Torque Control of IPMSM considering actual controller and driving condition

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Abstract

Wireless tram with independently rotating wheelsets(IRWs) requires fast and precise torque control, and it is necessary to perform robust torque control under various driving conditions. To satisfy this requirement, torque control using flux-based 2-D LUT (Lookup Table) which is obtained offline is advantageous. The required torque is converted into a current vector information using this 2-D LUT. This eliminates the current information calculation process, and reduces the DSP load. Moreover, stable torque control is possible even if voltage fluctuation occurs due to the charge / discharge of the battery. The current vector information of 2-D LUT can be determined offline using FEA. Although FEA is a powerful numerical analysis, but assumes various ideal conditions. It is difficult to consider the effects of actual controller and driving conditions. As a result, there is a difference between the FEA and the actual experimental results.

In this paper, we propose a method to obtain the current vector information using motor-inverter co-simulation. As a result, magnetic saturation and cross coupling effects can be considered. In addition, the influence of the actual controller can be considered. The proposed method was verified through experiments.

FLUX-BASED TORQUE CONTROL

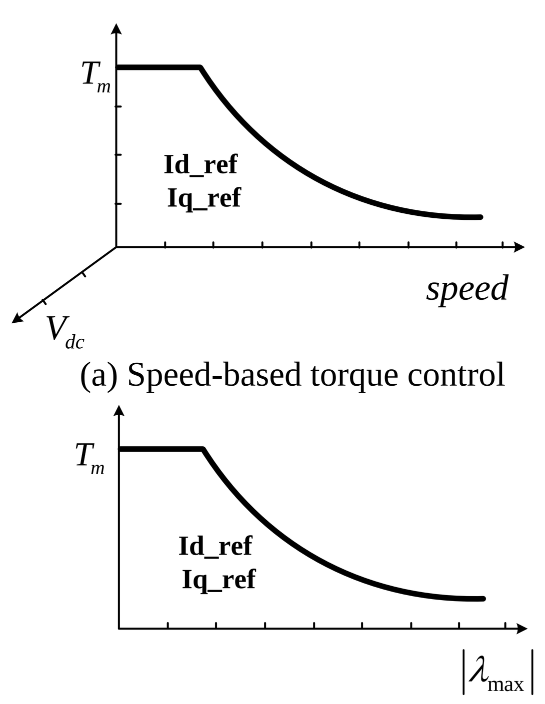


Fig. 1. Torque control using 2-D LUT

There are many studies on torque control of IPMSM. It can be divided into two ways.

1. the current vector information is calculated in real time to satisfy the required torque. It increases load of the DSP and makes it difficult to consider the nonlinearity and cross-coupling effects of IPMSM.

2. the current vector information is generated by using 2-D LUT .
   (1) The speed-based 2-D LUT converts the input speed-torque information into d- and q-axis current information. This method is difficult to consider the effect of battery voltage drop when the inverter voltage is saturated.
   (2) The flux-based 2-D LUT is more robust to changes in driving conditions because it depends on motor parameters. The current vector information of the 2-D LUT can be determined using FEA or experiment in an off-line manner.

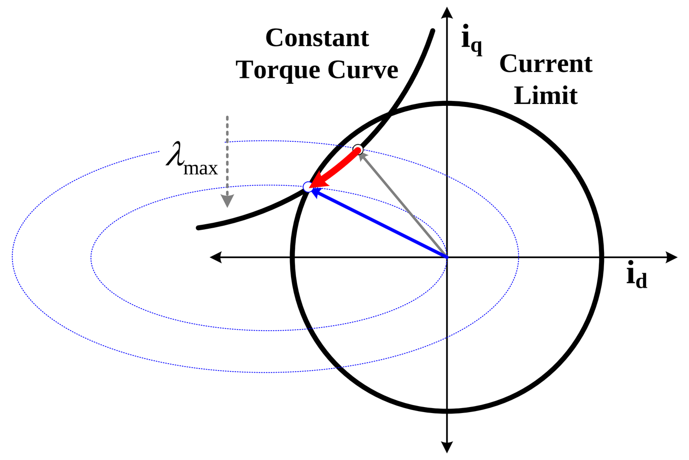


Fig. 2. Trajectory of the current considering linkage flux

- Below the base speed

$$\sqrt{i_d^2 + i_q^2} \le I_{s\_\max} \quad (1)$$

- Output voltage of the inverter is saturated

$$\left(L_d i_d + \lambda_f\right)^2 + \left(L_q i_q\right)^2 \le \left(\frac{V_0}{\omega_e}\right)^2$$

$$\left(\frac{V_0}{\omega_e}\right)^2 = \left(\frac{V_{dc}}{\sqrt{3}\cdot\omega_e}\right)^2 = \lambda_{\max}^2 \quad (2)$$

The ratio between the speed and the battery voltage can be expressed as a linkage flux in (2).
Therefore, torque control can be simplified because the effects of two variables (speed, battery voltage) can be considered with only linkage flux as shown Fig. 2. It can also reduce FEA or experimentation required for 2-D LUT.

FLUX-BASED 2-D LUT USING FEA

- the current amplitude was applied in 13 steps from 0A to 180A,
- the current angle was performed in 10 steps from 0 to 90 in the second quadrant.
- The d- and q- axis linkage flux and torque can be obtained directly by FEA. Based on this result, the minimum current satisfying both the equation and the required torque curve was determined by the current vector information in the flux-based 2-D LUT.

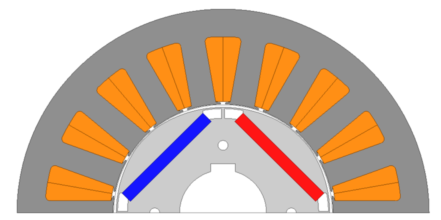
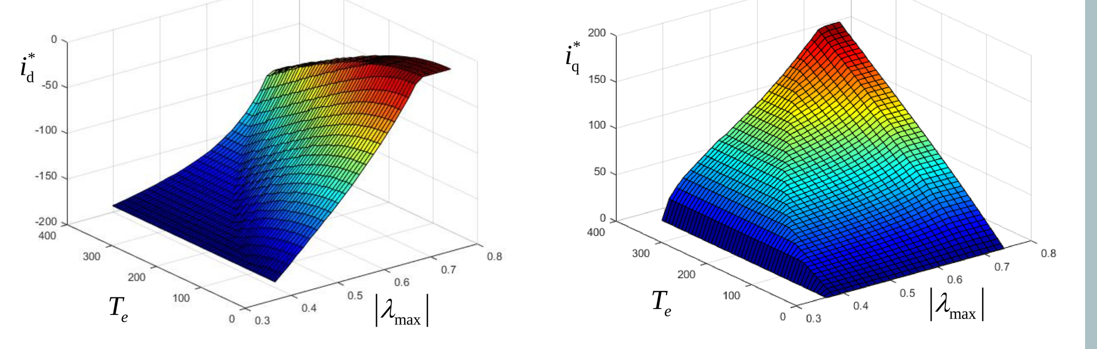


Fig. 3. Analysis model for the FEA

TABLE I. Specifications of the IPMSM

Parameters	Specification	Unit
Number of Poles/slots	4/18	-
Battery Nominal Voltage	750	V
Current Limit	180	A_{peak}
Rated Torque/Power	333/48.5	Nm/kW
Base speed/Max speed	1,390/4,449	RPM
Cooling method	Air-cooling	



(a) d-axis current information (b) q-axis current information

Fig. 4. Result of the flux-based 2-D LUT

TABLE II. Verification of flux-based 2-D LUT using FEA

	30Nm	90Nm	150Nm	210Nm	270Nm	330Nm
Linkage Flux 1st	0.624	0.624	0.624	0.624	0.623	0.622
Linkage Flux 3st	0.005	0.014	0.022	0.030	0.036	0.041
Induced Voltage 1st	415.36	415.23	415	415.04	414.4	413.81

ANALYSIS OF CONTROLLER EFFECT BY CO-SIMULATION

In order to take into account the effects of controller, the current vector information of 2-D LUT should be obtained using the motor-inverter co-simulation.

$$v_d = R_s i_d - \omega_e \boxed{\lambda_q} = R_s i_d - \omega_e\left(L_q i_q\right)$$
$$v_q = R_s i_q + \omega_e \boxed{\lambda_d} = R_s i_d + \omega_e\left(L_d i_d + \lambda_f\right) \quad (3)$$

FEA Result

TABLE III. Co-simulation conditions

Parameters	Specification	Unit
Dead time	4	us-
Switching frequency	4	kHz
Sample time	250	us
Vce sat	2.9	V
Rce	6	mΩ
PWM Method	SVPWM	

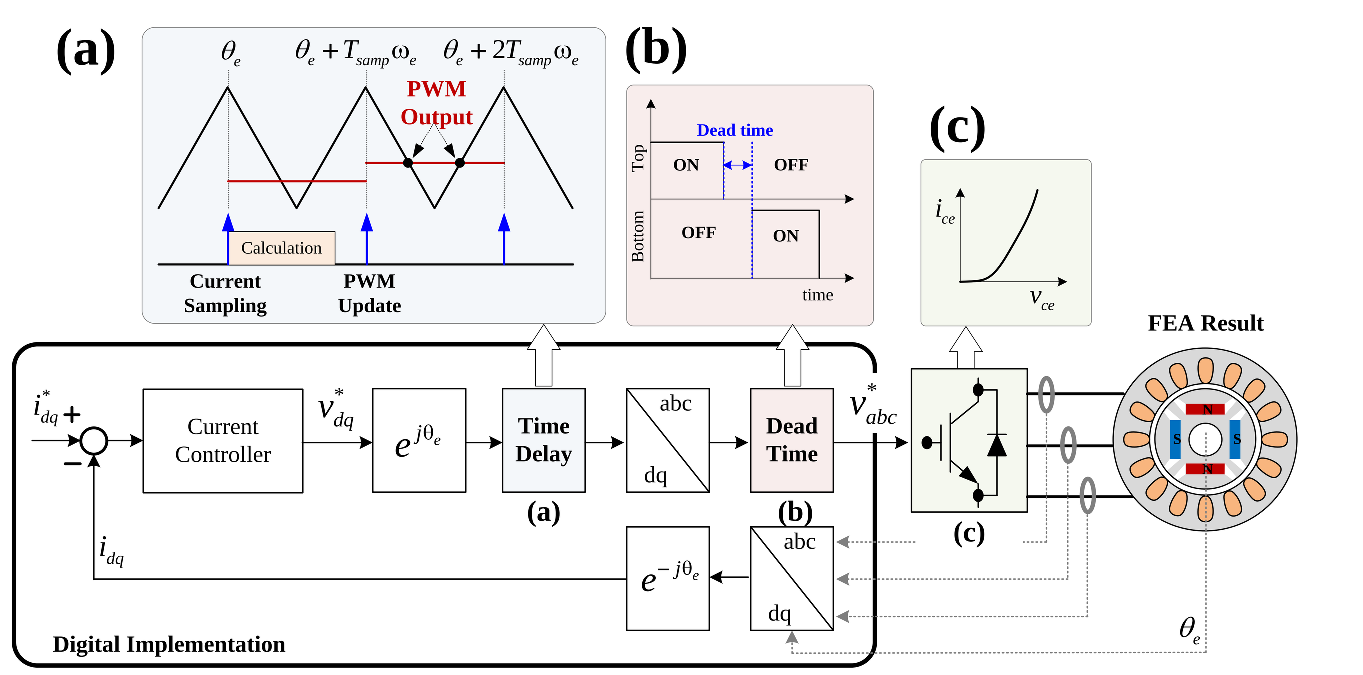


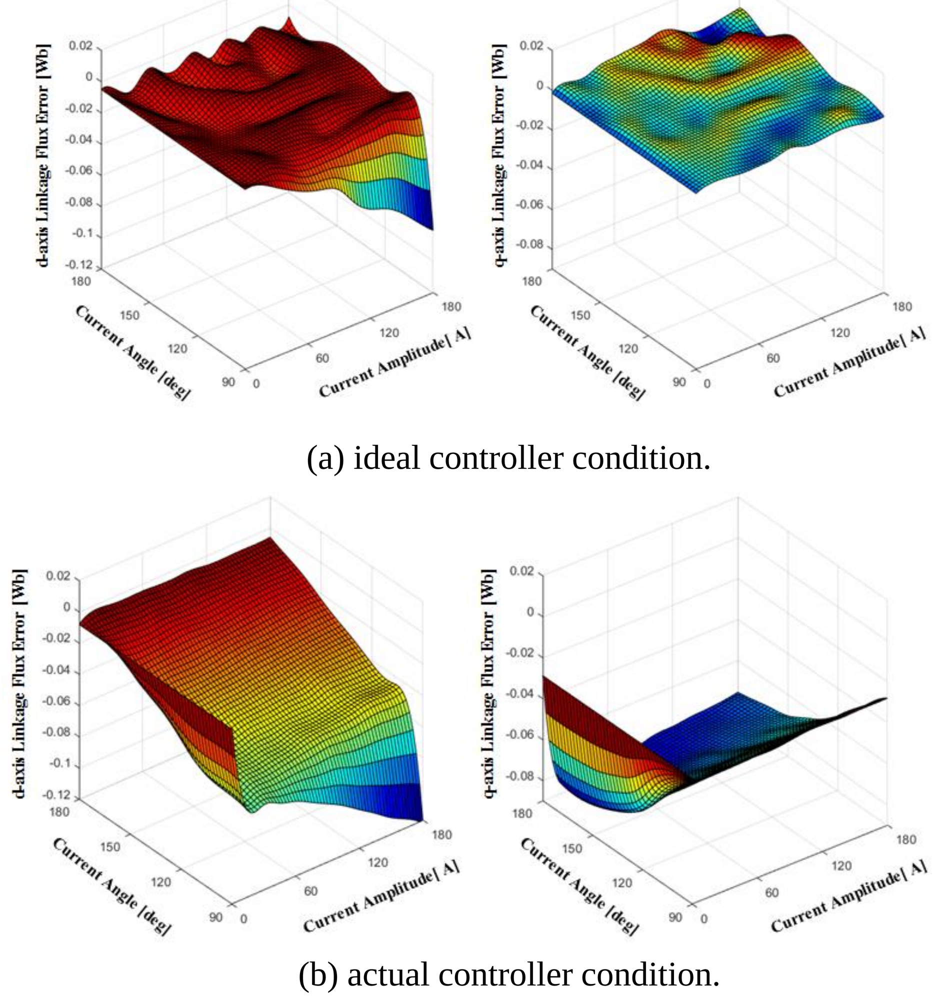
Fig. 5. Motor-Inverter co-simulation block

In the actual condition, the linkage flux information of the motor can not be directly obtained. Linkage flux is estimated using current controller output voltage. However, there is a difference in results depending on simulation condition as shown in Fig. 6.

(a) current controller in the synchronous coordinate system has the difference between the sampling point and the PWM output point. There is an error because the reference coordinate axis moves.

(b) The dead time generates the difference between the current controller output voltage and applied voltage to the actual motor.

(c) Wireless tram with IRWs use 750V batteries, rating voltage of IGBT are 1700V in consideration of stray inductance. As the voltage rating of the IGBT increases, collector-emitter saturation voltage increases.



(a) ideal controller condition.

(b) actual controller condition.

Fig. 6. d- and q-axis linkage flux error between FEA and co-simulation.

EXPERIMENTAL RESULTS

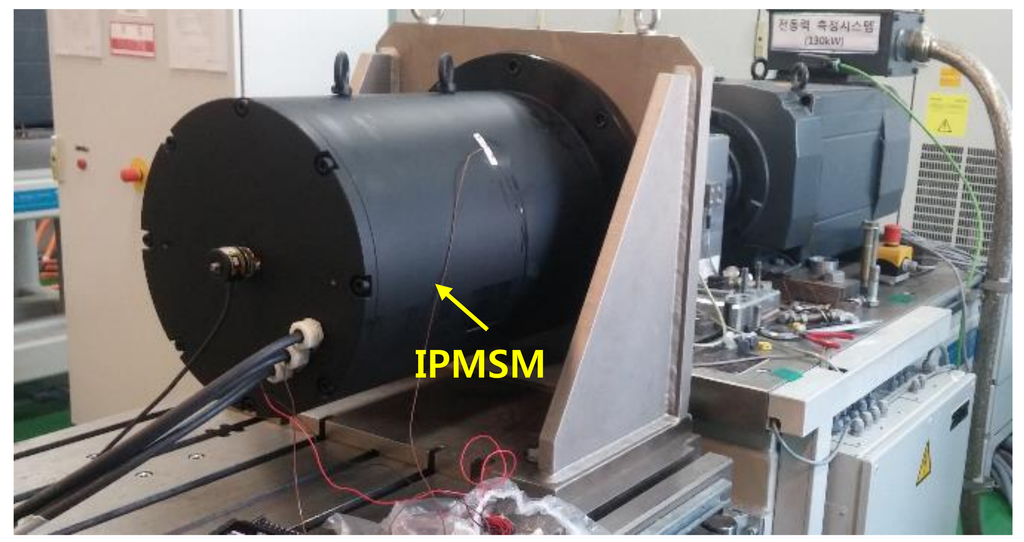


Fig. 7. Experimental setup.

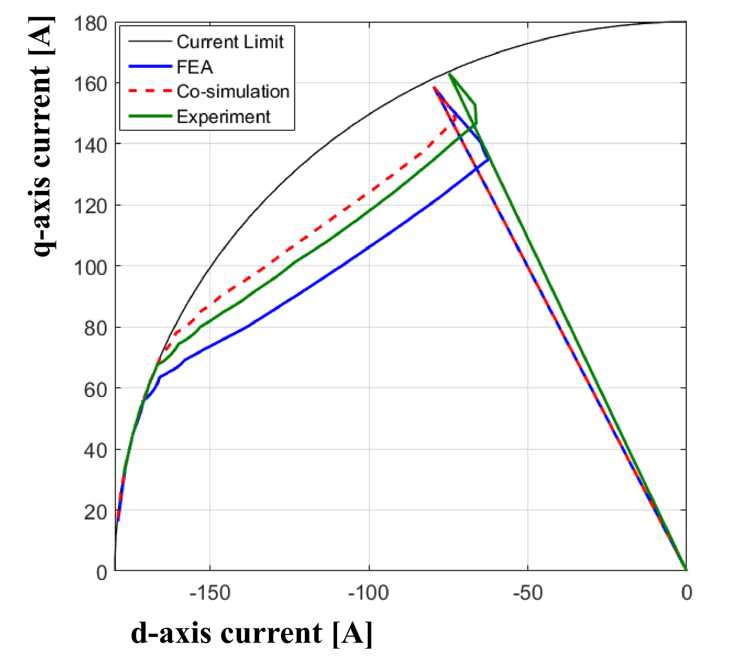


Fig. 8. Comparison of current trajectories.

The maximum power control is implemented by using the result of flux-based 2-D LUT obtained through FEA, co-simulation and experiment. The 2-D LUT extracted through co-simulation has a current vector trajectory similar to the actual experimental results as shown Fig. 8.

Conclusion

In this paper, we propose a method to obtain the current vector information using co-simulation. As a result, nonlinear and cross-saturation effects can be considered. In addition, the influence of the controller can be considered. The cause of the linkage flux error between the co-simulation and FEA is sampling time delay, dead time. The results of the 2-D LUT obtained through each simulation method were compared through the current trajectory during maximum power control. The result of considering the voltage error in co-simulation showed high accuracy compared with actual experimental results than FEA. Therefore, it is possible to analyze the characteristics of the motor considering the control without manufacturing of motor.