IOP Conference Series: Materials Science and Engineering

PAPER • OPEN ACCESS

DC-link voltage feedforwarded interpolation error compensation method for field weakening operation region of look-up table based PMSM drive

To cite this article: Jung-Hyo Lee 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **600** 012024

View the article online for updates and enhancements.

This content was downloaded from IP address 59.44.247.194 on 15/10/2019 at 23:45

IOP Conf. Series: Materials Science and Engineering **600** (2019) 012024 doi:10.1088/1757-899X/600/1/012024

DC-link voltage feedforwarded interpolation error compensation method for field weakening operation region of look-up table based PMSM drive

Jung-Hyo Lee[1,*]

[1,*]Kunsan National University, Electrical Engineering Department, Gunsan 54150, Korea

jhlee82@kunsan.ac.kr

Abstract. This paper proposes field weakening control method of the look-up table based permanent magnet synchronous machine (PMSM) with interpolation error compensation. The look-up table based control method has robust control characteristic than other control methods which use linear controller for current reference generation. However, it is impossible to store all current references under all circumstances for torque commands. General look-up table based control method using two input parameters, in order to mitigate the effect of discretely stored data, two-dimension-interpolation method (2D-Interpolation) is used for linear interpolating between discontinuous data. However, due to the current trajectories of PMSM are generally ellipsoidal, the error is occurred between linearly interpolated and controllable current references. This paper proposes a method to compensate this interpolation error using feedforward controller for fast compensation. The improvement of proposed method is verified by experiment and simulation.

1. Introduction

Recently, Permanent Magnet Synchronous Motor (PMSM) drive system has been adopted frequently for vehicles in order to improve efficiency and convenience. Generally, in the case of the PMSM used in a vehicle, two dimensions look-up table (2D-LUT) based current command control is widely used.[1]-[6] Among these control methods, flux-torque 2D-LUT based control method is most generally used due to the reflection of DC-link voltage variation which shown as Fig. 1.[1]

In this controller, the current data in the 2D-LUT is stored according to the respective memory addresses corresponding to flux-torque. Since the memory address is a discontinuous value, only current reference data for a specific flux and torque can be stored in the memory. Therefore, in the case of the PMSM torque control method using the 2D-LUT, it is inevitably impossible to store the appropriate current data in the entire driving region. In order to solve this problem, the two-dimension-interpolation (2D-Interpolation) method has been used to properly interpolate with input data that has not been previously stored in the memory.[7]-[9] This 2D-Interpolation makes discreet look-up table outputs to linear outputs according to two continuous input parameters which do not define at the specific torque-flux points of the look-up table. For instance, if the input parameters inserted in look-up table, related outputs are generated from the memory, and then, using these outputs for linear

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

interpolation called first order newton's interpolation method in order to calculate approximate output for input parameters.

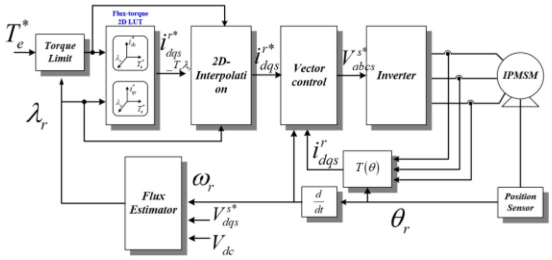
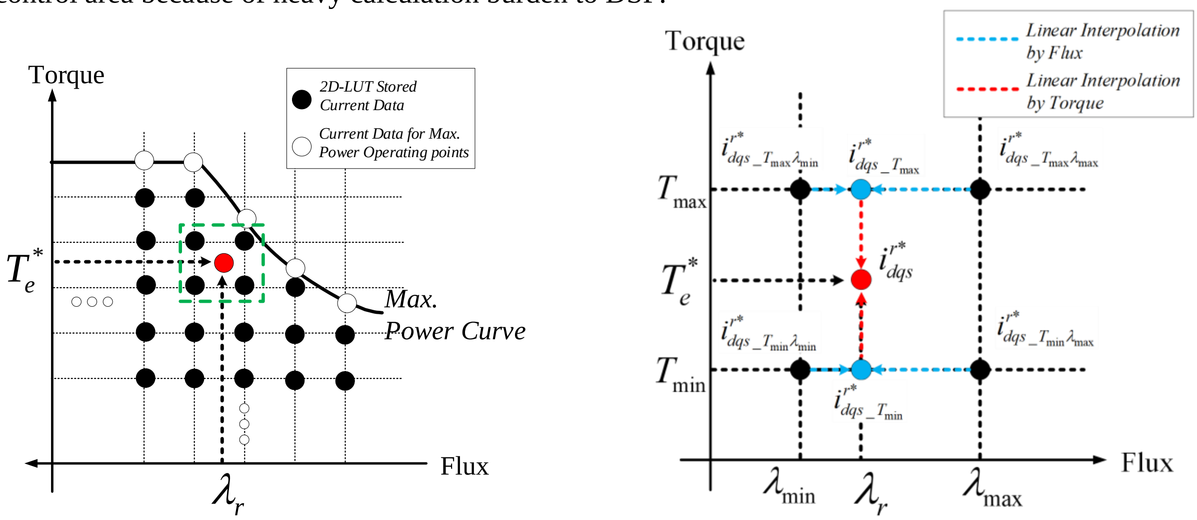


Figure 1. Flux-torque look-up table based PMSM control method [1].

This 2D-Interpolation method used in PMSM control is effective if the number of stored data is enough to ignore the interpolation error, however, if the number is insufficient, interpolation error can not be ignored because all PMSM current trajectories are not linear but ellipsoidal. Moreover, in automotive application, in order to fulfill the international standard ISO26262 which purpose is to retain driver safety, PMSM drive should have many fault diagnosis for retaining system safety and AUTOSAR which needs lots of memory for operating software.

To solve this problem, very few researches have been proposed to optimal use of memory. In [10], use the curve fitting method for reducing the memory, however, it does not suggest the solution for the error between the interpolated curve fitting output and optimal output. Constant torque control method for PMSM using any tables is shown on [11], however, this method needs exact parameters for PMSM, moreover, if the target PMSM does not have enough saliency, effectiveness is limited. As aforementioned, current trajectories for PMSM are ellipsoidal, the interpolation method used in this application needs second order interpolation method such as second order Lagrange or Spline method with parameter modification for each operating condition. [12] However, it is seldom used in motor control area because of heavy calculation burden to DSP.



(a) (b)

Figure 2. 2D-Interpoation procedure for current references output from 2D-LUT. (a) Stored data in 2D-LUT accordance with each speed and torque. (b) 2D-Interpolation procedure for specific speed and torque reference input.

This paper proposes a novel control method to reduce this interpolation error. First, we analyze the cause of interpolation error and defines the problem characteristic. And then, compensation method for interpolation error with DC-link voltage feedforward will be illustrated.

2. Interpolation error of 2D-Interpolation technique for PMSM drive

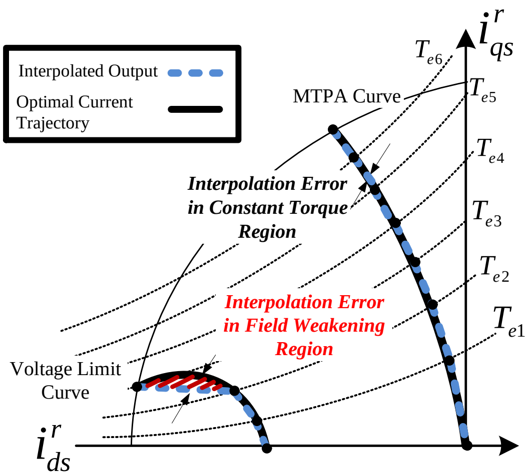


Figure 3. Interpolated current trajectories of PMSM with the current table data which has six torque input data.

2.1. 2D-Interpolation Technique

The 2D-Interpolation is a linear interpolation method for two input parameters. As aforementioned, 2D-LUT data on certain flux and torque have four different values: outputs on the ceil and floor of flux input ($\lambda_{\max}$, $\lambda_{\min}$); outputs on the ceil and floor of torque input ($T_{\max}$, $T_{\min}$) as shown on Fig. 2. To generate interpolated output, the following linear interpolation formula is applied to the input parameters three times as shown on Fig. 2(b).

$$f(x) = f(x_1) + \left(\frac{f(x_2) - f(x_1)}{x_2 - x_1} \right) \cdot (x - x_1) \tag{1}$$

For instance, the case of linear interpolation by speed on $T_{\min}$, x_2 and x_1 are ceil and floor of speed input ($\lambda_{\max}$, $\lambda_{\min}$), respectively, $f(x_2)$ and $f(x_1)$ are the current reference data on $T_{\min}$ correspond to $\lambda_{\max}$, $\lambda_{\min}$,the notations of Fig. 2(b) are $i_{dqs\_T_{\min}\lambda_{\max}}^{r*}$, $i_{dqs\_T_{\min}\lambda_{\min}}^{r*}$, respectively. x is the input of current speed (λ_r) and $f(x)$ is the interpolated output on $T_{\min}$ ($i_{dqs\_T_{\min}}^{r*}$).

To reduce the processing burden of microprocessor, division for variable has to be avoided as possible. This paper uses fixed unit for that as same as [9]. In this case, the current references from look-up table's are also established accordance with this unit value. Substitute the variable to fixed unit value, (1) can be changed as below.

$$f(x) = f(x_1) + \left(\frac{f(x_2) - f(x_1)}{x_{unit}} \right) \cdot (x - x_1) \tag{2}$$

where, x_{unit} is the fixed unit value of input parameter's deviation.

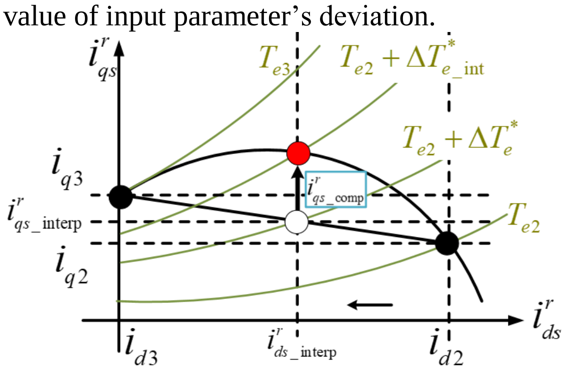


Figure 4. Magnified 2D-Interpolation error in field weakening operation region of Fig. 3.

IOP Conf. Series: Materials Science and Engineering **600** (2019) 012024 doi:10.1088/1757-899X/600/1/012024

Note that the flux is inverse value of the speed. If the speed is increasing, then, the flux is decreasing as shown on Fig. 2(a). Therefore, the calculated flux should be properly limited to avoid divergence.

2.2. 2D-Interpolation Error in Look-Up Table Based PMSM Control

Fig. 3 shows the interpolated current trajectories using only six torque inputs data. As shown on the figure, with 2D-Interpolation method, two current reference points stored in the memory are linearly connected while the operating condition that stored data is absent. Although it can reduce the error better than using only look-up table outputs, generated power is decreased than capable maximum power. In addition, the effect of interpolation error is hardly existed in constant torque operation region due to the sufficient current data for torque input. In contrast, the effect of interpolation error is enlarged in field weakening operation region because the current data is reduced in high speed operation.

Fig. 4 shows the magnified interpolation error described in Fig. 3. To calculate this 2D-Interpolation error, firstly, fundamental PMSM model equations are shown as below.

$$\begin{aligned} v_{ds}^r &= R_s i_{ds}^r + L_d p i_{ds}^r - \omega_r L_q i_{qs}^r \\ v_{qs}^r &= R_s i_{qs}^r + L_q p i_{qs}^r + \omega_r L_d i_{ds}^r + \omega_r \phi_f \end{aligned} \quad . \tag{3}$$

$$T_e = 3P/4\{\phi_f i_{qs}^r - (L_q - L_d) i_{ds}^r i_{qs}^r\} \tag{4}$$

$$\begin{aligned} V_{\max} &= \omega_r \sqrt{(L_d i_{ds}^r + \phi_f)^2 + (L_q i_{qs}^r)^2} \\ V_{\max} &= \frac{V_{dc}}{\sqrt{3}} \end{aligned} \quad . \tag{5}$$

where, v_{ds}^r, v_{qs}^r are d-/q-axis voltages of PMSM respectively, T_e is torque, $V_{\max}$ is voltage restriction of PMSM, ω_r is angular speed, R_s is phase resistance, L_d, L_q are d-/q-axis inductances, respectively, ϕ_f is permanent magnet flux, P is number of pole, V_{dc} is DC-link voltage.

As shown on the figure, the interpolation error does not affect d-axis current component ($i_{ds\_interp}^r$), however, it affects the q-axis current component ($i_{qs\_interp}^r$). This interpolated q-axis current reference can be expressed as (6) from (1).

$$\begin{aligned} & i_{qs\_\text{interp}}^r (T_{e2} + \Delta T_e^*) = i_{q3} + \frac{i_{q3} - i_{q2}}{T_{e3} - T_{e2}} \Delta T_e^* \\ & (\Delta T_e^* = T_e^* - T_{e2}) \end{aligned} \tag{6}$$

With (6), the back-EMF voltage magnitude by interpolated current reference can be expressed as (7).

$$\begin{aligned} & V_{mag} = \omega_r \sqrt{(L_d i_{ds\_\text{interp}}^r (T_{e2} + \Delta T_e^*) + \phi_f)^2 + (L_q i_{qs\_\text{interp}}^r)^2} \\ & V_{mag} < V_{\max} \end{aligned} \tag{7}$$

If the interpolated d-axis current according to the varied torque with (7), the magnitude of the maximum torque that can be generated by this d-axis current can be obtained through the intersection of the voltage restriction curve and the torque curve. The equation is expressed by a quadratic equation as shown in (8) which has four roots that are classified as two imaginary roots, and two real roots. Among these two real roots, effective d-axis current is the magnitude which has the minimum value of them.

$$
\begin{aligned}
&-(L_d-L_q)^2 L_q{}^2 i^r_{ds\_interp}{}^4 \\
&+\left\{-2L_d{}^2(L_d-L_q)-2\phi_f L_d(L_d-L_q)^2\right\} i^r_{ds\_interp}{}^3 \\
&+\left\{-2L_d{}^2\phi_f{}^2-4\phi_f L_d(L_d-L_q)-(L_d-L_q)^2\phi_f{}^2+(L_d-L_q)^2\left(\frac{V_{\max}}{\omega_r}\right)^2\right\} i^r_{ds\_interp}{}^2 \\
&+\left\{-2\phi_f{}^3 L_d-2(L_d-L_q)\phi_f{}^2+2(L_d-L_q)^2\left(\frac{V_{\max}}{\omega_r}\right)^2\right\} i^r_{ds\_interp} \\
&+\left\{\phi_f{}^2\left(\frac{V_{\max}}{\omega_r}\right)^2-\left(\frac{L_q(T_{e2}+\Delta T_{e\_int})}{P_n}\right)^2-\phi_f{}^4\right\}=0
\end{aligned}
\tag{8}
$$

The compensation value of q-axis current can be obtained by substituting d-axis current value from (8) to (4)

$$
i^r_{qs\_comp}=\frac{4}{3P}\frac{T_{e2}+\Delta T^*_{e\_int}}{(\phi_f+(L_d-L_q)i^r_{ds\_interp})}-i^r_{qs\_interp} \tag{9}
$$

From (9), increased torque output by compensated q-axis current ($\Delta T^*_{e\_int}$) is always higher than increased torque output by interpolated q-axis current (ΔT^*_e) as shown on Fig. 4.
As a result, it proves that the torque error is existed between interpolated output and optimal output, in addition, generated torque by interpolated output is always smaller than the generated torque by optimal output.

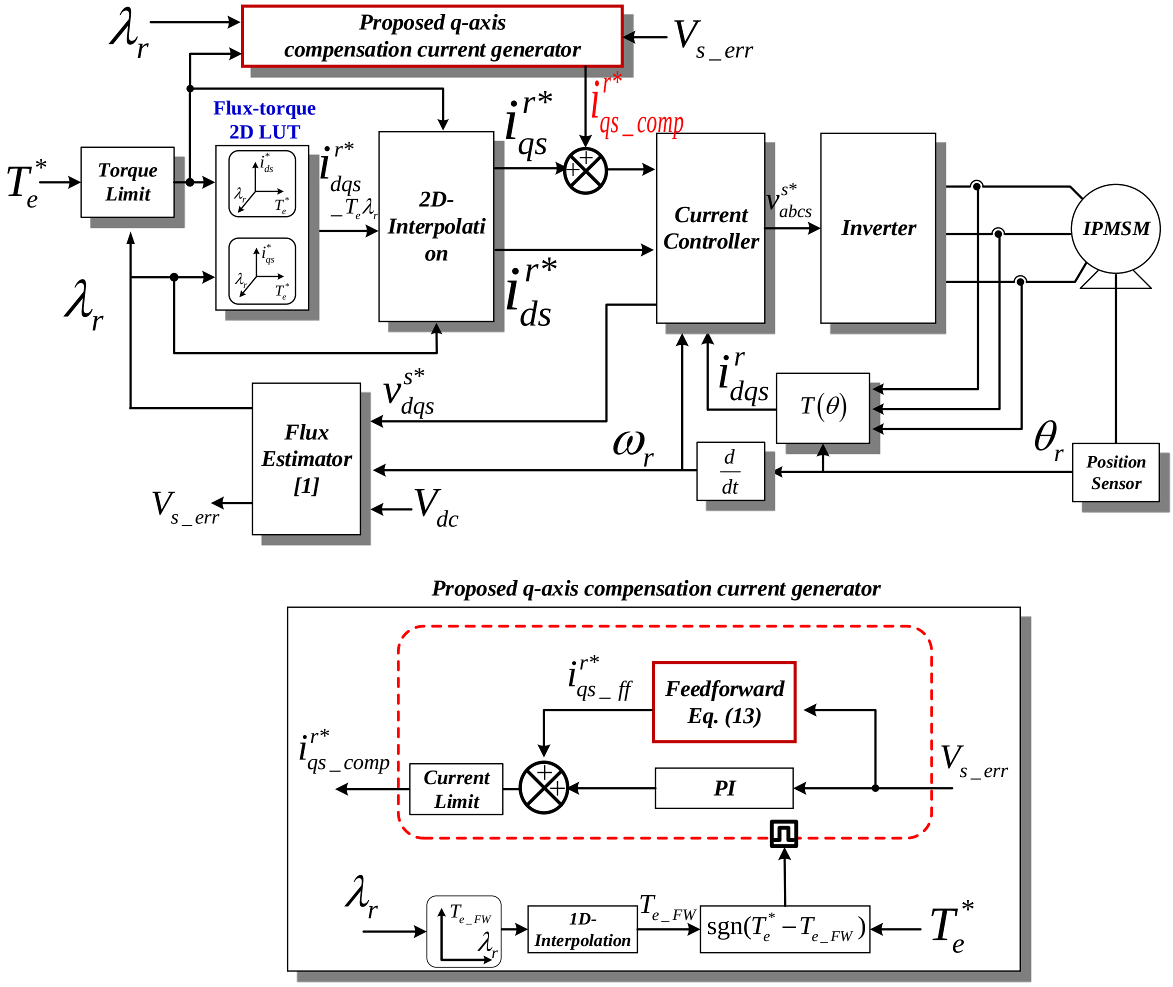


Figure 5. Overall proposed control block for q-axis current compenstion.

3. Interpolation Error Compensation Method with DC-link voltage feedforward Controller

Generally, in field weakening operation region, since the magnitude of the current is not large, the magnitude of the back-EMF voltage has a major influence on the components in permanent magnet flux. Therefore, the variation in the torque in this region is largely affected due to the variation in the q-axis current, and the voltage restriction is greatly affected by the speed and the d-axis current. Among them, the speed is not a direct control target of the electric motor but a restriction condition that is influenced by the machine-driving environment. Therefore, in order to compensate reduced output caused by the interpolation, q-axis current must be compensated so as to raise the torque.

The reason of occurring this torque error is the back-EMF magnitude of interpolated q-axis current is smaller than the voltage limit, which is determined by DC-link voltage. Therefore, compensated q-axis current can be obtained from the voltage error between the current back-EMF magnitude and voltage limit calculated by DC-link voltage. From this error, PI controller in this paper deducts compensated q-axis current.

$$i^r_{qs\_comp} = \frac{sK_p + K_i}{s}(V_{max} - V_{mag}) \tag{10}$$

However, as previously mentioned, all current trajectories for PMSM operation is ellipsoidal, PI controller is insufficient to calculate compensation current. As widely known, PI controller is effective in fixed reference, however, if the reference is ellipsoidal, the final output value has always error from delayed response.

The easiest way to respond suitably for ellipsoidal reference, using PID controller to increase the pole of the controller's characteristic equation or adapting numerous higher gain of PI controller for reducing this final output error. However, D controller needs suitable filter for avoiding divergent output, higher gained PI controller can be very unstable operation for disturbance.

In this paper, feedforward controller is added to improve the dynamic of PI controller. To obtain the feedforward compensation current, voltage error between the back-EMF and the voltage limit can be obtained as (11) with (7).

$$\begin{aligned} V_{s\_err} &= V_{max} - V_{mag} \\ &= \frac{V_{dc}}{\sqrt{3}} - \sqrt{(\omega_r L_q i^r_{qs\_linear})^2 + (\omega_r L_d i^r_{ds\_linear} + \phi_f)^2} \end{aligned} \tag{11}$$

As shown on Fig. 4, because interpolated d-axis current reference generates proper current for the voltage limit, (11) can be changed to (12).

$$\begin{aligned} V_{s\_err} &= V_{max} - V_{mag} \\ &= \frac{V_{dc}}{\sqrt{3}} - \omega_r L_q \left| i^r_{qs\_linear} \right| \end{aligned} \tag{12}$$

To make this voltage error to zero, compensation feedforward q-axis current can be established as (13).

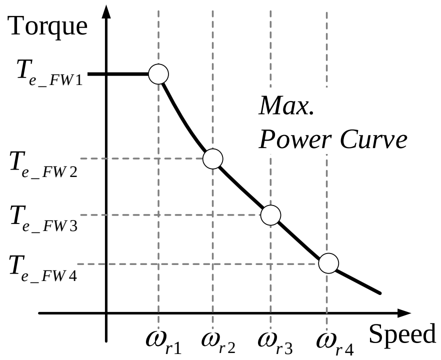


Figure 6. Field weakening operation start points of each speed

$$i^{r}_{qs\_ff} = \frac{V_{s\_err}}{\omega_r L_q} \tag{13}$$

With (13), proposed overall control block for q-axis compensation current is established as Fig. 5.
As aforementioned, interpolation error is hardly existed in constant torque operation region. Moreover, the back-EMF in this operation region has its own value at each operating point, compensating interpolation error in this operation region needs another back-EMF look-up table data according to each flux and torque. Therefore, in this paper, compensation block is deactivated while the PMSM is operating in constant torque operation region.

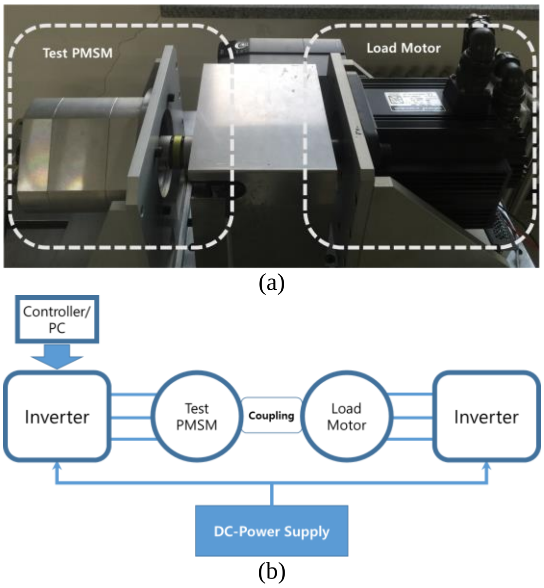


Figure 7. Experimental Msetup (a) Picture of the setup (b) Composition of the setup

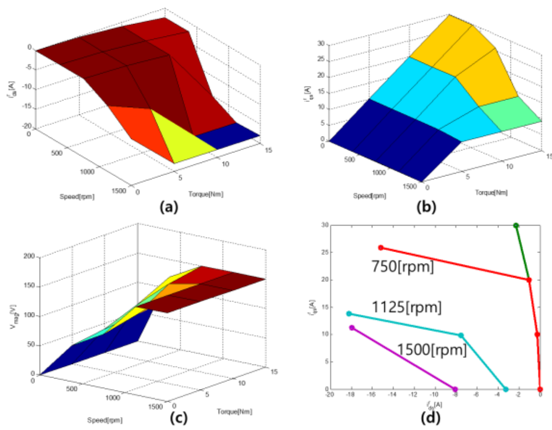


Figure 8. Current maps using in experiment (a) d-axis current map (b) q-axis current map (c) Back-EMF magnitude (d) dq-axis current maps plotting by dq-axis currents coordinates.

To reduce the stored memory for voltage magnitude, field weakening operation start points of each speed are obtained experimentally instead of obtaining voltage magnitudes all over the operation region. Fig. 6 shows the stored data of field weakening start points. As shown on the figure, as speed is increasing, generated torque is reducing to constant power generation. In addition, the error between practical torque-speed curve and linearly interpolated curve is hardly existed, the field weakening start torque, which is generated from flux-torque LUT of Fig. 5 can determine enable or disable compensation block. Instead of using speed input, estimated flux is used for reflecting input voltage variation. Converting method from speed to flux is simply defined as (14).

$$\lambda_r = V_{\max} / \omega_r \tag{14}$$

And then, activation condition of q-axis current compensation can be determined by following equation.

$$\begin{aligned} &if\,(T_e^* - T_{e\_FW} > 0) : \mathrm{sgn}(T_r^* - T_{e\_FW}) = 1 \\ &if\,(T_e^* - T_{e\_FW} \le 0) : \mathrm{sgn}(T_r^* - T_{e\_FW}) = 0 \end{aligned} \tag{15}$$

With this enable/disable control block, the proposed compensation block is only activated when the effect of compensation is maximized.

IOP Conf. Series: Materials Science and Engineering **600** (2019) 012024 doi:10.1088/1757-899X/600/1/012024

4. Experiment

To verify the proposed control algorithm, this paper uses experiment setup as Fig. 7. The test motor parameters are described in Table 1. Controller of inverter uses DSP, which is TMS320F28335 from Texas Instrument corporation.

Although this DSP has sufficient memory for storing current 2D-LUT data, for the worse environment configuration, the current map is constructed using very little memory compared to the conventional method.

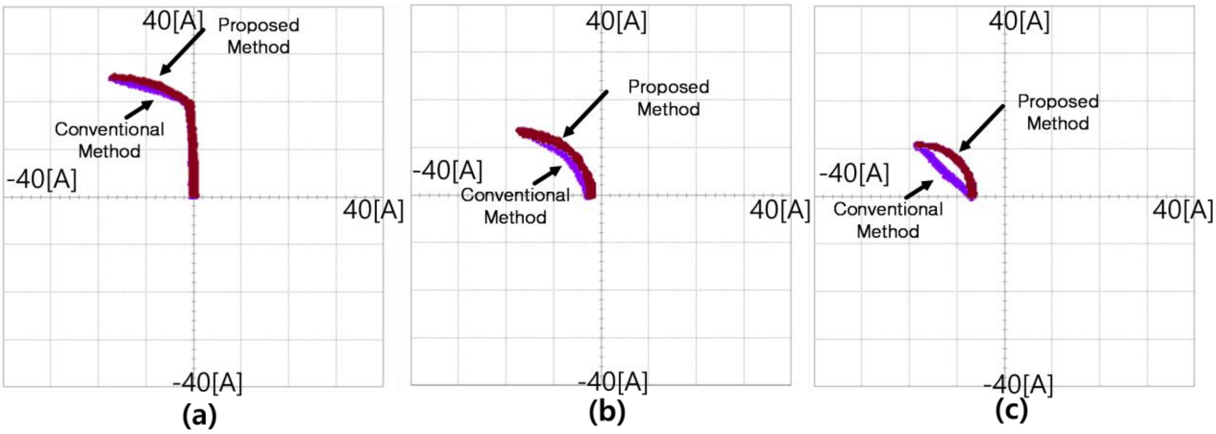


Figure 9. Comparison experimental results of the conventional and the proposed method with or without 2D-Interpolation compensation (a) 750[rpm] operation (b) 1150[rpm] operation (c) 1500[rpm] operation

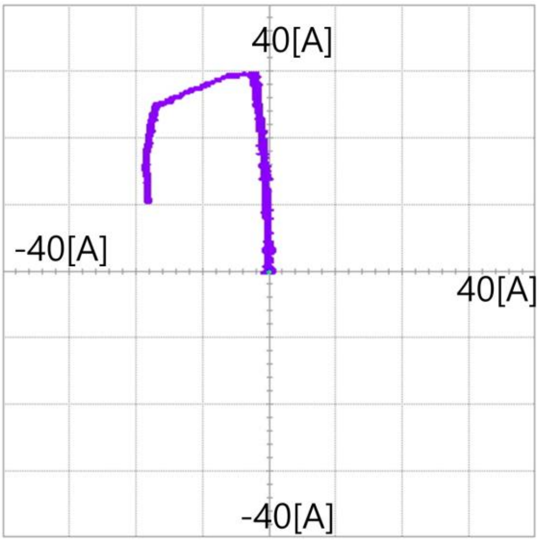


Figure 10. Experimental result of the maximum power control with proposed control method

The dq-axis current map for each speed-torque was measured through experiments by referring [6]. The results are shown in Fig. 8. In this paper, the experimental current map is stored at 1/3 of the rated torque and at 1/4 of the maximum driving speed. From this obtained speed-torque current map, it is transformed to flux-torque map with (14). As a result, it can be seen that only one torque data appears in the dq-axis current value for the torque command change at the maximum speed except for the dq-axis current value during the zero torque control. This is because the inductance expressed by the nominal value in the actual motor and the permanent magnet flux decreased due to the influence of saturation in the actual experiment.

Fig. 9 shows the comparison experimental results with or without proposed compensation method. It can be seen from the figure that the output is improved compared with the conventional method, and that it is controlled stably even in the speed region where the transition from the constant torque region to the weak field region is performed.
Fig. 10 shows the result of testing the maximum output control by increasing the speed of the load motor after setting the torque command to the maximum. As can be seen from the figure, it can be seen that the maximum output control is performed stably even if the proposed controller is added.

5. Conclusion
This paper proposes interpolation error compensation method for general flux-torque 2D-LUT based PMSM control method. To achieve this, firstly calculate the error between the back-EMF and the voltage limit in field weakening region, and then, obtaining q-axis compensation current from the controller, which input is this voltage error. To improve compensation control dynamic for ellipsoidal reference, feedforward controller, which is based on DC-link voltage, is attached on general PI controller.
With the proposed compensation blocks, generated power is enhanced than the power using only 2D-Interpolation method, although very restricted number of memory is allowed for flux-torque 2D-LUT. Proposed control method is verified by the experiment with test setup.

Table 1. Test motor parameters**.**

Pole	8
Phase resistance[mΩ]	20
d-axis inductance[mH]	2.03
q-axis inductance[mH]	2.13
Permanent magnet flux[Wb]	0.1439
Rated DC-link voltage[V]	48
Rated Torque[Nm]	15
Rated Speed[rpm]	200
Max. Speed[rpm]	1500
Max. Phase Current[A]	30

Acknowledgments
This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(NRF-2018R1C1B6008895).
This research was supported by Basic Science Research Program through the National Research Foundation of Korea(NRF) funded by the Ministry of Education(NRF- 2016R1A6A1A03013567).

References
[1] Y. Kusaka, E, Yamada, and Y. Kawabata, "Method and Apparatus for Driving and Controlling Synchronous Motor using Permanent Magnets as its Field System," US Patent 55169995, Oct, 1996.
[2] JaeHyuk Lee, JungHyo Lee, JinHo Park, ChungYuen Won, "Field-weakening strategy in condition of DC-link voltage variation using on electric vehicle of IPMSM" *IEEE-Conf. Electrical Machines and Systems* (ICEMS), pp. 1-6, Aug. 2011.
[3] Yang Nanfang, Luo Guangzhao, Liu Weiguo, Wang Kang, "Interior permanent magnet synchronous motor control for electric vehicle using look-up table" *Inter. Conf. on Elec. Mach. Sys.(ICEMS)*,pp.1015-1019,Jun.2012.
[4] Tae-Suk Kwon, Gi-Young Choi, Mu-Shin Kwak and Seung-Ki Sul "Novel Flux-Weakening Control of an IPMSM for Quasi-Six-Step Operation, " *IEEE-Trans. Ind. Appl.*, vol 44, no. 6 pp. 1722-1731, Nov. 2008.
[5] Bing Cheng, Tesch, T.R., "Torque Feedforward Control Technique for Permanent-Magnet Synchronous Motors," *IEEE-Trans. Ind. Elect.*, vol 57, no. 3, pp. 969-974, Mar. 2010.

IOP Conf. Series: Materials Science and Engineering **600** (2019) 012024 doi:10.1088/1757-899X/600/1/012024

[6] Jung-Hyo Lee, Chung-Yuen Won, Byoung-Kuk Lee, Hyun-Bae Kim, Jei-Hoon Baek, Kyu-Bum Han, U-In Chung, "IPMSM Torque Control Method Considering DC-link Voltage Variation and Friction Torque for EV/HEV applications," *IEEE-Conf., Vehicle Power and Propulsion Conference (VPPC),* pp.1063–1069, 2012.

[7] Marco Tursini, Enzo Chiricozzi, Roberto Petrella, "Feedforward Flux-Weakening Control of Surface-Mounted Permanent-Magnet Synchronous Motors Accounting for Resistive Voltage Drop", *IEEE-Trans. on Ind. Elec.*, vol 57, no. 1 pp. 440-448, Jan. 2010.

[8] Jin-Ho Park, Jung-Hyo Lee, Jae-Hyuk Lee, Chung-Yuen Won, "Current Control Method of IPMSM in Constant Power Region for HEV", *IEEE-Conf., Inter. Conf. on Elec. Mach. Sys.(ICEMS)*,pp.1015-1019, Aug.2011.

[9] Robert U. Lenke, Rik W. De Doncker, Mu-Shin Kwak, Tae-Suk Kwon, Seung-Ki SuI,"Field Weakening Control of Interior Permanent Magnet Machine using Improved Current Interpolation Technique" *IEEE-Conf. Power Electronics Specialists Conference (PESC),pp. 1-5,* 2006.

[10] Jorge G. Cintron-Rivera, Shanelle N. Foster, Carlos A. Nino-Baron, Elias G. Strangas, "High performance controllers for Interior Permanent Magnet Synchronous Machines using look-up tables and curve-fitting methods", *IEEE-Conf. International Electric Machines & Drives Conference (IEMDC),* pp. 268 - 275, 2013.

[11] Young-Doo Yoon, Wook-Jin Lee, Seung-Ki Sul, "New flux weakening control for high saliency interior permanent magnet synchronous machine without any tables",*IEEE-Conf. European Conference on Power Electronics and Applications (ECPEA)*, pp. 1 - 7, 2007.

[12] Shoudao Huang, Ziqiang Chen, Keyuan Huang, Jian Gao, "Maximum Torque Per Ampere and Flux-weakening Control for PMSM Based on Curve Fitting", *IEEE-Conf. Vehicle Power and Propulsion Conference (VPPC),* pp. 1 - 5, 2010.