Vector Control of a Current Superimposition Variable Flux Reluctance Motor

Noboru NIGUCHI*1 (Mem.), Katsuhiro HIRATA*1 (Mem.), Akira KOHARA*1 (Stu. Mem.) and Kazuaki TAKAHARA*1 (Stu. Mem.)

We propose a current superimposition variable flux reluctance motor for a traction motor of hybrid electric vehicles. This motor has 2 sets of 3-phase coils, and 2 current control methods (single and twin vector controls) can be applied. However, any effective control methods have not been seen. This paper discusses the current control method of the current superimposition variable flux reluctance motor. Single and twin vector controls are compared. The single vector control is effective for the current superimposition variable flux reluctance motor because even orders of the currents are removed by composing 2 phase currents. In addition, harmonic components of the phase current under single vector control contribute to increase a torque.

Keywords: variable flux reluctance motor, vector control, current harmonics.

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1. Introduction

Traction motors for hybrid electric vehicles require wide power band and high efficiency characteristics. In order to increase the power band of the traction motor, field weakening control is widely used in interior permanent magnet synchronous motors. However, the effectiveness of the field weakening control is not sufficient for the traction motors, and the efficiency in high rotation speeds is decreased.

In order to solve the problem, various variable flux reluctance motors have been proposed [1-2]. However, they are not practical due to 2 sets of coils: armature coils for generating a rotating magnetic flux, and field coils for controlling the DC magnetic field. In order to solve the problem of the previous variable flux reluctance motors, a current superimposition variable flux reluctance motor (CSVFRM) shown in Fig. 1 is proposed [3-8]. The CSVFRM has only 1 set of coils, and AC and DC voltages are superimposed using a 6-phase inverter. The 6-phase coils (A, B, C, D, E, and F) consist of 2 sets of 3-phase coils (U, V, and W), and they form a concentrated winding. Although a 6-phase inverter is used to drive the CSVFRM, the A and D, B and E, and C and F phases can also respectively correspond to the U, V, and W phases. There coils can be divided into 2 sets of 3 phases (A, E, and C, D, B, and F phases) in terms of the phase angle of the magnetic flux. A positive DC voltage (+Vdc) is applied into the A, C, and E phases, and a negative DC voltage (−Vdc) into the B, D, and F phases. 3-phase vector control can be applied to the CSVFRM because this motor has 2 sets of 3-phase coils.

However, any effective control methods have not been seen. In this paper, 2 types of vector controls for the CSVFRM are discussed: one is single vector control which is applied to a composite current, and the other is twin vector control which is applied to 2 sets of 3-phase currents. In this paper, these vector controls are compared, and the effectiveness is investigated using finite element analysis under vector control.

2. Fundamental Characteristics of the Current Superimposition Variable Flux Motor

2.1 Analysis Model

In order to investigate the application of the vector control for a CSVFRM, a CSVFRM shown in Fig. 2 is used for electromagnetic field analyses. The number of rotor salient poles and stator teeth is 10, and 12, respectively, and the stator has 6-phase coils where the number of coil turns is 20. The rotor and stator is made of laminated silicon steel sheets (35A300). The 6-phase coils are connected as shown in Fig. 3, and the A and D, B and E, and C and F phases respectively correspond to the U, V, and W phases. There coils can be divided into 2 sets of 3 phases (A, E, and C, D, B, and F phases) in terms of the phase angle of the magnetic flux. In Fig. 3, $V_{a1}$, $V_{a2}$, $V_{c1}$, $V_{c2}$, $V_{a1}$, $V_{a2}$, and $V_{dc}$ are the AC voltages of A, D, E,
2.2 Operational Principle

In the 10-pole-12-slot (12/10) CSVFRM, the rotor is rotated by applying voltages as shown in Fig. 3. First, $+V_{dc}$ is applied to A, C, and E phases, and $-V_{dc}$ is applied to B, D, and F phases. Due to these DC currents, a 6th-order magnetomotive force is generated in the air gap. The 6th-order magnetomotive force is modulated by the 10 rotor salient poles, and a 4th-order harmonics are generated in the air gap. A 4th-order rotating magnetic field is generated by applying 3-phase AC voltages on the 2 sets of 3-phase coils. The 4th-order rotating magnetic field synchronizes with the 4th-order harmonics, and the rotor is rotated.

2.3 Electromotive Force

The terminal voltages of the A and D phases when a DC current of 50 A is applied and the rotor is rotated at 120 rpm is shown in Fig. 4, where the terminal voltage is a composite voltage of a DC voltage which generates 50 A and Electromotive force (EMF) due to the rotation. The EMF of each harmonic component due to an FFT analysis is shown in Fig. 5, and the phase angle of the A- and D-phase EMFs is shown in Fig. 6.

From Fig. 5, it is observed that the EMF contains even-order components. This is due to the asymmetry of the A and D phases. In Fig. 2, the A phase coil faces the rotor salient pole, and the D phase coil faces the rotor slot. Due to this, the inductance of the A and D phases is different from each other, and this creates an asymmetry.

The inductance when the rotor is rotated by one electric period from the position shown in Fig. 2 is shown in Fig. 7. The inductance of each harmonic component due to an FFT analysis is shown in Fig. 8. From Figs. 7 and 8, it is observed that the inductance contains even-order components, and in particular the 2nd component is dominant. The inductance of a permanent magnet motor does not contain a 1st-order component, and the 2nd
component of the inductance is inherent characteristics of the CSVFRM. In addition, the phase angle difference between the 1st- and 2nd-order components of the A and D phases is 180 deg, and 0 deg, respectively.

3. Vector Control for a Current Superimposition Variable Flux Reluctance Motor

3.1 Single Vector Control

In this section, single vector control shown in Fig. 9 is described. In the single vector control, a 3-phase imaginary current is created by composing A- and D-, B- and E-, and C- and F-phase currents. The 3-phase imaginary current is controlled to be sinusoidal using a PI control. There are 3 AC voltages for U, V, and W phases, and the same AC voltage is applied to A and D, B and E, and C and F phases. Due to this, the current waveform of the A and D phases is different from each other because the inductance and EMF waveforms of the A and D phases are different from each other, and this applies to the B- and E-, and C and F-phase currents. In other words, the phase current is not sinusoidal even if the imaginary current is sinusoidal. However, there is a possibility that the harmonics in the EMF (magnetic flux) may create torques because the current contains harmonics.

Only the 2nd component is considered here. From Fig. 9, the A- and D-phase inductances \((L_a)\) and \((L_d)\) are shown in (1) and (2), respectively.

\[
L_a = L_0 + L_1 \cos \theta - L_2 \cos 2\theta \\
L_d = L_0 - L_1 \cos \theta - L_2 \cos 2\theta
\]  

where \(L_0\) is the average inductance and \(L_1\) and \(L_2\) are the amplitude of the 1st and 2nd components, respectively.

The A- and D-phase EMF \((E_a\) and \(E_d)\) can be defined in (3) and (4), respectively.

\[
E_a = E_1 \sin \theta - E_2 \sin 2\theta \\
E_d = E_1 \sin \theta + E_2 \sin 2\theta
\]  

where \(E_1\) and \(E_2\) are the amplitude of the 1st and 2nd components, respectively. Vector control is applied to a composite current of the A and D phases \(I_u\), and \(I_u\) is shown in (5).

\[
I_u = I_a + I_d = I \sin \theta
\]  

The circuit equation of the A and D phases is shown in (6) and (7), respectively.

\[
V_u = I_a R + L_a \frac{dI_a}{dt} + E_a \\
V_u = I_d R + L_d \frac{dI_d}{dt} + E_d
\]  

Equation (8) is obtained by summing (6) and (7).

\[
2V_u = I_a R + \frac{d(I_a I_a + L_1 I_1 + L_2 I_2)}{dt} + E_a
\]  

The composite EMF of the A and D phases \(E_u\) is shown in (9).

\[
E_u = 2E_1 \sin \theta
\]  

The 2nd component is removed by the summation of the A and D phases, and \(V_u\) is shown in (10) from (5), (8), and (9).

\[
V_u = V_1 \sin \theta
\]  

There is only the 1st component in the left side of (8). Therefore, the right side of (8) must be composed of only the 1st component. The A- and D-phase currents \((I_a\) and \(I_d)\) are defined in (11) and (12).

\[
I_a = I_0 + I_1 \sin \theta + I_2 \sin 2\theta \\
I_d = -I_0 + I_1 \sin \theta + I_2 \sin 2\theta
\]
The 2nd term of the right side of (8) $L_a I_a + L_d I_d$ is expanded using (1), (2), (11), and (12). Conditions when $L_a I_a + L_d I_d$ becomes zero are $I_a = I_d$. This relationship means that the fundamental and 2nd orders of the A- and D-phase currents are in the same and opposite phase angles, respectively. From these, it is proved that the phase current contains the 2nd-order component.

The torque is shown in (13).

$$T = \sum_{n,k=1}^{2} \left[ I_a \sin n\theta \times E_a \sin k\theta + I_a \sin \left( n\theta - \frac{2\pi}{3} \right) \times E_a \sin \left( k\theta - \frac{2\pi}{3} \right) + I_a \sin \left( n\theta - \frac{4\pi}{3} \right) \times E_a \sin \left( k\theta - \frac{4\pi}{3} \right) \right]$$

A torque is generated only when $n = k$ is satisfied, where a positive torque is generated only when the phase angle difference between the phase current and EMF is between $\pm 90$deg. In this way, in the single vector control, magnetic harmonics contribute to torques.

3.2 Twin Vector Control

In this section, twin vector control shown in Fig. 10 is described. The 6 phases in the CSVFRM can be divided into 2 sets of 3 phases. The twin vector control is applied to each 3-phase coils.

In the twin vector control, the phase currents of the 6 phases are sinusoidal. Therefore, only the fundamental component of the magnetic flux generates torques, and magnetic harmonics generate torque ripples.

4. Comparison of the Single and Twin Vector Controls

The single and twin vector controls are compared. A load of 8.5 Nm is applied to the model shown in Fig. 2, and the rotation speed is computed using a coupled magnetic field-control-circuit analysis, where the DC-link voltage is 7.5 V.

The rotation speed under single vector control is 607 rpm, and the phase current waveforms of the A and D phases are shown in Fig. 11. Fig. 12 shows the harmonic components of the A phase current. From Fig. 12, it is observed that the ratio of the 2nd component is about 27%. In addition, the phase angle difference between the 2nd-order component of the EMF and phase current is 53 deg, and a positive torque is generated by the 2nd-order component of the phase current.

Next, the rotation speed under twin vector control is computed. The rotation speed is 475 rpm, and this is lower than that under single vector control. This means that larger currents are needed for the twin vector control than the single vector control to generate the same torque.
The phase current waveform and harmonic components under twin vector control are shown in Figs. 13 and 14. From Fig. 14, it is observed that the fundamental order is dominant, and small harmonic components are due to inadequate PI gains. In this way, the 2nd-component which is dominant under single vector control can be removed using the twin vector control.

In the single vector control, a 2nd component of 27% is included in the phase current waveform. A twin vector control which a 2nd component of 27% is injected is applied. A transformation matrix from UVW to dq coordinate systems is shown in (14).

$$[D][C] = \begin{bmatrix} \frac{2}{3} & \cos \theta & \cos \left( \frac{2}{3} \pi \right) & \cos \left( \frac{2}{3} \pi + \frac{2}{3} \pi \right) \\ \sin \theta & -\sin \left( \frac{2}{3} \pi \right) & -\sin \left( \frac{2}{3} \pi + \frac{2}{3} \pi \right) \end{bmatrix}$$

(14)

A 3-phase current which the 2nd component is injected is shown in (15).

$$\begin{align*}
I_u &= A \sin \theta + B \sin (2\theta + \alpha) \\
I_v &= A \sin \left( \theta - \frac{2}{3} \pi \right) + B \sin \left( 2\theta - \frac{2}{3} \pi + \alpha \right) \\
I_w &= A \sin \left( \theta + \frac{2}{3} \pi \right) + B \sin \left( 2\theta + \frac{2}{3} \pi + \alpha \right)
\end{align*}$$

(15)

where $A$ is the amplitude of the fundamental component, and $\alpha$ is the phase angle of the 2nd component. Equation (16) is obtained by applying (14) to (15).

$$[D][C] \begin{bmatrix} I_u \\ I_v \\ I_w \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}}{2} B \sin (3\theta + 2\alpha) \\ -\frac{\sqrt{3}}{2} (A - B \cos (3\theta + 2\alpha)) \end{bmatrix} = \begin{bmatrix} I_d \\ I_q \end{bmatrix}$$

(16)

The ratio of the 2nd component is 27% of the fundamental component. A 27% 2nd component can be injected by controlling that $B/A = 0.27$.

The rotation speed under twin vector control which a 27% 2nd component is injected is 586 rpm. The phase current waveforms of the A and D phases are shown in Fig. 15. The harmonic components of the phase current is shown in Fig. 16. From Fig. 16, it is observed that the 2nd component is about 27% of the fundamental component. However, the rotation speed is lower than that under...
single vector control. This is because harmonic components more than the 3rd order are not considered. This means that the single vector can automatically consider all harmonic components which contribute to generate torques.

5. Conclusion

In this paper, single and twin vector controls for a current superimposition variable flux reluctance motor were compared. The single vector control was applied to an imaginary 3-phase current, and this generated torques using the fundamental component and harmonic components of the phase current. On the other hand, in the twin vector control, harmonic components can be injected. However, it was difficult to inject all harmonic components. Therefore, a torque under single vector control was larger than that under twin vector control. In this way, the single vector control was more effective for the current superimposition variable flux reluctance motor than the twin vector control.

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