Research Report

Novel Torque Control Technique for High Efficiency/High Power Interior Permanent Magnet Synchronous Motors

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IPMモータの高効率･高出力トルク制御

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Abstract

The motors of hybrid electric vehicles must be able to offer high efficiency, a high power/weight ratio, and excellent reliability across the entire rotor speed range. Interior permanent magnet synchronous (IPM) motors are used to satisfy these requirements. The goal of this study was to develop an IPM motor control method that would increase the torque and the efficiency at high and medium rotor speeds. A method for increasing the torque and efficiency at high speeds was described in a previous paper, and is known as voltage phase compensation (VPC).

The method described in the previous paper involved combining VPC with normal current compensation to control the torque across the entire range of speeds, and to increase the torque at high speeds. This method failed, however, to achieve sufficient torque at mid-range speeds.

This paper introduces a new type of compensation (Overmodulation Current Compensation: OCC) that increases the torque at mid-range speeds while achieving current control in the overmodulation range of the inverter. Combining the conventional current compensation, VPC, with OCC achieves an increase in the torque and the efficiency at both high- and mid-range rotor speeds. The type of compensation applied is switched automatically by using the proposed transitional algorithm. This paper shows the validity of the proposed method by using the experimental evaluations.

Keywords Hybrid vehicles, AC motor drive, Interior permanent magnet motors, Torque control, Voltage control, Overmodulation range

要　旨

ハイブリッド電気自動車（HV）の永久磁石モータ制御には，当初PWM電流制御が用いられてきた。しかし，広範囲の弱め励磁運転が要求される領域（定出力領域）において，電池電圧の低下，電流制御の安全余裕などを考慮し高めの弱め励磁を行うため，電池電圧利用率が悪く，高速領域で出力限界が低下していた。本研究では，磁石モータに対して，この課題を解決するトルク制御法を開発した。開発した技術の特長は，以下のようである。

(1) 高回転域において矩形波電圧でトルク制御を行う矩形波電圧制御技術（既報告）。

(2) インバータの過変調域を利用し，汎用の電流制御の運転範囲を中回転域まで拡大する過変調電流制御技術。

(3) 矩形波電圧制御，過変調電流制御と汎用の電流制御とを回転域にあわせて，自動選択し，トルク変動最小で制御を切替える技術。

矩形波電圧制御技術は既に詳細を報告しているので，本報では主に過変調電流制御技術を中心に記載する。本技術により，モータのハード構成を変えることなく，モータの高速回転域でのモータ出力（トルク）アップとインバータ損失低減を実現し，HVの動力アップに大きく貢献した。

キーワード　ハイブリッド自動車，モータ駆動，内磁型モータ，トルク制御，矩形波制御，過変調

1. Introduction

The development of hybrid electric vehicles and electric vehicles is being pursued by many manufacturers.[1, 2] The main components of the electric drive system are the energy source, the traction motor with its inverter and controller, and the main control unit.

The motor drive system of a hybrid electric vehicle must offer high efficiency, a high power/weight ratio, and excellent reliability. To satisfy these requirements, manufacturers have adopted the interior permanent magnet synchronous (IPM) motor. The aim of this study was to obtain more torque from the IPM motor, whose energy is supplied from the battery pack, without reducing the efficiency of the motor and the inverter.

To control the motor torque exactly, a method that uses the current error and PI compensation to determine the motor terminal voltage is used. In this paper, this method is called current error feedback (CEF) compensation. While this method is excellent at controlling the motor torque exactly, it fails to make full use of the battery pack voltage. At high speeds, however, the effect of the rotor inertia reduces the vibration caused by torque ripple. Therefore, at high speeds, increasing the average torque is more important than controlling the torque exactly. Central to achieving this is devising a technique that makes maximum use of the battery pack voltage.

Our previous paper[3] introduced the Voltage Phase Compensation (VPC) algorithm that achieves the above in the high speed range. At high speeds, the voltage occurred the rotor magnet is higher than the inverter DC voltage. By corroborating the proposed algorithm with CEF, we were able to improve the power and efficiency across the entire speed range. Improvement is still necessary at mid-range speeds, however. This paper introduces a method that realizes improvements at mid-range speeds, and illustrates its effectiveness. We refer to this method as over-modulation current compensation (OCC).

2. Control algorithm

2. 1 Normal current control (current error feedback compensator) for IPM motor

Figure 1 shows a basic motor drive system that consists of a motor, an inverter and a battery pack. The battery pack supplies a DC voltage to the inverter. The inverter, which is a semiconductor switching device, performs switching at more than 1 kHz to convert the DC voltage into an AC voltage (PWM). The system also incorporates a rotor position sensor, a battery pack voltage sensor and two motor current sensors.

Current control involves controlling the amplitude and phase of the current. A diagram of the compensator block, which matches the current to the reference currents on the direct and quadrature axes (dq-axes), is shown in **Fig. 2**.

2. 2 Realizing high torque

Figure 3 shows a comparison of three

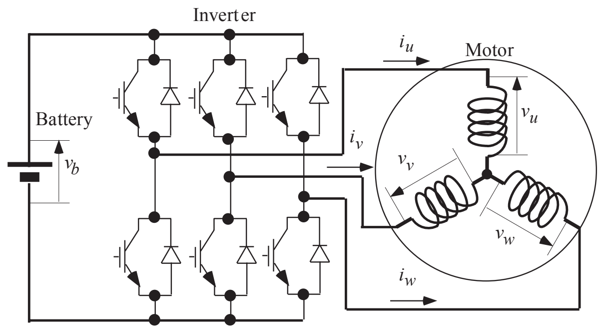


Fig. 1 Basic motor drive system.

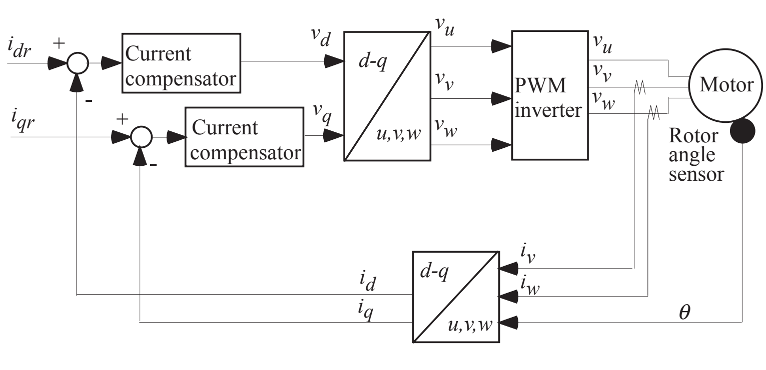


Fig. 2 Block diagram of current error feedback compensation.

compensation techniques, namely, CEF, OCC and VPC, from the viewpoint of the voltage utilization factor, inverter output voltage, and so on. This paper proposes the application of OCC to mid-range speeds. We define the voltage utilization factor λ, as follows:

$$\lambda = \sqrt{\frac{3}{2}} \int_0^{\pi/2} \frac{a \sin\theta}{v_b}\, d\theta \qquad \cdots\cdots\cdots\cdots\cdots (1)$$

Where v_b is the battery pack voltage and $a \sin \theta$ is the voltage fundamental frequency component for which the frequency is the same as the rotor frequency. The value a satisfies the later equations.

$$\begin{aligned} &0 \le a \le \frac{v_b}{2} && \text{(CEF)} \\ &\frac{v_b}{2} \le a \le \frac{4}{\pi}\frac{v_b}{2} && \text{(OCC)} \qquad \cdots\cdots\cdots\cdots (2) \\ &a = \frac{4}{\pi}\frac{v_b}{2} && \text{(VPC)} \end{aligned}$$

CEF, described above, outputs a voltage signal that is calculated from the error in the current, and determines the motor terminal voltage (inverter output voltage) using the signal and inverter carrier signal. If the frequency on which the output voltage signal and the PWM carrier frequency are based is much higher than the rotor frequency, this compensator can minimize the torque ripple across the range from low to high rotor speeds. The amplitude of the output voltage signal is, however, restricted to within the inverter DC voltage. The voltage utilization factor of this compensator is less than 61 %. This value restricts the motor torque.

Figure 4 shows the relationship between the voltage phase and the average motor torque when the motor terminal voltage is a sine wave having the same frequency as the rotor electrical speed and the amplitude does not vary with time. Within a certain range, the torque is a monotonous sequence for the voltage phase. The VPC controls the motor torque based on the voltage phase within the monotonous sequence range. The voltage phase is defined using the angle between the motor terminal voltage produced by the inverter and that produced by the rotor's magnetic field, relative to the sine wave element whose frequency is the same as the rotor electrical speed. This compensation, illustrated in

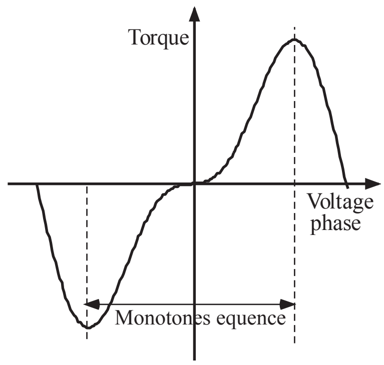


Fig. 4 Relationship between voltage phase and average torque.

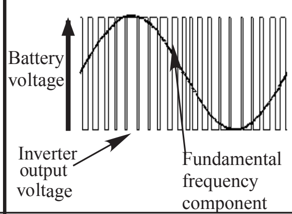
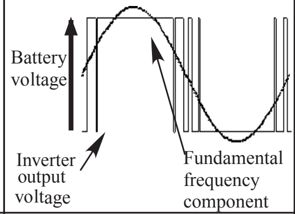
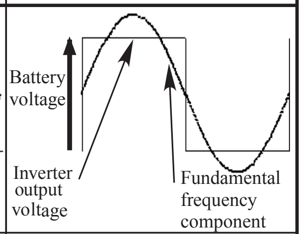
	CEF : Current error feedback compensator	OCC : Overmodulation current compensator	VPC : Voltage phase compensator
Inverter output voltage			
Voltage utilization factor	0 ~ 0.61	0.61 ~ 0.78	0.78
Speed range	all speed range	middle speed range	high speed range
Torque control method	already established	not established yet	established in previous paper
Efficiency	1	○	◎

Fig. 3 Comparison of three compensation methods.

Fig. 5, determines the voltage phase ψ using the reference torque T_r and the estimated torque T_e. The estimated torque is calculated from the motor input power, which is obtained using the motor terminal voltage and the motor terminal current, divided by the rotor's rotational speed. The rectangular waveform motor terminal voltage is created using the rotor frequency, the inverter DC line voltage and the voltage phase. The amplitude of the rectangular waveform is same as the inverter DC line voltage. Therefore, the voltage utilization factor is 78%, which is constant, with the maximum being when the inverter DC line voltage is fixed. This means that the compensator realizes the maximum torque when the inverter DC line voltage is fixed. The fact that the amplitude of the voltage is fixed, however, results in the amplitude of the current exceeding the current constraints at low speeds. Moreover, this compensator changes the inverter leg state once every revolution of the rotor. While this has a detrimental affect on the torque ripple, it does improve the efficiency relative to CEF. Our previous paper described the details of the torque control method and the characteristics of this method.

OCC is used at mid-range rotor speeds and when the voltage utilization factor is between 61% and 78%. The amplitude of the average torque and the torque ripple, caused by this compensation, falls between that caused by CEF and that caused by VPC. The torque control method has not yet been perfected but will be described in detail in a later paper.

To realize high torque and excellent efficiency across the entire speed range, the torque control method proposed in this paper combines the above three types of compensation and automatically switches from one to another as the voltage output from the compensator changes.

2. 3 Overmodulation current compensator

Figure 6 shows a block diagram of the OCC. This compensator consists of a filtering block, a voltage calculator block and a voltage-correcting block. The filtering block removes noise from measured currents i_d, i_q and creates filtering currents i_{dl}, i_{ql}. The voltage calculator calculates voltages v_d, v_q using reference currents i_{dr}, i_{qr} and the above signals i_{dl}, i_{ql}. When this block uses PI compensation, the values v_d, v_q are described using error currents i_{dr}-i_{q1}, i_{qr}-i_{q1}. Then, v_d, v_q are translated into motor terminal voltages v'_u, v'_v and v'_w.

The amplitudes of the motor terminal voltages are greater than that of the inverter DC line voltage, that is, the battery pack voltage v_b in the OCC. Therefore, it is not impossible to realize the voltage signal by applying the usual PWM method to the inverter. To realize the voltage using the ordinary PWM method in the inverter, this compensator uses a voltage-correcting block that changes v'_u, v'_v, v'_w to v_u, v_v, v_w using the battery pack voltage v_b. This block also synchronizes the inverter carrier

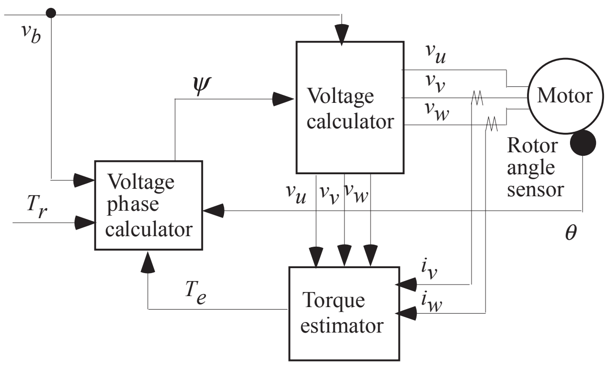


Fig. 5 Block diagram of voltage phase compensator.

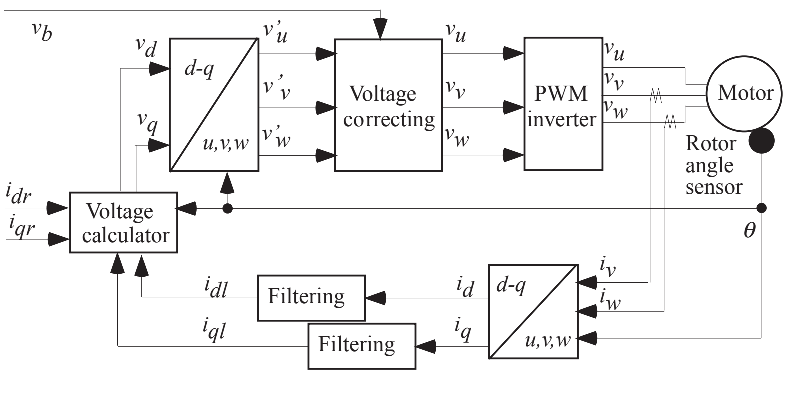


Fig. 6 Block diagram of overmodulation current compensator.

frequency with the rotor revolution frequency. There are periods in which this block output signal is lower than the DC voltage, as well as periods in which it is equal to the DC voltage. During this period, the output signal is realized using the ordinary PWM method, as shown in **Fig. 7**. Meanwhile, the inverter carrier frequency is not high enough relative to the rotor revolution frequency at mid-range speeds. For example, suppose that a 4-pole-pair motor rotates at 6000 rpm and the inverter carrier frequency is 2 kHz. In this case, the electrical revolution velocity (400 Hz) is not high enough relative to the carrier frequency. In such a case, the DC voltage arises on the motor terminal unless the inverter carrier frequency synchronizes with the rotor speed.

2. 4 Experimental results and discussion

This section presents the actual behavior of the IPM motor (number of pole-pairs: 4, maximum power: 30 [kW]), as observed by experiment. The resulting torque is shown in **Fig. 8**. The dashed line shows the maximum torque that can be obtained with the conventional method. The solid line indicates the maximum torque possible with the proposed method. With the conventional method, the CEF is effective from low speeds to high speeds, including that range in which the field weakened. This torque is less than that indicated by the dashed line due to the application of CEF in mid- and high-speed ranges. The method described in our previous paper, which combines CEF and VPC, increases the torque in the high speed range. However, this method cannot achieve a torque increase in the area enclosed by points B, C and E. By incorporating OCC, the method proposed in this paper can achieve a torque increase in this area.

A comparison between the conventional method and proposed method in respect to total loss (sum of the motor loss and the inverter loss) is shown in **Fig. 9**. This loss was measured while the rotor speed was fixed and the torque was increased. In the low-torque area, CEF was applied. There is no difference in the loss. In the medium-torque area, the proposed method applies OCC, or CEF when the field weakens. The difference between the proposed and conventional method increases. In the high-torque area, the proposed method applies VPC. The

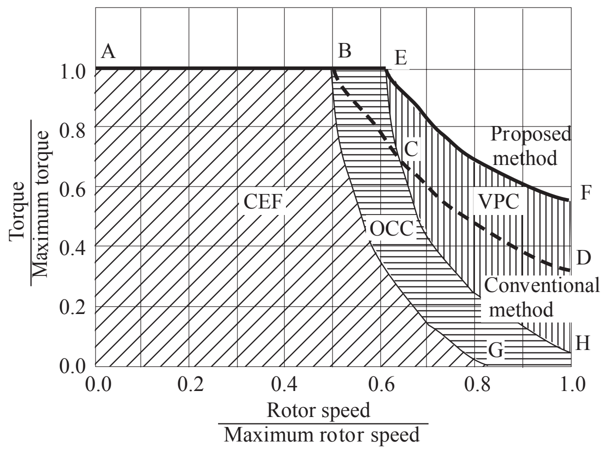


Fig. 8 Comparison of torque with proposed method (solid line) and conventional method (dashed line).

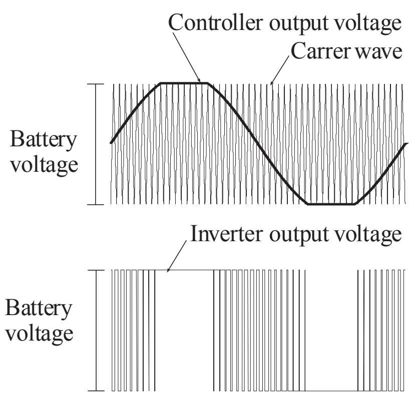


Fig. 7 Controller output, carrier frequency, and inverter output waveform.

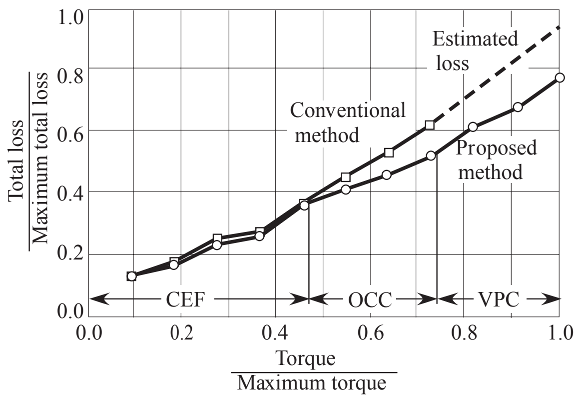


Fig. 9 Comparison of motor and inverter loss with proposed method (solid line) and conventional method (dashed line).

conventional method cannot produce the torque, and an estimated line is drawn on the graph. The difference between the proposed and conventional method is almost constant and larger than that in the medium-torque area. This corresponds to the number of the inverter switching. Therefore, we believe that this difference arises as a result of inverter loss.

The phase current in the transitional period from CEF to OCC is shown in **Fig. 10**. The phase current in the transitional period from OCC into VPC is shown in **Fig. 11**. The phase currents in the two figures are not disturbed during the transitional method. Therefore, we can regard this method as being practical.

3. Conclusions

The objective of this study was to develop a motor control method that is capable of improving the motor torque without degrading efficiency in the mid-speed range. We developed an OCC for use in this mid-speed range. The method involves a filtering block, a voltage-calculator block, and a voltage-correcting block. The proposed method, which combines the OCC with the VPC and a CEF, could achieve an increased torque without reducing the efficiency of the experiment.

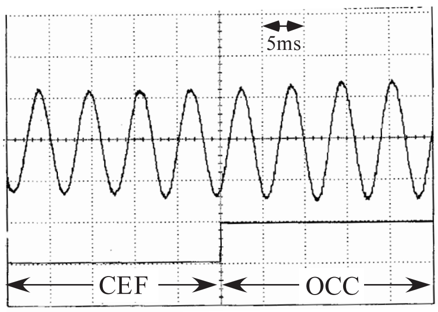


Fig. 10 Phase current waveform in transitional period from CEF to OCC.

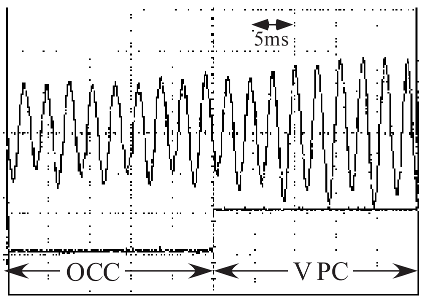


Fig. 11 Phase current waveform in transitional period from OCC to VPC.

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References

1) Yoshioka, T. and Sugita, H. : "Noise and Vibration Reduction Technology in Hybrid Vehicle Development," SAE Tech. Pap. Ser., No.2001-01-1415(2001), 1-9
2) Moriya, K., Ito, Y., Inaguma, Y. and Satoh, E. : "Design of the Surge Control Method for Electric Vehicle Powertrain", Future Car Congr. 2002, No. 2002-01-1935(2002)
3) Nakai, H., Ohtani, H, Satoh, E. and Inaguma,Y. : "Development and Testing of the Torque Control for the Permanent-Magnet Synchronous Motor", Proc. of IECON '01/The 27th Annu. Conf. of the IEEE, (2001), 1463-1468

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