

ELECTRIC & MAGNETIC LOADING OF TWO MOTORS

	Electric loading [kA/m]	Magnetic loading [mWb]
Prototype motor	107.25	1.04
Improved motor	68.97	1.34



. (a) d-axis equivalent circuits



(b) q-axis equivalent circuits.

Fig 6. Equivalent circuits of IPMSM.

Table 2. shows the electric loading and the magnetic loading of two motors. As shown in Table 2, Electric loading of the improved motor is smaller than those of the prototype motor. And Magnetic loading of the improved motor is larger than those of the prototype motor. From this results, it is expected that the inductance of improved motor has the minimum value at the center of the magnet, d-axis, without variation of rotor position. In other words, the improved IPMSM model is effective motor for sensorless control.

B. *Characteristics of IPMSM for sensorless control*

In order to calculate characteristics of IPMSM, d-q equivalent circuit analysis is employed. Equivalent circuit frame including iron loss are presented Fig 6. The mathematical model of the equivalent circuits is given as follow equations. Iron loss is considered by equivalent resistance R_c. Using (11), (12) and (13), the d- and q-axis voltages and effective torque equations are given respectively.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1+\frac{R_a}{R_c}\right)\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \quad (11)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\psi_a \end{bmatrix} \quad (12)$$

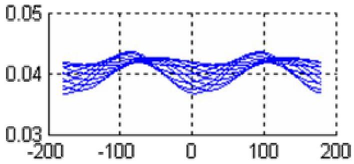
$$T = P_n\left\{\psi_a i_{oq} + (L_d - L_q) i_{od} i_{oq}\right\} \quad (13)$$

Where i_d and i_q are d- and q-axis component of armature current, i_{cd} and i_{cq} are d-and q-axis component of terminal voltage, R_a is armature winding resistance per phase, R_c is iron loss resistance, Ψ_a is flux linkage of permanent magnet per phase (rms value), L_d and L_q are d-and q-axis armature self inductance, and P_n is pole pair [5].

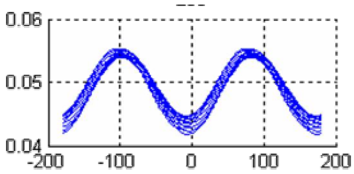
IV. RESULTS

A. *Inductance of IPMSM*

Fig. 7. is the inductance of two IPMSM as voltage injection angle. As shown in Fig. 7(b), the inductance profile does not shift without variation of rotor position. Thus, the inductance has minimum value at the center of permanent magnet, d-axis. Therefore, rotor position can be estimated by inductance profile and the improved motor designed to have inductance profile taking the smallest value at d-axis is better than prototype motor for sensorless control, as shown in Fig. 7(a).



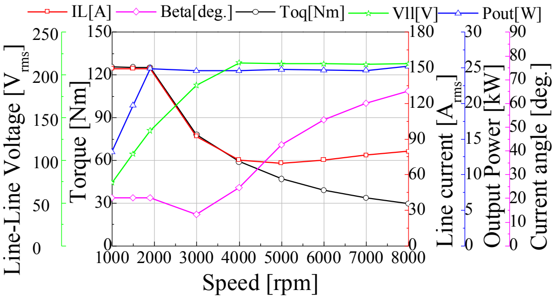
(a) Inductance profile in prototype In-Wheel type IPMSM



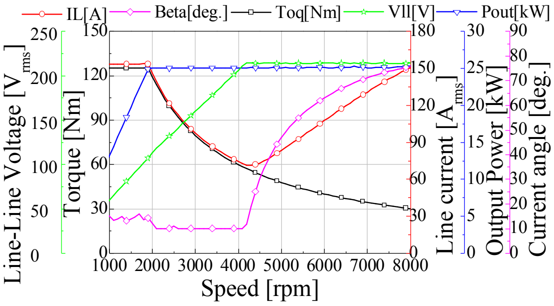
(b) Inductance profile in improved In-Wheel type IPMSM

Fig. 7. Inductance profile as voltage injection angle

(x : Voltage injection angle [°], y : Inductance [mH/30])



(a) Characteristic of prototype motor



(b) Characteristic of improved motor

Fig. 8. Characteristic of two In-Wheel type IPMSM

B. Characteristics of IPMSM

This In-Wheel type IPMSM's characteristic are estimated by voltage equations. As shown in Fig. 8, two of IPMSM is possible to satisfy the max power 25kW and the torque 125Nm. In Fig. 8(b), however, the improved motor has high input current and large current angle for flux weakening. Because it designed regarding large magnetic loading and small electric loading, the input current for flux weakening is high. Thus, it is necessary to consider selection of appropriate coil.

V. CONCLUSION

This paper estimates inductance profile well adapted to position sensorless control method based on the high frequency signal injection and proposes a direction to design for sensorless control in interior permanent magnet synchronous motor having a high power density.

The inductance is calculated by the FEM using frozen permeability method and d-q matrix transformation for estimating minimum d-axis inductance as high-frequency injection angle. In sensorless control, controller estimates the position of rotor at smallest d-axis inductance from high frequency injection. Thus, the motor using this sensorless control method is designed to have inductance profile taking the smallest value at d-axis. In order to satisfy this characteristic, this paper designs a motor having a large magnetic loading and a small electric loading. When the IPMSM has a large magnetic loading and a small electric loading, it is good at the sensorless control.

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