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BLDC Motor Drive System of Air-condition of Hybrid Electric Vehicle

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Abstract — Recently the research and development of electric compressor in the electric automobile have being focused on. In HEV (Hybrid Electric Vehicle), the engine is turned off in the case of stop to raise fuel efficiency and prevent air pollution. The conventional air conditioner system which is worked by the engine power through belt connection can't provide cool air to inside at the time of engine stop. Therefore, the full or hybrid electric compressor is applied for HEV. In this paper, the motor drive system of hybrid electric compressor which is using IPM type PMSM for HEV has been studied and a novel curve fitting method for getting maximum torque per unit current is proposed..

I. INTRODUCTION

As the number of passenger car is increasing rapidly the air pollution and the energy exhaustion are becoming the most serious global problem in the future. In addition, the cost of oil is going up continuously, so the customer demand for the high fuel efficiency car is increased nowadays [1].

HEV (Hybrid Electrical Vehicle) becomes commercialized recently because of high fuel efficiency and low air pollution. The highest output power system except the traction motor is an air conditioner compressor in HEV system.

If the conventional air conditioner system which is worked by the engine power through belt connection is applied for HEV, it can't provide cool air to inside of car at the time of idle stop. Therefore, the full or hybrid electric compressor should be applied for HEV [2], [3]. The full electric compressor is driven by only electric motor, and the hybrid electric compressor is driven by the combination of engine power and electric motor. The full electric compressor requires large output power motor and high capacity battery. On the contrary, the general HEC (Hybrid Electric Compressor) requires the half power motor and drive system of the full electric compressor because the rated output power of motor drive system is designed to charge the minimum cooling capacity at the time of idle stop. Therefore, this hybrid electric is more economical and practical solution.

In this paper, we studied about the motor drive system of hybrid electric compressor for HEV. The applied voltage specification is 42V, an IPMSM (Interior Permanent Magnet Synchronous Motor) is designed and applied as the compressor drive motor. In order to control the motor DSP controlled inverter drive system is designed. The Allometic Curve Fiiting method and the Back EMF compensation method are applied for driving performance improvement.

A novel IPM which is suitable for electric compressor has been proposed. By using the proposed novel curve fitting method the maximum torque per unit current can be achieved. The position information of the rotator is gotten from the proposed virtual encoder. In this way the presumption performance of motor's phase current is improved. The feasibility of above method has been improved by simulation and the effect is better than the control method of existing system. The structure of hybrid electric compression system is shown as fig.1. The compressor is connected with the motor in parallel through the engine and the inverter.

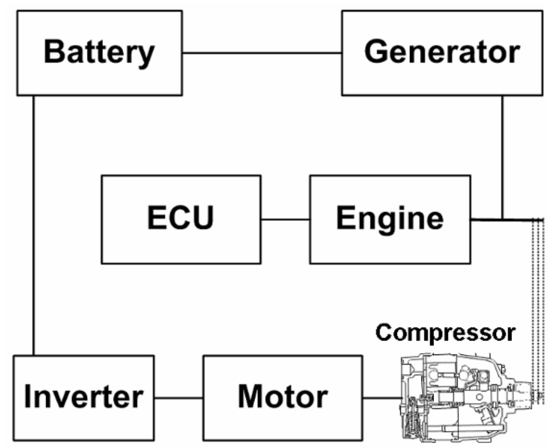


Fig.1 Structure of hybrid electric compression system

II. IPMSM DESIGN FOR HEC

As a compressor drive motor, IPMSM using NdFeB magnet is designed suitably to the specification those are the applied voltage 42V, the rated output 2kw and the max speed 7,500 rpm.

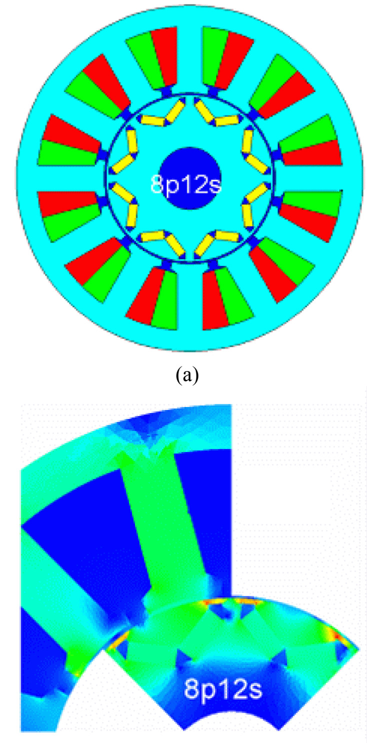
The main design points are to enhance high temperature operating stability and high torque density per volume. The compressor driving motor is generally located at the inside of compressor cell. The operating temperature of motor is over than 100℃ because the pressure of inner side of compressor is very high. And, the low voltage application like as 42V causes that the current density of winding coil becomes higher in order to generate the rated output power.

In this study, 8/12 pole IPMSM is optimally designed by DOE (Design Of Experiment) and RSM (Response Surface Method). The simulated efficiency of rated output power is over than 90 %.

The design of the proposed IPM for electric compressor of the electric automobile is shown as fig. 2. There are rotor of 8-poles and stator of 12-poles in this structure.

The section of the IPM is shown fig. 2(a) and the analysis on magnetic field of IPM is shown fig. 2(b).

The results of magnetic field analysis are shown as Table 1.



(a)

(b)

Fig.2 Design of the IPM
(a) Section of the IPM
(b) Analysis on magnetic field of IPM

	E-L Map		Initial Design	
	Parameter Scope	Maximum Efficiency Branch	8p9s	8p12s
D Axis Inductance	0.01~ 0.2mH	0.09mH	0.161mH	0.099mH
Phase Counter Electromotive Force	13 ~ 16 V	15.4 V	14.66 V	14.25V
Lq/Ld	1.5	1.5	1.44	1.63
Current	47 ~ 53 A	48 A	48A	48A
Current Phase Angle	0 ~ 50°	28°	28°	28°

Table 1 the result of magnetic field analysis

III. Design of Controller

In the inverter circuit design for low voltage and high power, the high current commutation is an important design consideration point. The MOSFET is selected as the high frequency switching device, and two MOSFETs are connected in parallel to commutate high current. It is a good solution for the economical feasibility and the reliability.

DSP TMS320F is used as a control processor, and the peripheral circuit is designed. The Allometic 1 curve fitting method is utilized to simplify the nonlinear high order relationships between d-axis current and q-axis current for the maximum torque production per unit current.

In the sinusoidal current controller, the BEMF compensation technique is applied to reduce response time and eliminate harmonic torque current component.

In this control method, the current distortion is reduced, and the output torque characteristics are improved.

The voltage equation of IPM is

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + P\left\{ \begin{bmatrix} a+b\cos 2\theta_r & -b\sin 2\theta_r \\ -b\sin 2\theta_r & a-b\cos 2\theta_r \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \Phi_f \begin{bmatrix} \cos\theta_r \\ \sin\theta_r \end{bmatrix} \right\} \quad (1)$$

Here,

$$L_d = \frac{3}{2}(L_0 - L_2), L_q = \frac{3}{2}(L_0 + L_2), a = \frac{L_q + L_d}{2}$$

$$b = \frac{L_q - L_d}{2}$$

The torque equation of IPM is able to be derived from the output of electromotor. The torque equation is

$$T_e = \frac{3}{2}\frac{P}{2}(\Phi_f i_q + (L_d - L_q) i_d i_q) \quad (2)$$

In equation (2), the first term is depend on the torque in permanent magnet, the second term is depend on the torque in salient characteristic, so the SPM(Surface Mounted Permanent Magnet Motor) can be consider as a special kind of IPM.

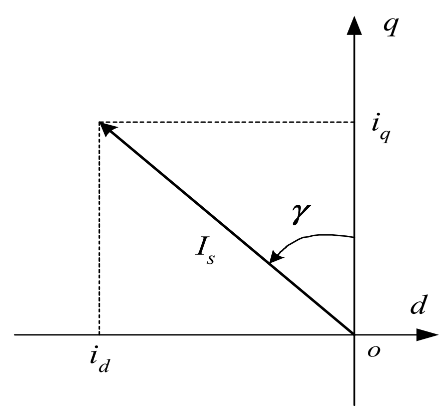


Fig. 3 Phase diagram of stator current

As shown as fig. 3 if expressed with I_s of the stator current and the phase-angle γ, i_d and i_q can be shown as

$$i_d = -I_s \sin\gamma$$
$$i_q = I_s \cos\gamma \quad (3)$$

The torque equation is able to be expressed to equation (4) from equation (3).

$$T_e = \frac{3}{2}\frac{P}{2}(\Phi_f I_s \cos\gamma + \frac{1}{2}(L_q - L_d) I_s^2 \sin 2\gamma) \quad (4)$$

In equation (4), the magnetic torque is proportioned to $\cos\gamma$ which is the function of current phase angle, and the reluctance torque is proportioned to $\sin 2\gamma$. So from that, whole torque equation is determined. Fig. 4 shows the waveform of the torques by magnet and reluctance defending on the current phase angle γ.

In fig. 4 when maximum torque is assumed to 1, at the point of maximum torque, the torque by permanent magnet is 70% of a total torque and reluctance torque is about 30% of a total torque. When γ is 0°, the magnetic torque is maximum. When γ is π/4, the reluctance torque is maximum. Because total torque which is the sum of magnetic and reluctance torques, the maximum value is between the two maximum torques.

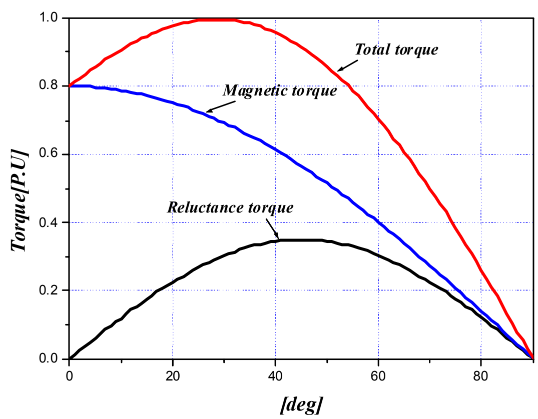


Fig.4 Torque element of the IPM

The way of achieving maximum sum of magnetic torque and reluctance torque is "maximum torque per unit current control" method. The torque control is decided by the largest torque per unit current.

For getting maximum torque per unit current, the equation (4) can be rewritten as

$$T_e = \frac{3}{2}\frac{P}{2}(L_d - L_q)i_q(\frac{\Phi_f}{L_d - L_q} + i_d) \tag{5}$$

$$(i_d, i_q) = (\frac{\Phi_f}{L_q - L_d}, 0) \tag{6}$$

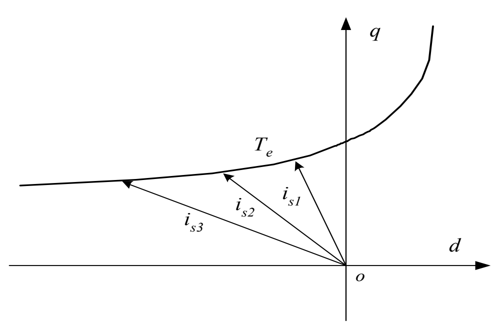


Fig. 5 Current trace of the uniform toque

Fig. 5 is the current trace of the uniform toque. There are lots of current solutions for necessary torque; i_d and i_q of maximum torque per unit current should be searched.

As shown in Fig. 6, we seek the locus of the point of intersection, i_d and i_q between I_{sn} with radios circle. It is distance of the shortest.

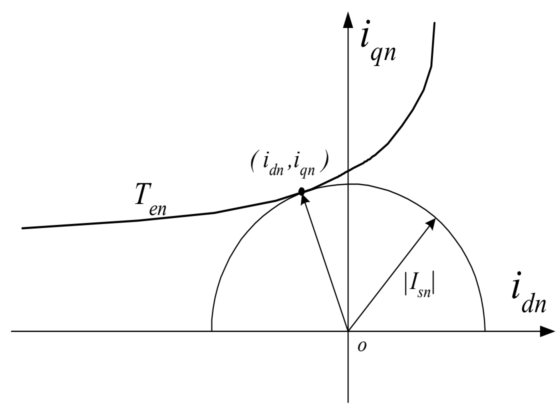


Fig. 6 Current according to discretional toque curve

The toque equation is

$$T_{en} = \sqrt{i_{dn}(i_{dn} - 1)^3} \tag{7}$$

$$T_{en} = \frac{i_{qn}}{2}[1 + \sqrt{1 + 4i_{qn}^2} \tag{8}$$

The toque equation is the showed as the 4 order equation of the normalization current. The nonlinear solution can be sought which is

$$i_{dn} = \frac{3}{4} - \frac{a_1}{b_1} - \frac{c_1}{d_1} \tag{9}$$

$$i_{qn} = \frac{T_{en}}{1 - i_{dn}} \tag{10}$$

Here,

$$\left\{ \begin{array}{c} a = T_{en}^2 \\ k_1 = -9a + \sqrt{3}\sqrt{27a^2 + 256a^3} \\ a_1 = \sqrt{-773728^{1/3}a + 3k_1^{1/3} + 96^{1/3}k_1^{2/3}} \\ b_1 = 4\sqrt{3k_1^{1/6}} \\ c_1 = \sqrt{3^{3/2}\sqrt{k_1} + 96^{2/3}aa_1 - 12^{1/3}k_1^{2/3}a_1} \\ d_1 = \sqrt{24k_1^{1/6}}\sqrt{a_1} \end{array} \right.$$

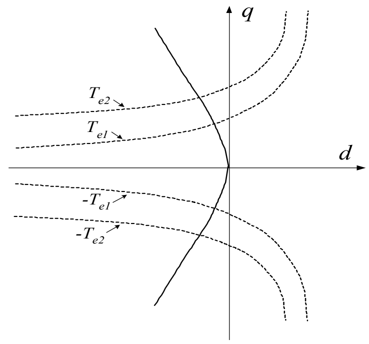


Fig. 7 The locus of maximum torque per unit current

Fig. 7 is the locus of maximum torque per unit current. The solution of the equation (9), (10) and is very complicate to be applicable in practical system. In this paper, to find the relational expression of the i_q and i_d current, the curve fitting method is used easily in microprocessor. The curve fitting method here uses the Allometic1 technique.

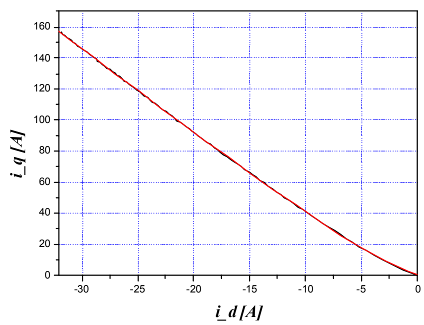


Fig. 8 Result of the curve fitting

In fig. 8, the black line shows the relationship of the d-q axis current which is got from equation (9), (10) and the red line shows the Allomitic1 curve fitting technique by equation (11). It can be expressed by the 5order function.

$$i_q = 3.2169 \cdot 10^{-6} \cdot i_d^{\,5} + 3.16589 \cdot 10^{-6} \cdot i_d^{\,4} + 0.0122 \cdot i_d^{\,3} + 0.24359 \cdot i_d^{\,2} - 2.260869 \cdot i_d \quad (11)$$

Fig. 9 shows curve fitting error. Error is under 0.1% at all regions.

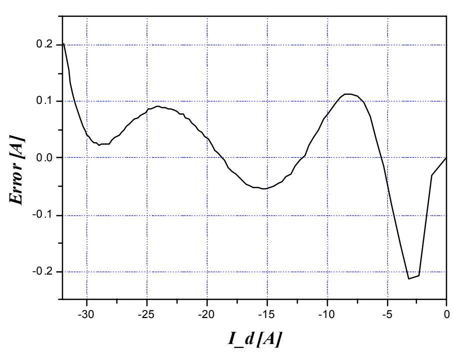


Fig. 9 Curve fitting error

The position information of the rotor is necessary along the switching accomplished in IPM.

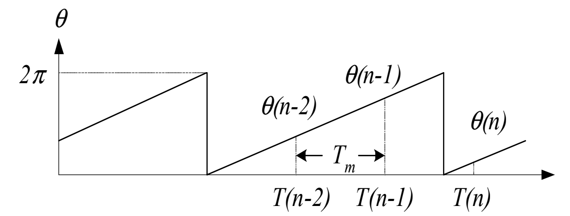


Fig. 10 Conventional method

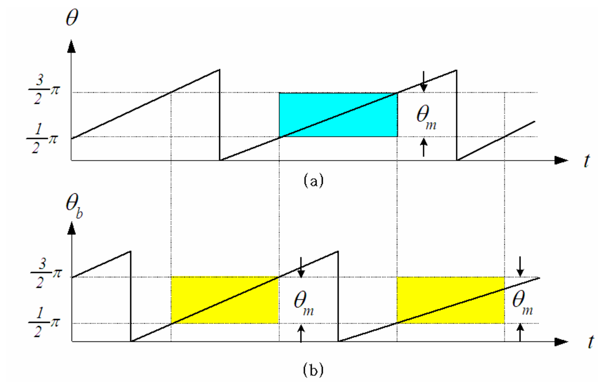


Fig. 11 Proposed method

Generally when detecting the speed of motor, position-detecting sampling time is set to constant according to the basic frequency of oscillator. The number of pulse during Tm time is decided by the counter of encoder, but it overflows each 360° mechanically. For example shown as fig. 11, in time between T(n-2) and T(n-1) without overflow the number can be made by the subtraction of present counter value and last one. But in time between T(n-1) and T(n) with overflow, there is some problem because it is not only use the subtraction of present counter value and last one but also need think about the direction of mechanical rotation.

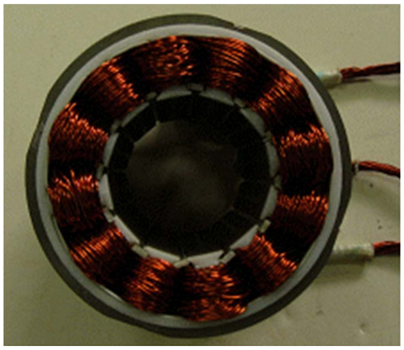
In this paper a novel method is proposed. For getting the angle displacement of encoder irrelevant of overflow in timer, the virtual encoder with 180° phase difference in program is applied to system. The proposed method is shown as fig. 11. The angle displacement is taken with real angle displacement during 90° to 270° and with the virtual angle displacement in other area. By this way the angle displacement during Tm time can be taken irrelevant of the angle overflow and rotation direction.

IV. Experiment Results

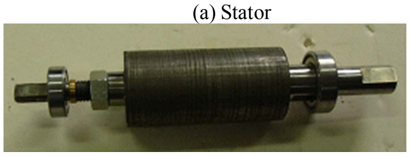
The proposed motor drive system for HEC is configured, and the driving characteristics are verified.

In the driving performance test, the rated driving characteristics and maximum output characteristics are ensured. The rated driving efficiency is over 92 %, so it will be a high efficient compressor drive

Fig. 12 shows the structure of rotor and stator of the prototype IPM which is manufactured for the compressor used for automobile.

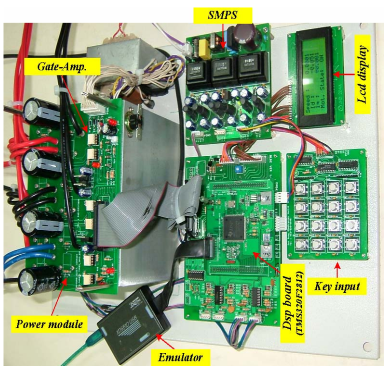


(a) Stator

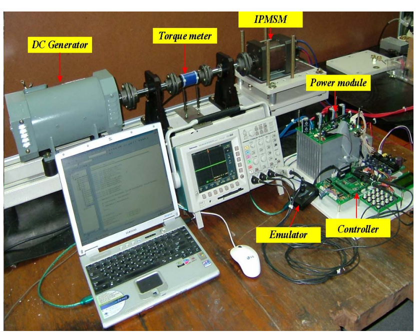


(b) Rotor

Fig. 12 structure of the rotor and stator



(a)



(b)

Fig. 13 power circuit and controller of the IPM

Fig. 13 shows the photo of the test system. The load is DC motor, and the torque sensor (NC-T100-175-R) is applied to measure the torque.

Stator pole number	12	rotor pole number	8
Stator pole arc	16°	rotor pole arc	20°
stator outside diameter	102.4 mm	rotor outside diameter	48.4 mm
Gap	0.2 mm	iron core length	28.0 mm
appropriate inertia value	140 turn	conductor diameter	0.52 mm
appropriate resistance	2.0Ω	regular speed	3000 rpm

Table.2 Design parameters of the experimental IPM

Table.2 shows the design parameters of the experimental motor.

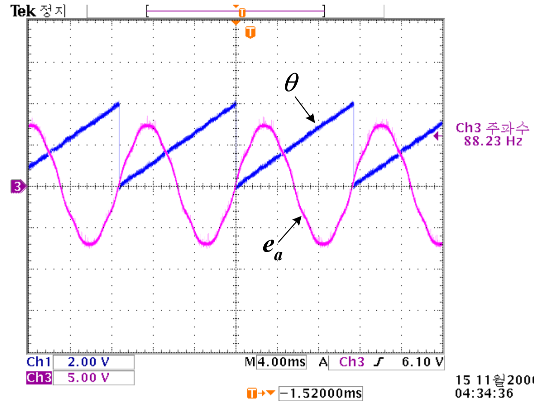


Fig. 14 Angle and emf waveforms

Fig. 14 is the waveform measuring the electromotive force in the rotor position angle of the IPM. The electromotive force contains the 5 harmonic and 9 harmonic components.

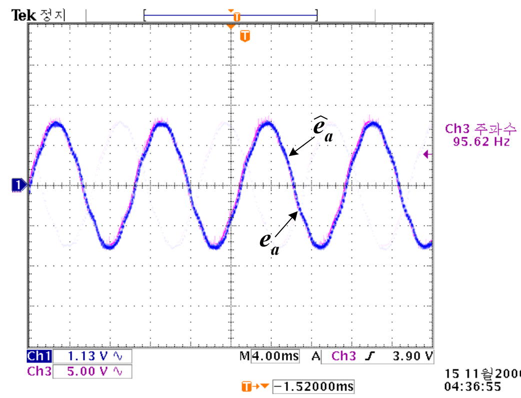


Fig. 15 Waveforms of actual emf and estimated emf

Fig. 15 is the waveforms which are the comparison between the estimate a-phase electromotive and the practical electromotive force.

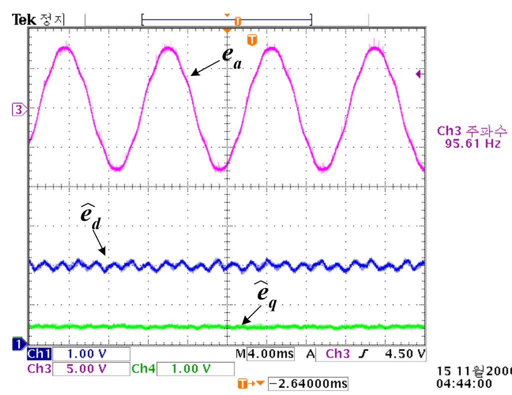


Fig. 16 Emf and d-q estimate emf waveforms

Fig. 16 shows the waveforms of the estimated d-q electromotive force at a-phase electromotive force.

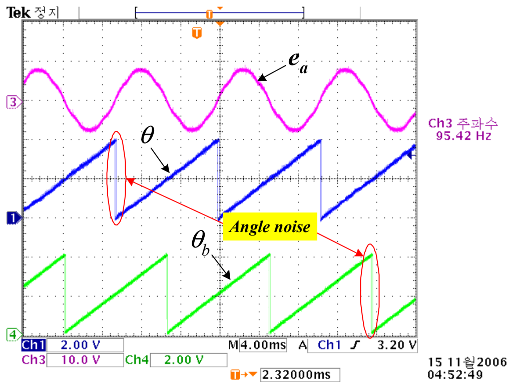


Fig 17 Emf, actual angle and virtual angle

Fig. 17 is the waveform which shows the supposed angle which holds the phase offset of the practical angle and 180^o phase offset.

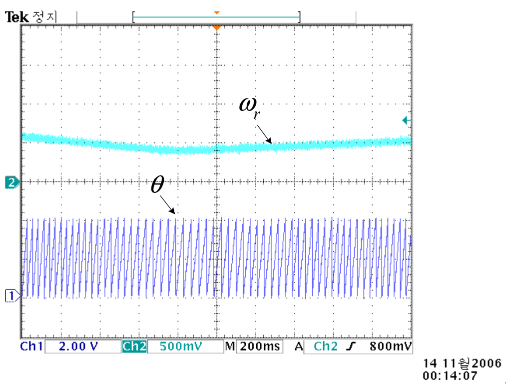


Fig. 18 Waveforms of rotor position and speed

Fig. 18 shows the practical angle degree and speed waveforms.

V. CONCLUSION

The proposed motor drive system for HEC is configured, and the driving characteristics are verified in this paper. In the driving performance test, the rated driving characteristics and maximum output characteristics are ensured. The rated driving efficiency is over 92 %, so it will be a high efficient compressor drive.

In this paper a novel curve fitting method for getting maximum torque per unit current is made by the multiply function suitable for the microprocessor and designed IPM is suitable for electric compressor of the automobile. Also the position information of the rotator is gotten by the proposed virtual encoder. The simulation and test have been done to clarify the reasonableness of the proposed method.

VI. REFERENCES

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