Voltage Saturation Prevention Control for Internal Permanent Magnet Synchronous Motor (IPMSM)

Shizunori Hamada,
Hajime Kubo,
Yugo Tadano,
Takaharu Takeshita

Keywords IPMSM, torque control, Inverter, Voltage saturation

Abstract

In place of an engine, a driving dynamometer for automotive testing is required to generate vibration torque even in the middle of high-speed revolution in order to simulate torque vibration. When a high-speed torque response is realized with a generated vibration torque, a high voltage is needed.

In this case, however, a current response has deteriorated due to voltage saturation and it became impossible to simulate a torque reference. Since the synchronous motor generates an induced voltage in proportion to the number of rotations, this induced voltage is raised at the time of the high speed revolutions. This causes some problems such as voltage saturation and deterioration of torque response.

We developed dynamometers connected with Internal Permanent Magnet Synchronous Motor (IPMSM). These dynamometers are improved to obtain a better torque response even at the time of high-speed revolution. By conducting experiments, we confirmed the validity of voltage saturation prevention control. This control was made against the engine vibration torque reference and the current reference value was derived by applying the weak magnetic flux control.

1 Preface

Against the background of rising industry demands for a shorter automotive development period and improvement of car driving performance, motor control technologies for dynamometer systems are advancing. The driving motor used in place of an automotive engine puts the test piece under test so that the same load is applied to the test piece as if the engine would be mounted on the vehicle.

In this case, current control is needed for the driving motor used to simulate an engine torque. This driving motor is a large-capacity Internal Permanent Magnet Synchronous Motor (IPMSM).

For the IPMSM, permanent magnets are embedded in its rotor core to obtain a saliency. In this case, a reluctance torque can be utilized in addition to a magnet torque. Using these torques effectively, it is possible to establish a high efficiency motor where losses can be reduced compared with another conventional method. The IPMSM, however, generates induced voltage in proportion to the rpm figure. Consequently, this induced voltage is raised at the time of high-speed revolutions. If this occurs, the inverter leads to voltage saturation, which leads to a drive failure. Still more, in the case of engine torque reproduction, a high voltage is required since the current changing rate becomes large.

For conventional Maximum Torque Per Ampere (MTPA) method, voltage tends to be caused easily and the torque response becomes worse. For this solution, voltage saturation is avoided by weak magnetic flux control. By the Maximum Torque Per Voltage (MTPV) control method, a high current is needed, which results in an increase in copper loss. Both methods are, therefore, a trade-off.

This paper introduces the current control approach of IPMSM by which an inverter's voltage saturation is avoided against the instantaneous engine torque reference. By calculating the variation in maximum torque based on the engine torque reference value, a maximum voltage is estimated from a voltage vector. According to the maximum voltage, the d-axis current is reduced to avoid voltage saturation. In addition, the validity of the proposed control method was examined by verification by a machine.

2 Torque Control Method

2.1 Current Control Method of IPMSM

The voltage equation of d-axis voltage vd and q-axis voltage vq of the IPMSM and equation of torque τ are given by Expression (1) and (2) below.

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + \begin{bmatrix} v_{dt} \\ v_{qt} \end{bmatrix} = \begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \cdots\cdots (1)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = R_a \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega K_E \end{bmatrix} \cdots\cdots (2)$$

$$\tau = P_n \{K_E + (L_d - L_q)\, i_d\} i_q \cdots\cdots\cdots\cdots\cdots\cdots\cdots (3)$$

Where, v_{od} and v_{oq} are constant voltages, v_{dt} and v_{qt} are transient voltages, P_n is pole pairs, and K_E is induced voltage constant.

Fig. 1 shows a current control block diagram. The non-interference control functions to compensate for the effect of interference term and induced voltage between d-axis and q-axis. The feedforward control is used to improve current response by means of an inverse function of a motor model.

2.2 Engine Torque Reference

Fig. 2 shows a waveform of data torque τ_c and engine torque reference τ^* for an engine model. The data torque is an engine torque reference input to be applied by a user of an engine dynamometer. The engine torque reference τ^* is composed of sine and cosine waves having fundamental angular frequency ω_τ and doubled angular frequency $2\omega_\tau$. It is defined by the following expression:

$$\tau^* = A_0 + A_{1s} \sin \omega_\tau t + A_{1c} \cos \omega_\tau t + A_{2s} \sin 2\omega_\tau t + A_{2c} \cos 2\omega_\tau t \cdots\cdots\cdots (4)$$

The mean torque component is assumed to be A_0 and size of each amplitude is A_{1s}, A_{1C}, A_{2s}, and A_{2c}, respectively. These values are arbitrarily set by the user of the engine dynamometer. As shown in **Fig. 2**, engine torque amplitude and mean component are changed. The engine torque reference value τ^* of the inverter is required to follow up these changes.

Fig. 3 shows a block diagram of engine torque amplitude and mean torque presumption to compute the respective coefficients A_0, A_{1s}, A_{1c}, A_{2s}, and A_{2c}. Value τ^* is determined by making a feedback of Value τ_c done by the customer. By making Fourier

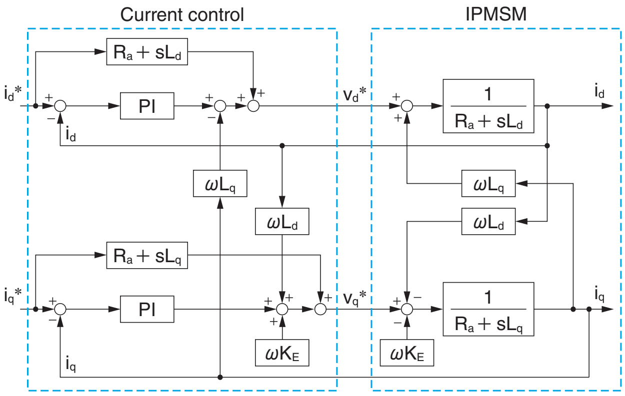

Fig. 1 Current Control Block Diagram

The current control system is composed of the respective blocks of PI control, non-interference control, and feedforward control.

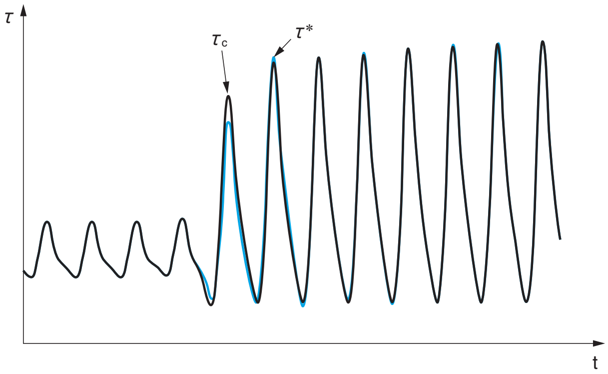

Fig. 2 Data Torque and Engine Torque Reference

The fundamental frequency ω_τ of engine torque is assumed to be already known as an integral multiple of motor rpm number.

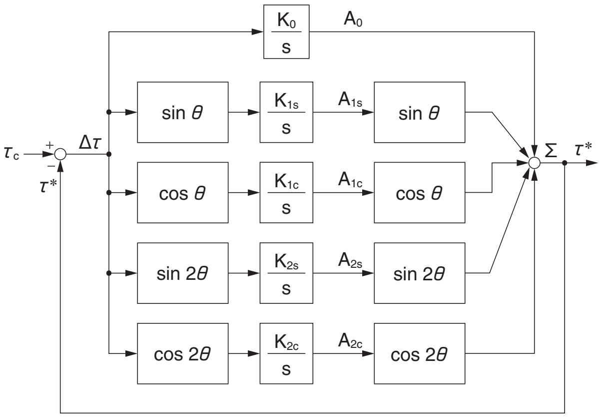

Fig. 3 Block Diagram of Engine Torque Amplitude and Mean Torque Presumption

An instantaneous value of torque per unit time is assumed by Fourier transform and inverse Fourier transform in order to estimate torque amplitude and mean torque.

transform of $\varDelta_\tau$ that is a deviation between τ_c and τ^*, amplitude of each frequency component can be determined. When each amplitude is multiplied by sine and cosine waves, Value τ^* is determined by a return to the time axis.

When engine torque reference τ^* shown in Expression (4) is operated for composition by means of trigonometric functions, the following expression holds:

$$\tau^* = A_0 + A_1 \sin(\omega_\tau t + \phi_1) + A_2 \sin(2\omega_\tau t + \phi_2) \quad \cdots\cdots (5)$$

Where, Values A_1, A_2, ϕ_1, and ϕ_2 are expressed as follows:

$$A_1 = \sqrt{A_{1s}^2 + A_{1c}^2},\ A_2 = \sqrt{A_{2s}^2 + A_{2c}^2} \quad \cdots\cdots\cdots\cdots (6)$$

$$\phi_1 = \arctan\frac{A_{1c}}{A_{1s}},\ \phi_2 = \arctan\frac{A_{2c}}{A_{2s}} \quad \cdots\cdots\cdots\cdots (7)$$

Now, the calculation is forwarded on the basis of fundamental wave contained in Expression (5). Assuming that Phase $\omega_\tau t + \phi_1 = 0$ based on the fundamental wave, Expression (5) is replaced by the following Expression:

$$\tau^* = A_0 + A_1 \sin\theta + A_2 \sin(2\theta - \phi_a) \quad \cdots\cdots (8)$$

Where, ϕ_a is given by Expression (9) below.

$$\phi_a = 2\phi_1 - \phi_2 \quad \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots (9)$$

3 Method of Voltage Saturation Avoidance

Since the engine torque reference τ^* determined in **Section 2** has a large variation in torque, the transient voltage becomes high. Influenced by this transient voltage and high induced voltage at the time of high-speed revolutions, the inverter's voltage saturation tends to easily occur. For a solution, the engine torque reference value was used to calculate a maximum voltage reference value in order to estimate the amount of voltage saturation. Voltage saturation was averted by reducing the d-axis current based on the presumed amount of voltage saturation.

Fig. 4 shows a voltage locus of engine torque. The voltage locus used to realize an engine vibration torque is expressed by a vector sum of a steady-state voltage vector and a transient voltage vector that crosses at right angles with a steady-state voltage line. Since the engine vibration torque has a large variation, the amount of current change also becomes large. When the current variation is large, the effect of transient voltage in Expression (1) is large. Accordingly, the phase of a maximum transient voltage is assumed to be a maximum voltage. Based on this assumption, the phase of a maximum variation θ_m can be calculated by deriving from the expression of instantaneous engine torque reference.

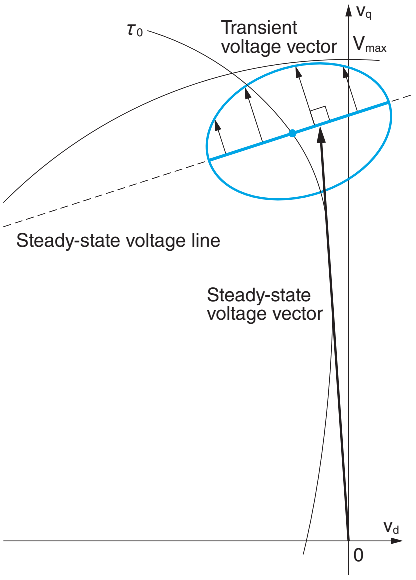

Fig. 4 **Voltage Locus of Engine Torque**

The voltage locus is expressed by a vector sum of steady-state voltage vector and transient voltage vector.

In the first place, using the obtained phase θ_m, transient voltages v_{dt} and v_{qt} that maximize the variation in instantaneous engine torque reference were obtained by the substitution of current reference into Expression (1).

The maximum voltage was then estimated from the voltage locus that realizes engine torque. The steady-state voltage locus was obtained when the engine torque reference value was substituted in Expression (2) appears in a form of a straight line as shown in **Fig. 4**. The transient voltage vector was also obtained when the engine torque reference value was substituted in the transient term of Expression (1) appeared in a form of an output that crosses at right angles with the steady-state voltage line. Based on these vectors of steady-state voltage and transient voltage, maximum voltages (v_{dmax}, v_{qmax}) were derived.

The presumed voltage saturation $\varDelta V$, which is a difference between the intensity of the obtained maximum voltage and the maximum value of inverter voltage V_{max}, was given by the following expression:

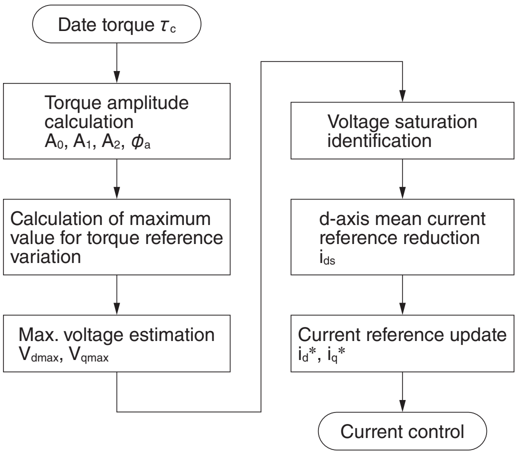

Fig. 5 **Current Reference Generation Flowchart**

Presence of voltage saturation is identified. If it is anticipated, the d-axis current is reduced to avert it.

$$\Delta V=\sqrt{v_{dmax}^2+v_{qmax}^2}-V_{max} \cdots\cdots\cdots\cdots\cdots\cdots \tag{10}$$

According to the presumed voltage saturation ΔV, the d-axis mean current reference value i_{ds} is reduced. In this fashion, a current reference averting voltage saturation can be generated. Fig. 5 shows a current reference generation flowchart explaining the process of derivation of a current reference from the obtained engine torque data. Based on the obtained instantaneous engine torque reference value, a maximum voltage was estimated. The reducing current value i_{ds} was determined from the presumed voltage saturation defined based on the resultant maximum voltage. When a current reference was determined based on the reduced i_{ds}, it became possible to realize an engine torque that does not lead to any voltage saturation.

4 Experimental Result

Through experiments, the validity of the introducing voltage saturation prevention control was examined. Table 1 shows motor constants and experimental conditions. The data torque τ_c used for our experiments was based on the assumption that the accelerator of the engine model is wide open after the lapse of a specified time. For this reason, the mean engine torque A_0 amplitude A_{1s}, A_{1c}, A_{2s}, and A_{2c} changed on the way.

Table 1 **Motor Constants and Experimental Conditions**

IPMSM constants used for experiments and experimental conditions for engine torque reproduction are shown.

Item	Variable	Values
Armature resistance	R_a	0.602 Ω
Electromotive force constant	K_E	0.952 V/(rad/s)
Control period	T_s	100 μs
d-axis inductance	L_d	5.63 mH
q-axis inductance	L_q	14.3 mH
No. of poles	P_n	4
Motor revolving speed	ω	1800 min^{-1}
Torque vibration frequency	f_τ	60 Hz
Carrier frequency	f_s	10,000 Hz

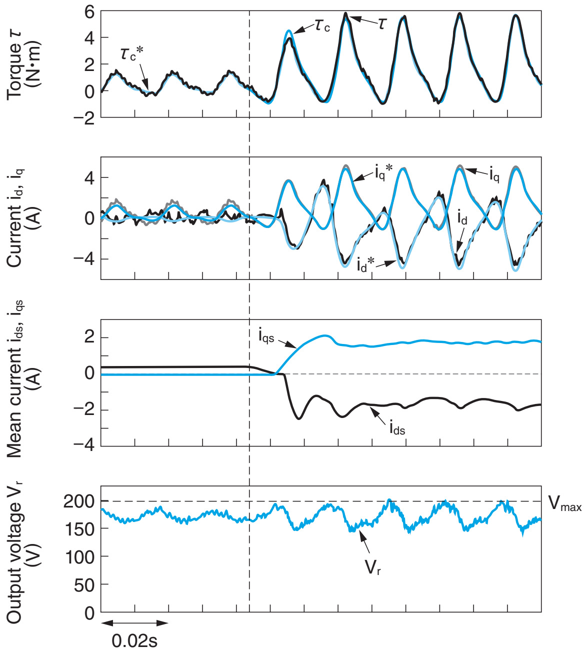

Fig. 6 **Experimental Waveforms during Engine Torque Reproduction**

A torque reference is presumed from the data torque and torque control is carried out while voltage saturation is averted.

Fig. 6 shows experimental waveforms during engine torque reproduction and Fig. 7 shows a voltage locus after the appearance of a change in engine torque. Fig. 6 shows that torque τ kept generating an output just as specified by the engine torque reference. In addition, Fig. 3 shows that Value τ^* follows up Value τ_c according to the mean torque presumption block diagram. After the vertical dotted line, torque amplitude and mean torque was changed. When amplitude was expanded, the maximum voltage was changed. Since voltage saturation tends to occur easily after the appearance of these changes, Value i_{ds} changed in response to the presumed voltage saturation value in order to avert such a situation. It became possible to confirm that no voltage saturation was caused as a result of i_{ds}

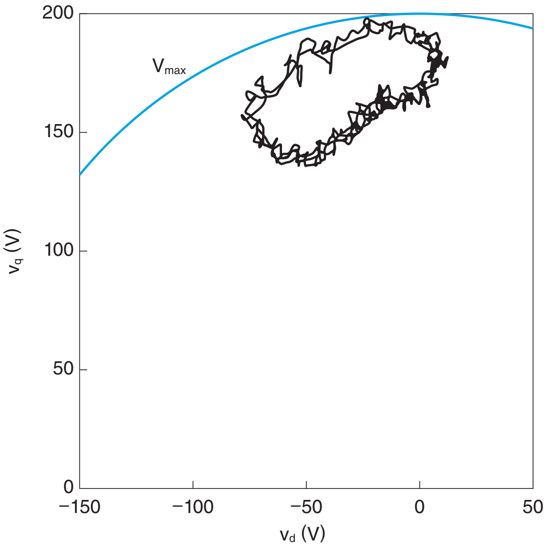

Fig. 7 Voltage Locus after Appearance of a Change in Engine Torque

The voltage locus at the time of engine torque reproduction is present within the domain of maximum voltage V_{max}.

reduction. **Fig. 7** shows that voltage saturation is averted even after changes in torque reference values. By making presumption of a maximum voltage at an instantaneous engine torque reference value, it became possible to make torque control without causing voltage saturation.

5 Postscript

In the case of current control for the IPMSM, voltage saturation is caused when MTPA control is carried out under the condition of high-speed revolutions during the engine torque simulation. This paper introduced a method of control by calculating a maximum amount of change to estimate the amount of voltage saturation when an instantaneous engine torque reference is issued. By this method, d-axis current is reduced according to the amount of estimated voltage saturation. In doing so, the engine torque simulation is realized while voltage saturation is averted. After a series of experiments, we could confirm the validity of the proposed control method.

《Reference》

(1) Ryohei Matsuura, Takaharu Takeshita, Shizunori Hamada, Hajime Kubo, Yugo Tadano: "Current Control of IPMSM without Voltage Saturation for Engine Torque Simulator", International Conference on Electrical Machines and Systems, pp.1127-1132, 2018