Reduction of Torque Ripple in AC Motor Drives for Electric Power Steering

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***Abstract*—EPS(Electric power steering) have attracted much attention for their advantages with respect to improved fuel consumption and have been widely adopted as automotive power-steering equipment in recent years. In the EPS system, the fact that motor vibration and torque fluctuations are directly transferred through the steering wheel to the hands of the driver must be considered.**

Because of switching device and current offset according to the temperature variation, torque fluctuation in the motor has many undesirable harmonic ripples.

In this paper, the offset current error compensation method to overcome high temperature variation and compensation method to reduce current distortion caused by FET voltage drop and dead time for low voltage and high current applications is demonstrated.

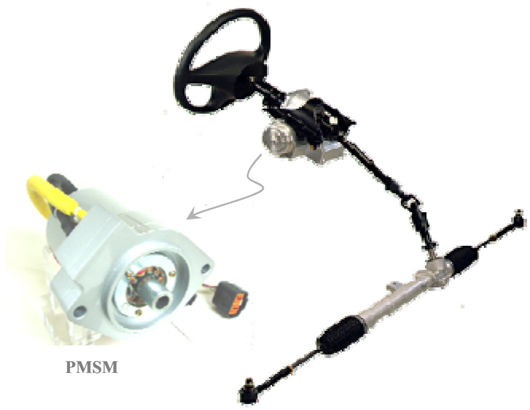


Fig.1. Column typed EPS system and PMSM

I. INTRODUCTION

Electric Power Steering(EPS) systems like Fig.1 have attracted much attention for their advantages with respect to improved fuel consumption(saving 3~6%, reduction of weight 3~5kg) and have been widely adopted as automotive power steering equipment in recent years.

The permanent magnetic field Direct Current(DC) motors are widely used for EPS system, but nowadays many engineers are trying to adopt the Permanent Magnet Synchronous Motor(PMSM). It is because the fact that motor vibration and torque fluctuations are directly transferred through the steering wheel to the hands of the driver must be considered[1][2].

It is most important to drive the motor with minimum fluctuations so that manufacturers have become aware of the torque fluctuations requirement to be 1~3% of rated torque. This motor for EPS has the following operating requirements: generating torque at standstill, reversing its rotation abruptly, small fluctuations in torque during operation, and very low vibration and noise.

To produce high dynamic performance and to reduce the torque fluctuation, many methods for the current control of ac motor drives have been developed. These include the hysteresis regulator[4], stationary and synchronous frame Proportional Integral(PI) regulator, and current measurement error[4]. Because of switching device and current measurement error, torque fluctuation in the motor has many undesirable harmonic ripples, which are, particularly, six, one and two times the stator electrical frequency[3][6][8].

Although the effect of current offset error and dead time compensation method were mentioned in [3] and [6], it has some problem for the low voltage and high current application(12V, 80A) and the high temperature variation like EPS system. In this paper, the offset current error compensation method to overcome high temperature variation and the compensation method to reduce current harmonics caused by dead time and high on-voltage of FET and diode for low voltage and high current applications are demonstrated.

II. CURRENT DISTORTION IN THE LOW VOLTAGE DRIVER

A. Offset Current by Temperature Variation

To detect accurately the current of PMSM is most important to drive smoothly the electric power steering. Many components are used to detect the motor current like hall effect current sensor, operational amplifier and analog to digital converter.

The current error can be produced because of the offset of current sensor output that has asymmetry between positive and negative source. Therefore, the output of sensor has non-zero voltage during current is not flowing. The direct current offset is produced by OP Amp. in A/D converter and its magnitude has relationship with resolution of A/D converter closely. Because the current sensor commonly has 1~3 LSB offset, offset current is scaled by current sensor offset and its magnitude is enlarged by current range increasing.

The current detection error produced by the above reason is compensated by differential between A/D conversion current value obtained before motor driving and real time A/D conversion current value during driving the motor.

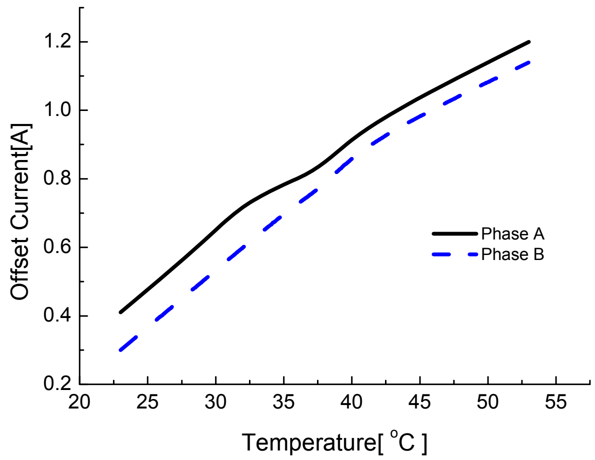


Fig.2. Offset current according to the temperature (Voltage typed Hall Effect Current Sensor,150A)

$$I_{as} = I_{as\_AD} - I_{asOffsetInit} \quad (1)$$

$$I_{bs} = I_{bs\_AD} - I_{bsOffsetInit} \quad (2)$$

Where, I_{as}, I_{bs} are motor phase current, I_{as_AD}, I_{bs_AD} are A/D conversion value and $I_{asOffsetInit}$, $I_{bsOffsetInit}$ are A/D conversion value at before running(initial offset value).

Although the offset current can be detected and compensated, it is difficult to detect and compensate in the system which temperature is varied extremely, because an offset is increased by hall effect sensor and OP Amp. A/D converter on the detection pass.

The component to measure motor current are composed of current sensor, operational amplifier and A/D converter. Widely used hall effect current sensor has more severe offset value than any other components according to the temperature drift. Fig.2 shows offset value according to temperature. The temperature drift from 25 $°C$ to 55 $°C$ produces 1A current offset in case of 150A rated sensor.

Especially, the automotive system has very high temperature drift(40~50 degree) between starting and driving so that temperature variation must be considered.

Torque distortion is caused by offset current[3]. To consider the current offset effect, stationary reference frame *d, q* axis current and rotating reference frame *d, q* axis current are expressed to (3), (4) and (7), (8) respectively.

$$I^s_{qs\_AD} = I_{as\_AD} = I_{qs} + \Delta I_{as} \quad (3)$$

$$I^s_{ds\_AD} = -\frac{1}{\sqrt{3}}\left(I_{as\_AD} + 2I_{bs\_AD}\right) = I_{ds} - \frac{1}{\sqrt{3}}\left(\Delta I_{as} + 2\Delta I_{bs}\right) \quad (4)$$

Where, $I^s_{qs\_AD}$, $I^s_{ds\_AD}$, I_{as_AD}, I_{bs_AD}, ΔI_{as}, ΔI_{bs} are stationary reference frame *d, q* axis current, phase *a* and phase *b* sensing current and phase *a* and phase *b* offset current respectively.

If current controller controls current using the $I^s_{qs\_AD}$, $I^s_{ds\_AD}$ in the steady state, real motor current is like (6) so that stationary frame current locus is shifted like Fig.3.

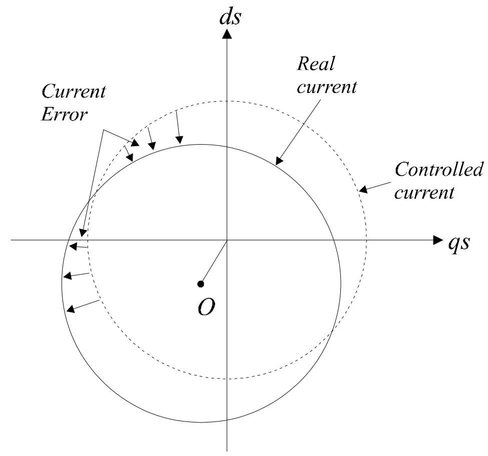


Fig.3. Stationary frame current locus caused by offset

$$I^s_{qs\_AD}{}^2 + I^s_{ds\_AD}{}^2 = I^2 \quad (5)$$

$$\left(I^s_{qs\_AD} + \Delta I_{as}\right)^2 + \left(I^s_{ds} - \frac{1}{\sqrt{3}}\left(\Delta I_{as} + 2\Delta I_{bs}\right)\right)^2 = I^2 \quad (6)$$

$$I^e_{ds\_AD} = I^e_{ds} + \Delta I^e_{ds} \quad (7)$$

$$I^e_{qs\_AD} = I^e_{qs} + \Delta I^e_{qs} \quad (8)$$

where, I^e_{qs}, ΔI^e_{qs} are rotating reference frame *q, d* axis current respectively.

$$I^e_{ds} = I^e_{ds\_AD} - \Delta I^e_{ds} = I^{e*}_{ds} - \Delta I^e_{ds} \quad (9)$$

$$I^e_{qs} = I^e_{qs\_AD} - \Delta I^e_{qs} = I^{e*}_{qs} - \Delta I^e_{qs} \quad (10)$$

$$I_{as} = \cos\theta_e,\ I_{bs} = \cos\left(\theta_e - \frac{2}{3}\pi\right),\ I_{cs} = \cos\left(\theta_e + \frac{2}{3}\pi\right) \quad (11)$$

Equation(12) is according to (9), (10), (11).

$$\Delta I^e_{qs} = \frac{2}{\sqrt{3}} \cdot \sqrt{\Delta I^2_{as} + \Delta I_{as}\Delta I_{bs} + \Delta I^2_{bs}} \cdot \sin\left(\theta_e + \alpha\right) \quad (12)$$

where,

$$\alpha = \tan^{-1}\left(\frac{\frac{\sqrt{3}}{2}\Delta I_{as}}{\frac{1}{2}\Delta I_{as} + \Delta I_{bs}}\right) = \tan^{-1}\left(\frac{\sqrt{3}\Delta I_{as}}{\Delta I_{as} + 2\Delta I_{bs}}\right) \quad (13)$$

and θ_e is electrical angle of motor driving frequency.

By same processing, rotating reference frame *d*-axis current is expressed (14).

$$\begin{aligned}\Delta I^e_{ds} &= \frac{2}{3}\left(-\sin\theta_e \Delta I_{as} - \sin\left(\theta_e - \frac{2}{3}\pi\right)\Delta I_{bs}\right) \\ &\quad - \frac{2}{3}\left(\sin\left(\theta_e + \frac{2}{3}\pi\right)\left(-\Delta I_{as} - \Delta I_{bs}\right)\right) \\ &= \frac{2}{\sqrt{3}} \cdot \sqrt{\Delta I^2_{as} + \Delta I_{as}\Delta I_{bs} + \Delta I^2_{bs}} \cdot \cos\left(\theta_e + \alpha\right)\end{aligned} \quad (14)$$

Stator currents are transduced to the voltage signal by current sensor and transformed into digital values via A/D converter. If DC offset current is superimposed on the real current, measured synchronous q-axis current can be expressed like (12). Equation(12) means that offset current by temperature variation causes the torque oscillation at the electrical frequency.

Since d-axis rotor flux is the output of the first order filter with rotor time constant, it is nearly unaffected and can be assumed to be constant[3].

$$T_e = \frac{3}{2}\cdot\frac{P}{2}\cdot\lambda_{dr}^e\cdot I_{qs}^e = K_T\cdot\left(I_{qs}^{e*} - \Delta I_{qs}^e\right) \qquad (15)$$

$$\Delta T_L = K_T\cdot\frac{2}{\sqrt{3}}\cdot\sqrt{\Delta I_{as}^2 + \Delta I_{as}\Delta I_{as} + \Delta I_{bs}^2}\cdot\sin\left(\theta_e + \alpha\right) \qquad (16)$$

Where, T_e, ΔT_L, λ_{dr}^e, K_T are motor torque, torque ripple, rotor flux and torque constant .

From (16), offset current makes 1times electrical frequency torque fluctuation.

B. Current Distortion by Voltage Drop of FET and Dead Time

Field Effect Transistor(FET) is widely used for the automotive application like EPS, which is able to minimize on voltage of the switch. However, the different on voltage level in the FET and diode in the Fig.5 makes difficult to the dead time compensation and causes current distortion. And R_{ds} of FET makes voltage distortion which generates current harmonics.

Considering the dead time T_d, turn on time t_{on} and turn off time t_{off}, the relationship between the a-phase ideal and actual inverter voltages for $I_a>0$ is shown in Fig.6. Due to the similar voltage drop and voltage saturation between switch and freewheeling diode in the high voltage inverter using the IGBT, consideration of voltage drop in the switch is not important.

However, the voltage drop in the low voltage inverter should not be disregard because voltage drop in the switch is proportional to the phase current and on voltage of FET and diode has different level(refer to Fig.5). Therefore, voltage drop in the switches and diodes are considered in the dead time compensation.

III. MINIMIZATION OF CURRENT DISTORTION

To overcome the current distortion offset, CPU reads the current offset value before starting the AC motor and then the sampled current during motor running is subtracted to the measured offset value. On-line current offset method differentiating speed signal was proposed but it is difficult to apply to the high frequency conditions due to its high sensitivity.

In this paper, to measure the offset current at a given ω_e, the speed ripple is measured at the ω_e frequency using the Discrete Fourier Transform (DFT). This form of Fourier analysis is implemented in the DSP as a running sum. The

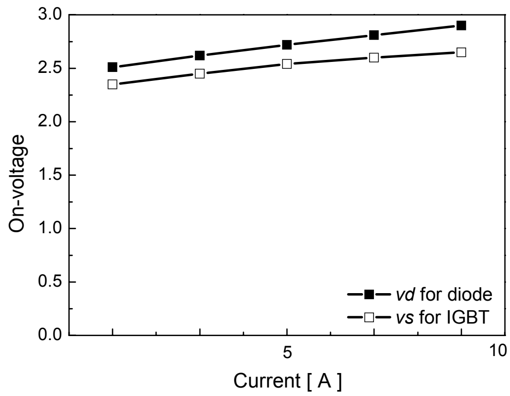


Fig.4. On Voltage of High Voltage IGBT and Diode

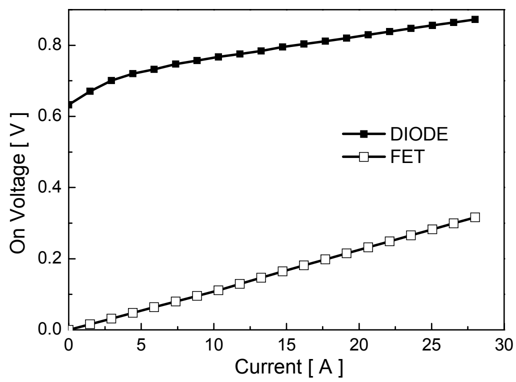


Fig.5. On Voltage of Power FET and Diode(Low Voltage)

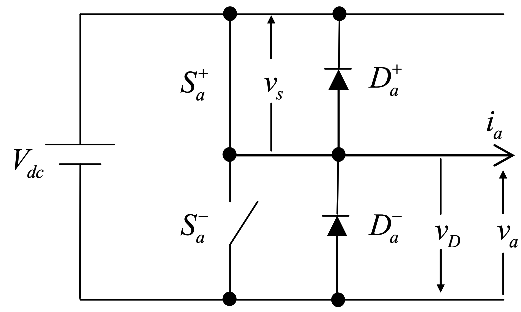


Fig.6. One arm of inverter($Ias>0$)

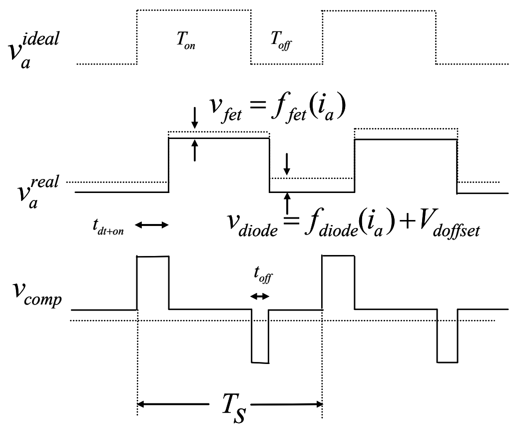


Fig.7. A-phase ideal voltage and real voltage($ia>0$)
(V_s: on voltage of FET, V_d : on voltage of diode)

current offset value(I_{offset}) is calculated from inertia, damping and torque coefficient. Then, I_{offset} is updated and used as a compensation value, when the ω_e remains constant for a while.

$$\omega_r(\omega_e) = \frac{1}{N}\sum_{n=0}^{N-1}\omega_r(nT_s)\cdot e^{-j\omega_e nT_s} \quad (17)$$

$$\Delta I_{offset} = \frac{DFT(\omega_r)}{K_T}\cdot(J\cdot\omega_e + B) \quad (18)$$

$$I_{as} = I_{asAD} - I_{asOffset} \quad (19)$$

$$I_{bs} = I_{bsAD} - I_{bsOffset} \quad (20)$$

$$I_{asOffset} = I_{asOffsetInit} + \sum \Delta I_{Offset} \quad (21)$$

$$I_{bsOffset} = I_{bsOffsetInit} + \sum \Delta I_{Offset} \quad (22)$$

In Fig. 2, the initial offset between $I_{asOffsetInit}$ and $I_{bsOffsetInit}$ is different but the drift has similar characteristic according to temperature. Therefore, the initial offset can be obtained from each phase and the drift according to temperature can be commonly compensated by each phase. The block diagram of proposed method is shown in the Fig. 8.

For low cost, the one current of three phases is estimated by calculation of two phase currents detected. And the offset value to compensate current offset of each phases is extracted by speed that calculated by resolver to detect position of rotor. The flowchart of current offset calculation algorithm is shown in the Fig. 9.

Whether ΔI_{offset} has positive or negative value, it is decided by (23).

$$sign\left[DFT(\omega_r)(n) - DFT(\omega_r)(n-1), \Delta I_{offset}(n-1)\right] \quad (23)$$

To overcome 6 times current distortion of rotating reference frame in the low voltage AC drivers, the voltage drop of FET and diode must be considered like 22. This compensation voltage(V_{comp}) is added to final reference PWM voltage command.

$$V_{comp} = (t_{dt+on} - t_{off})\cdot V_{dc} + V_{fet}\cdot\frac{(T_{on} - t_{on} + t_{off})}{T_s} + V_{diode}\cdot\frac{(T_{off} - t_{off})}{T_s} \quad (24)$$

where, $V_{diode} = f_{diode}(i_{as}) + V_{doffset}$, $V_{fet} = i_{as}R_{ds}$ and t_{dt+on} , t_{off} , T_{on} , T_{off} refer to Fig.7.

During supplying any offset, the result of offset(simulated by Matlab) estimated by algorithm presented in this study is shown in the Fig. 10 and the offset is compensated comparatively.

The voltage compensation value during increasing speed, according to increasing the PWM duty, to confirm the compensation effect of voltage distortion is shown in the Fig. 11. The positive voltage compensation value is larger than the

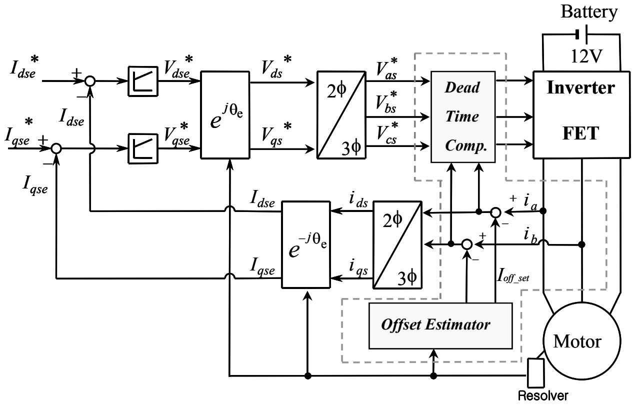


Fig.8. Block diagram of proposed compensation scheme

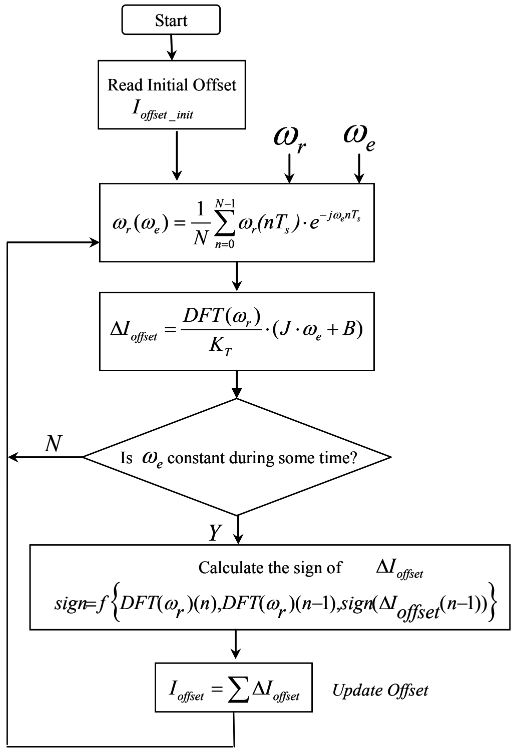


Fig.9. Flow Chart of Current Offset Calculation

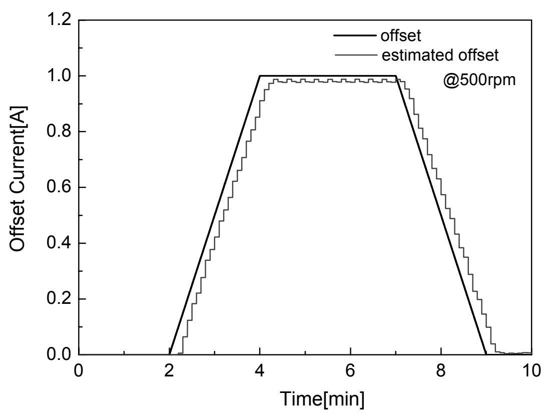


Fig.10. Offset Simulation result caused by Temperature Drift (Simulation by Simulink)

negative voltage compensation value when motor speed is low, but the voltage compensation value in high speed domain has opposite tendency, because the on-voltage of the diode is larger than on-voltage of power FET at high voltage.

The voltage compensation value according to the phase current is shown in Fig. 12.

IV. Experimental Results

The specification of permanent magnet synchronous motor and driver for test is presented at the Table I. Normal DC link

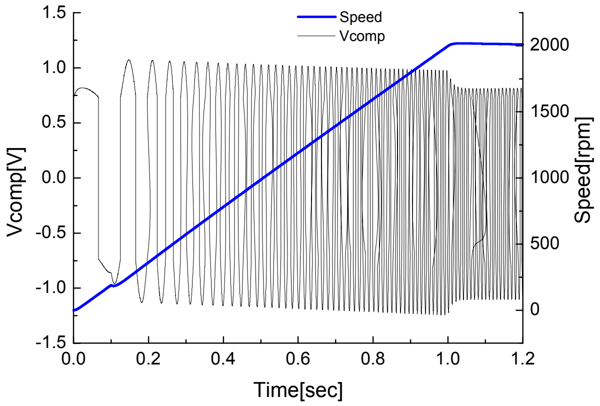


Fig.11. Distortion Voltage compensation according to the speed

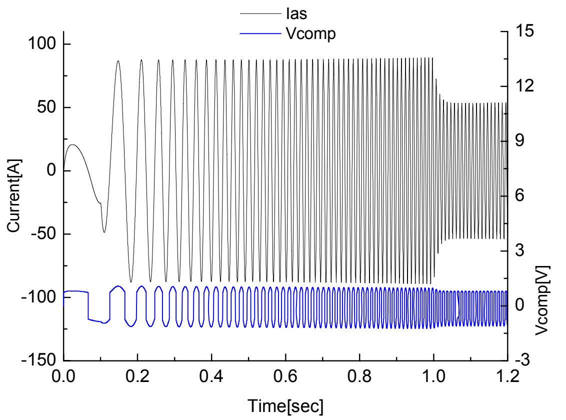


Fig.12. Dead time compensation voltage and phase current

TABLE I

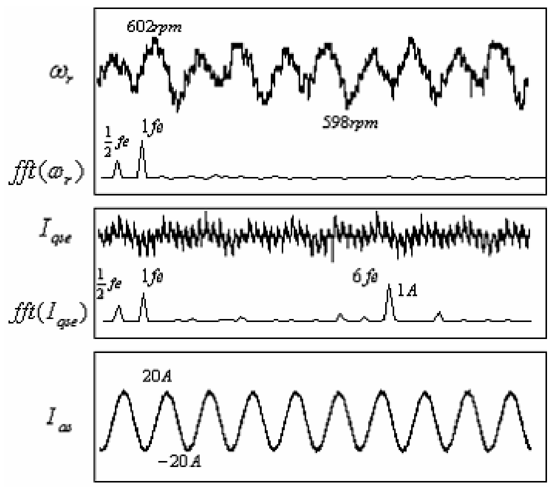
Brief Specifications of PMSM and Driver

Parameter	Value	Remark
PMSM Pole	6Pole	
Normal DC Link Voltage	12V	
Rated Current	80 A	Motor
Rated torque	5Nm	
Rated speed	2100 rpm	
Rotor Position Sensing	Resolver	
CPU	TMS320F2811	TI DSP
FET	160A, 55V	R_{ds} 5mΩ

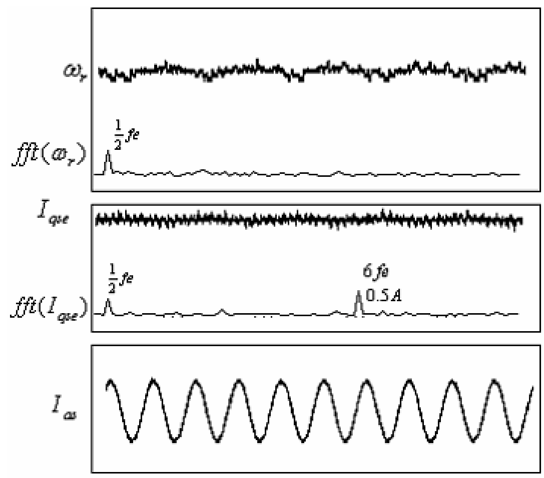
voltage(battery voltage) is 12V and rated current of permanent magnet synchronous motor is 80A. Resolver was installed in the rotor shaft to minimize the torque distortion caused by rotor position error.

In the Fig.13, the test results of conventional and proposed method in the 12V EPS motor are shown. Where ω_r, $fft(\omega_r)$, I_{qse} and I_{as} mean motor speed, FFT of motor speed, rotating frame q-axis current and motor phase current respectively. In the conventional method, $1/2\,f_e$ frequency is caused by mechanical problem and $1f_e$ is by offset current according to temperature variation. $6f_e$ frequency does not appeared in the speed component, however it appears in the I_{qse} component. In the proposed method, $1f_e$ frequency ripple is removed perfectly and $6f_e$ frequency ripple of I_{qse} is reduced by 50%.

Test result of PMSM according to temperature variation



(a) Conventional method
(with only initial offset compensation, 600rpm)



(b) Proposed method compensation

Fig.13 Experimental results of conventional and proposed method
(30degree variation after starting, 600rpm)

TABLE II

TEST RESULT OF TORQUE RIPPLE WITH PROPOSED ALGORITHM

Torque[Nm]	Torque Ripple[%] @25°C	Current THD [%] @ 25°C	Current THD [%] @ 85°C
1	9.10	2.94	2.97
2	4.90	2.62	2.81
3	4.60	2.52	2.49
4	3.54	1.66	1.38
5(rated)	2.86	1.40	1.37

and torque is presented in the Table II. By using the proposed algorithm, current distortion is not increased although the temperature is drifted by $60\,°C$ and torque ripple at the rated torque is less than 3%.

V. CONCLUSION

In this paper, to minimize the torque and current distortion for EPS application(low voltage and high current applications), the offset current error compensation method to overcome high temperature variation and voltage compensation to minimize current harmonics caused by FET voltage drop and dead time is demonstrated.

Proposed algorithm was verified by simulation and experiment. Current distortion was not increased according to temperature drift and torque ripple at the rated torque was less than 3%.

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