

Current Control Method of WRSM in High-speed Operation Range

Jae-Jun Lee*, Ki-Doek Lee*, Ik-Sang Jang**, Sung-Gu Lee***, Woong-Chan Chae§, Hyung-Woo Lee§§ and Ju Lee†

Abstract – This Paper analyzes the characteristics of the WRSM in high-speed operation range. To verify the control characteristics of various WRSM models, the relative position of the central point of current limit circle and voltage limit ellipse is defined as M value and 3 models according to M_{max} value are designed through inductance change. Through the designed models, the current control method of 3-variables control for maximum power especially in high-speed operation range is presented.

Keywords: Current limit circle, High-speed operation, Voltage limit ellipse, WRSM

1. Introduction

Due to the depleting pool of natural resources and pollution issues which came hand in hand with the recent dramatic increase of fossil fuels use, studies on eco-friendly vehicles such as Hybrid Electric Vehicle (HEV) and Electric Vehicle (EV) which are to be used as alternative means of transportation are conducted at national and corporate level.

Permanent Magnet Synchronous Motor (PMSM) is mainly used as the traction motor of HEV and EV, because it has the high torque density and the wide operating range. However, due to the price increase and uncertainty of supply of rare earth materials used in the PMSM, the development of non-rare earth electric motors have been highly demanded [1].

Recently, Wound Rotor Synchronous Motor (WRSM), one of the non-rare earth motors, has been researched for traction motor of HEV and Integrated Starter Generator (ISG) motor.

The commonly known advantages of WRSM are that temperature coefficient correction due to high temperature of permanent magnet and demagnetization phenomenon do not need to be considered and power factor control is possible. In aspect of control, WRSM which has 3 control variables (i_d, i_q, i_f), has the advantage that there are various control methods due to increase of degree of freedom [2]. But it means that finding appropriate current combinations is difficult work.

For this complexity, we propose the maximum power control method for 3 variables at especially high-speed operation range from the perspective of M value defined as the ratio of current limit circle and the central point of voltage limit ellipse.

2. Basic Theory of Control

To analyze the characteristics, basic model design of 150kW-class WRSM for traction in an HEV is conducted. Fig. 1 is Basic model of WRSM and Table 1 shows

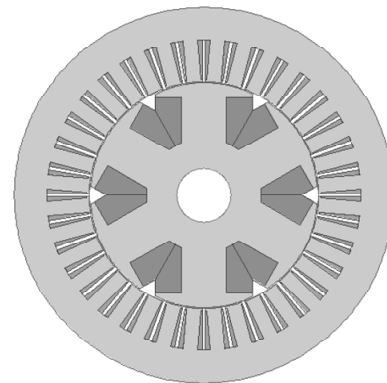


Fig. 1. Basic model of WRSM

Table 1. Specifications of basic model

	Value	Unit
Poles / Slots	6 / 36	-
Stator Diameter	350	mm
Stack Length	140	mm
Battery Voltage	620	V
Stator Current Density	10.6	A_{rms}/mm^2
Stator Phase Current	275	A_{rms}
Turns per Phase	24	-
Rotor Current Density	5.5	A_{DC}/mm^2
Rotor Current	20	A_{DC}
Turns per Pole	110	-

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specifications of the WRSM.

To check power characteristics at high speed area of WRSM, driving area satisfying the current constraints and voltage constraints needs to be checked. First, field current and phase current can be applied under the maximum field current i_{fm} and phase current I_{am} which are determined by heat saturation or controller data, etc, as shown in (1), (2).

In d-q reference frame [3], current phase angle is defined as angle between q -axis and stator current vector, and as positive value when stator current vector is located to the second quadrant.

Voltage constraint also needs to be checked for high speed operation as shown in (3).

$$i_f \leq i_{fm} \quad (1)$$

$$i_d^2 + i_q^2 \leq I_{am}^2 \quad (2)$$

$$\frac{\left(i_d + \frac{L_m i_f}{L_d}\right)^2}{\left(\frac{V_{om}}{\omega_e L_d}\right)^2} + \frac{(i_q)^2}{\left(\frac{V_{om}}{\omega_e L_q}\right)^2} = 1 \quad (3)$$

where L_d is the d -axis inductance, L_q is the q -axis inductance, L_m is the mutual inductance between rotor and stator, V_{om} is the constraint of voltage.

In (3), it can be seen that the voltage limit ellipse is related with the field current. This feature of WRSM is distinguished from that of PMSM. By reducing field current, called Field-weakening control, the central point of voltage limit ellipse can be moved to the starting point side as shown in Fig. 2.

In (3), the d -axis and q -axis inductances which are used in the flux-weakening control of PM brushless ac machines can be calculated from [4]. However, inductances have to be calculated by considering saturation [5, 6]. Under the saturation condition, inductances of WRSM can be calculated using FE analysis as follows.

$$L_m = \frac{\psi_o \cos \alpha}{i_f} \frac{F_f}{F_f + F_d} \quad (4)$$

$$L_d = \frac{\psi_o \cos \alpha}{i_d} \frac{F_d}{F_f + F_d} \quad (5)$$

$$L_q = \frac{\psi_o \sin \alpha}{i_q} \quad (6)$$

Where ψ_o is the total magnetic flux interlinkage, α is the load angle, F_f is the MMF source representing the rotor, F_d is the MMF source representing the d -axis current of stator.

As shown in Fig. 2, the size of voltage limit ellipse reduces as the field current becomes smaller due to the increase of d -axis, q -axis inductance.

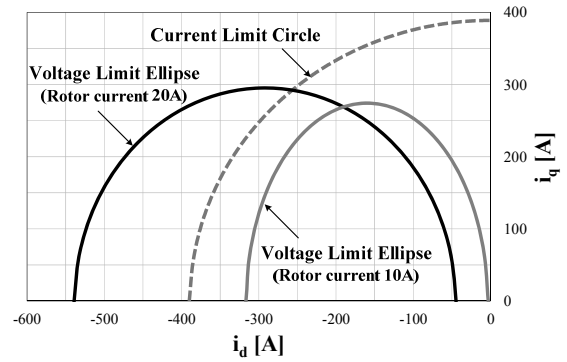


Fig. 2. Voltage limit Ellipse @ 5000rpm

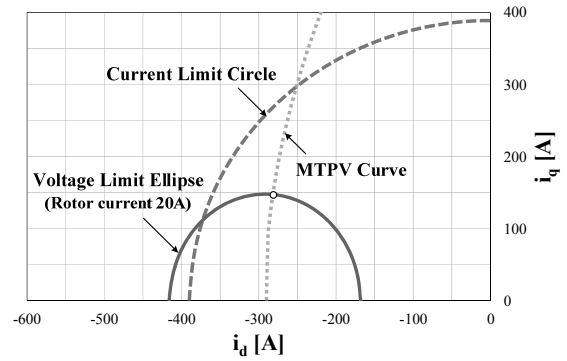


Fig. 3. Voltage limit Ellipse & MTPV curve @ 10000rpm

Fig. 3 shows current limit circle and voltage limit ellipse, MTPV curve at 10000rpm for WRSM when field current is maximum value ($i_f = i_{fm}$). MTPV curve is the condition of generating maximum torque for the same magnetic flux linkage [7]. MTPV curve related to the central point of voltage limit ellipse is formed inside of current limit circle as shown in Fig. 3. Therefore, the point of intersection with MTPV curve becomes the maximum power control condition of basic model when driving at 10000rpm.

3. Design According to M_{max}

The ratio for parameters ($-L_m i_f / L_d$), I_a determining current limit circle and the central point of voltage limit ellipse is defined as M.

$$M = \frac{L_m i_f}{L_d I_a} \quad (7)$$

To determine the control characteristics at high speed of motor, fixed M value when applying maximum field current and maximum phase current is defined as (8).

$$M_{max} = \frac{L_m i_{fm}}{L_d I_{am}} \quad (8)$$

Basic model is the model that the central point of

voltage limit ellipse is located inside than current limit circle ($M_{max} < 1$).

As shown in (9), (10), L_m is proportional to the multiplication of turns of rotor and stator, and L_d is proportional to the square of turns of stator [8].

$$L_m = \frac{N_a N_f}{R_d} \quad (9)$$

$$L_d = \frac{N_a^2}{R_d} \quad (10)$$

where R_d is the reluctance of d-axis, N_f is the turns of rotor, N_a is the turns of stator.

Design of changing M_{max} is conducted by changing turns of rotor and stator under the same stator diameter, stack length, current constraints.

Case 2 ($M_{max} = 1$) is that the central point of voltage limit ellipse matches with current limit circle and case3 ($M_{max} > 1$) is that the central point of voltage limit ellipse is located outside of current limit circle. Specifications of WRSM redesigned by size of M_{max} value are shown in Table 2.

In the low speed operation region, MTPA control is required [9]. The values of comparing FEA results of torque, efficiency at rated speed are shown in Table 3.

Table 2. Specifications of WRSM

	Case1	Case2	Case3	Unit
M_{max}	0.75	1	1.32	-
Stator Diameter	350			mm
Stack Length	140			mm
Rotor Diameter	210	219	230	mm
Turns per phase	24	22	20	-
Turns per pole	110	114	120	-

Table 3. Maximum torque of WRSM @ rated speed

	Case1	Case2	Case3	Unit
Torque	394.1	396.7	393.8	Nm
Current Phase Angle	5	7	8	degE
Efficiency	96.5	96.7	96.9	%

4. Control Method for Maximum Power in High-speed Operation Range

4.1 Model of case1 ($M_{max} < 1$)

Fig. 4 shows the torque (contour line) & voltage limit area (white dotted line area) according to the current phase angle and the field current of case 1. It can be seen in Fig. 4 that maximum field current must be maintained without reducing field current to generate larger torque in the area satisfying voltage limits.

And while fixing field current to the maximum value, the torque graph according to the change in phase current

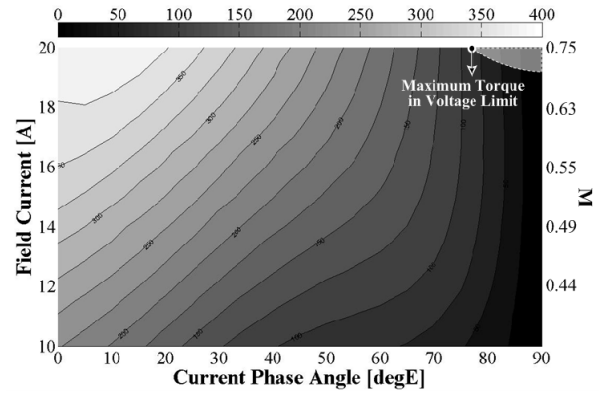


Fig. 4. Torque, voltage limit area, M value of case 1 according to the field current and the current phase angle

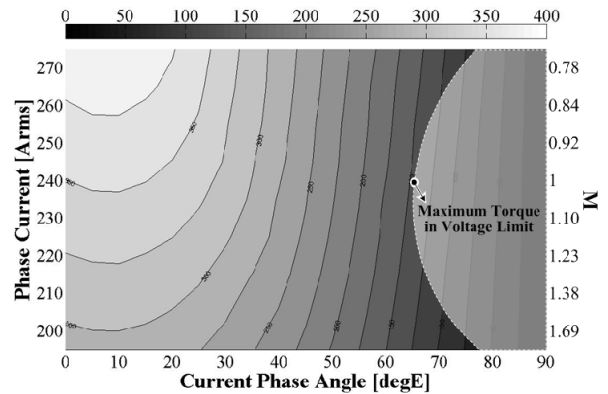


Fig. 5. Torque, voltage limit area, M value of case 1 according to the phase current and the current phase angle

size is shown in Fig. 5. It can be seen in Fig. 5 that maximum torque is generated when driving 10000rpm at phase current $240A_{rms}$ not maximum phase current. This area meets MTPV control condition. As phase current I_a is reduced, M value increases gradually and the analytical results showed that M value at phase current $240A_{rms}$ was close to 1.

Therefore, in the case 1, control for maximum power is to maintain field current as the maximum value and control current phase angle and then MTPV control.

4.2 Model of case2 ($M_{max} = 1$)

In case2, the torque and operable area at maximum speed are shown in Fig. 6. It is seen that the control method for maximum power is to maintain field current and phase current as the maximum value and adjust current phase angle in the case 2.

4.3 Model of case3 ($M_{max} > 1$)

In Fig. 7, it is seen that the maximum torque generation point for case 3 in the voltage limit area satisfying

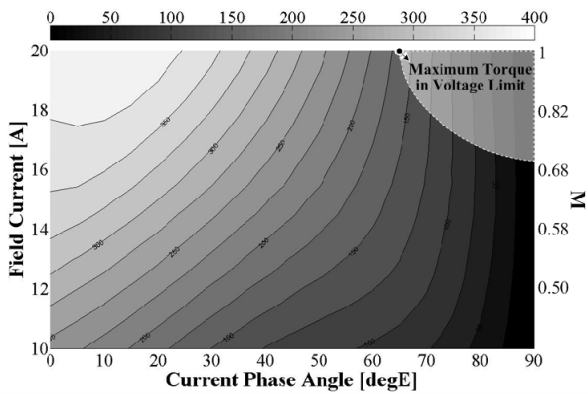


Fig. 6. Torque, voltage limit area, M value of case 2 according to the field current and the current phase angle

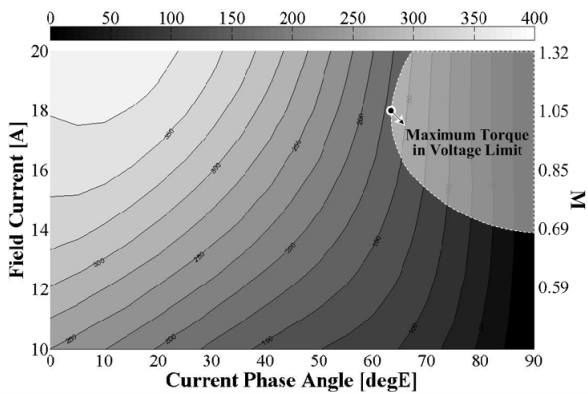


Fig. 7. Torque, voltage limit area, M value of case 3 according to the field current and the current phase angle.

10000rpm driving is not when maximum field current is applied. When applying field current 17.5A rather than maximum field current 20A, maximum torque is generated in the area satisfying the voltage limit.

As M value decreases gradually, it can be seen that the case of field current 17.5A is the point of $M=1$.

Accordingly, in the case 3 ($M_{max} > 1$), the control condition for maximum power is to reduce field current during high speed control. At that time field current is reduced up to the area where M value satisfies 1.

5. Conclusion

This paper analyzed power characteristics of 150kW-class WRSM for traction and presented the direction on the current control method at high-speed range. High-speed operation control of WRSM is more complicated than that of PMSM due to the field current control.

Due to the complexity of 3-variables current control, M value was defined by the relative position of the central point of voltage limit ellipse and current limit circle. The current control method at high speed varies depending on

unique M_{max} value of each model. The cases are classified into 3 depending on M_{max} values and the current control method at high speed was presented for each case.

In those three cases, controlling phase current and field current to converge M value to 1 at high speed can be seen to be the maximum power condition.

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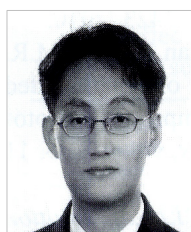
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