Research Article

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AC/DC current ratio in a current superimposition variable flux reluctance machine

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Abstract: We have proposed a current superimposition variable flux reluctance machine for traction motors. The torque-speed characteristics of this machine can be controlled by increasing or decreasing the DC current. In this paper, we discuss an AC/DC current ratio in the current superimposition variable flux reluctance machine. The structure and control method are described, and the characteristics are computed using FEA in several AC/DC ratios.

Keywords: finite element analysis, vector control, rotating machines, traction motors

PACS: 84.50.+d

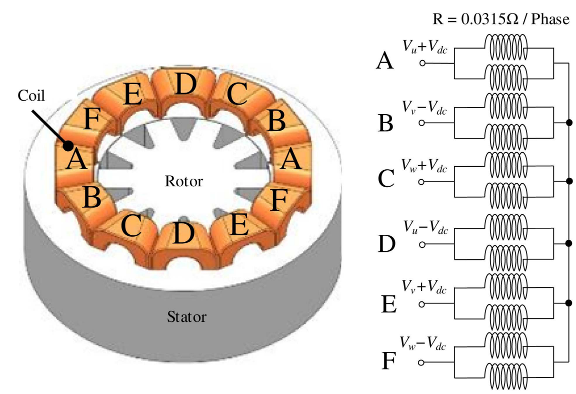

Figure 1: Structure and winding pattern

1 Introduction

Traction motors for electric vehicles and hybrid electric vehicles require wide power band characteristics. In order to increase the power band and reduce the usage of costly rare-earth permanent magnets, variable flux reluctance machines (VFRMs) have been proposed [1–4]. The VFRM is composed of armature and field coils. By controlling the voltage applied on the field coils, the torque constant of the VFRM can be controlled. However, since two separate sets of coils are required, the size of the machine is large and the manufacturing process becomes more complicated. In order to solve these problems, a current superimposition variable flux reluctance machine (CSVFRM) (Figure 1) has been proposed.By using the superimposed current of AC and DC currents, the machine requires only a single set of coils that can perform both armature- and field-coil functions simultaneously [5–9]. By using a single set of coils, the structure is simplified.

Previously, a 6-phase half bridge inverter (Figure 2a) is used for the CSVFRM. By controlling the AC/DC current ra-

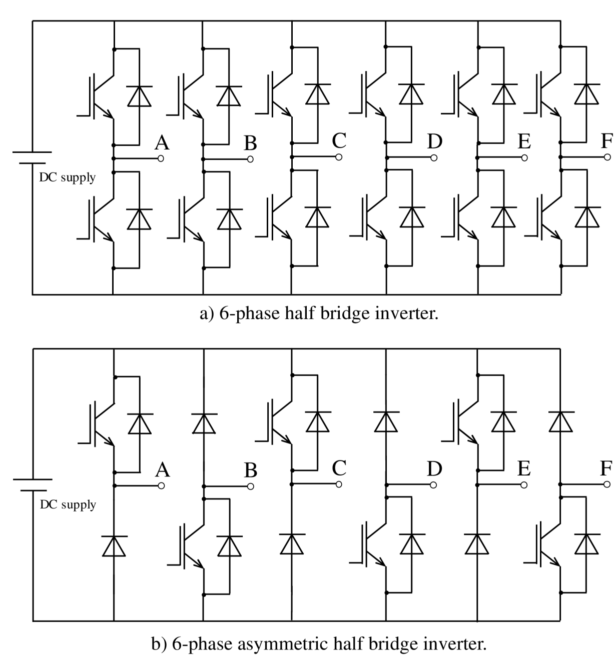

Figure 2: Drive circuit

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tio, the machine can be driven with unipolar currents like a 3-phase switched reluctance machine. If the asymmetric inverter (Figure 2b) is used, there is a possibility that the inverter cost can be reduced. In this paper, we discuss the effect of the AC/DC current ratio in the CSVFRM. First, the structure and the control method are described. Next, the characteristics are computed using 2-D FEA in several AC/DC ratios. Finally, the characteristics under unipolar drive are described.

2 Operational principle and control

Figure 1 shows the structure and winding pattern of the CSVFRM, which consists of a 10-pole rotor and a 12-slot stator. The coils consist of 6 phases (A, B, C, D, E, and F), which correspond to 2 sets of 3 phases alternating current. Therefore, the A and D, B and E, and C and F phases correspond to the U, V, and W phases, respectively. 3-phase AC voltages (V_u, V_v, and V_w) and DC voltages ($+V_{dc}$ and $-V_{dc}$) are applied to each coil as shown in Figure 1. Therefore, the phase current consists of AC and DC components. The magnetomotive force due to the DC current is modulated by the salient poles of the rotor, and the rotating magnetic field due to the 3-phase AC current synchronizes with this modulated flux.

Figure 2 shows the control diagram of the CSVFRM operated under vector control and DC current control. The relationship between the phase current amplitude I_{ac}, d- and q- axes currents i_d, i_q are shown in (1).

$$I_{ac} = \sqrt{\frac{2}{3}}\sqrt{i_d^2 + i_q^2} \tag{1}$$

Furthermore, in order to perform a unipolar drive, equation (2) must be satisfied.

$$I_{ac} \leq I_{dc} \tag{2}$$

In this paper, we verify the characteristics by changing the current ratio n shown in (3).

$$I_{dc} = n\sqrt{\frac{2}{3}}\sqrt{i_d^2 + i_q^2} \tag{3}$$

3 Characteristics analysis

The computed characteristics, when the current ratio changes from 0.1 to 2.0, are shown in Figures 3 and 4, where, the load and rotation speed are 1 Nm and 1000 rpm, respectively. In addition, the DC supply voltage is adjusted so as to satisfy the target rotation speed. Figure 3 shows the phase current I_{phase} and iron loss W_i. The iron losses are calculated using the magnetic flux density distributions that are computed using FEM analysis. From this figure, it is observed that the phase current minimizes when the current ratio is 0.7. The phase current is represented in (4).

$$I_{phase} = \sqrt{I_{dc}^2 + \frac{I_{ac}^2}{2}} \tag{4}$$

From this equation, it is clear that the phase current is minimized when the $I_{dc}/I_{ac} = 1/\sqrt{2} \approx 0.7$. Due to the reduction of t current amplitude, the iron loss decreases.

Figure 4 shows the efficiency and power factor. The maximum efficiency is about 54%, when the current ratio is 0.7, because of the decrease of copper losses. The power factor increases as the current ratio increases. This is because the reactive power decreases with the reduction of AC component in the phase current.

The transient characteristics of the phase current when the current ratio are 1.0 and 0.7, are shown in Figures 5 and 6. From these figures, I_{ac} are 17.1 and 20.3A, and I_{dc} are 17.1 and 14.2A, respectively. The phase currents are successfully controlled according to the command value.

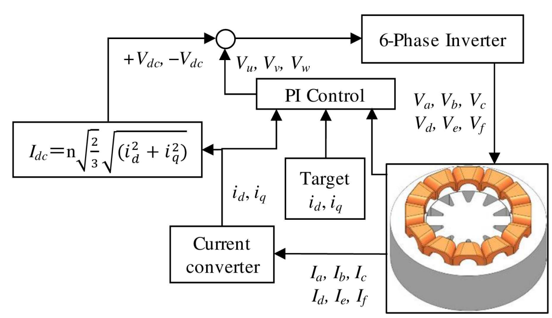

Figure 3: Control diagram

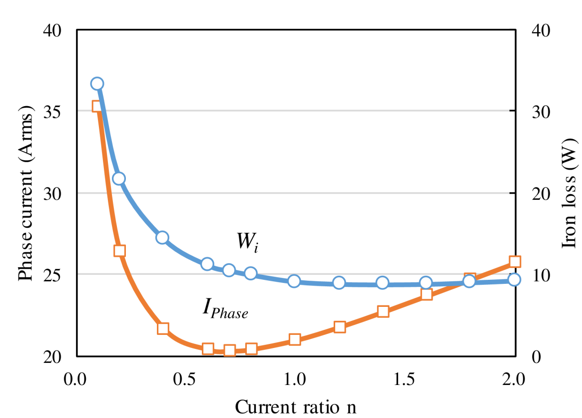

Figure 4: n-I_{Phase} and n-W_i characteristics

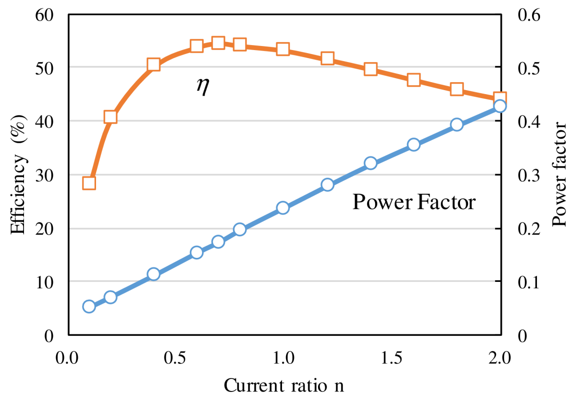

Figure 5: n-Efficiency and n-PF characteristics

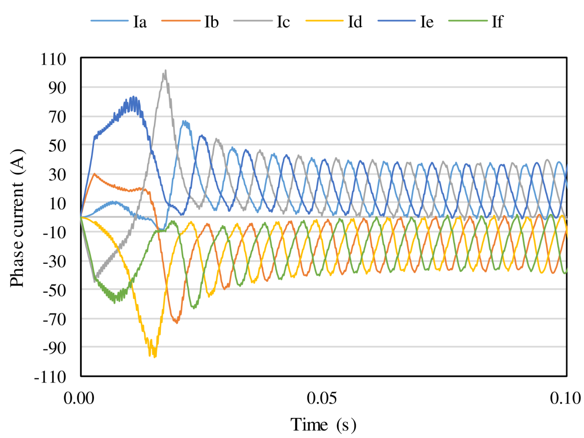

Figure 6: Phase current waveform (n = 1.0)

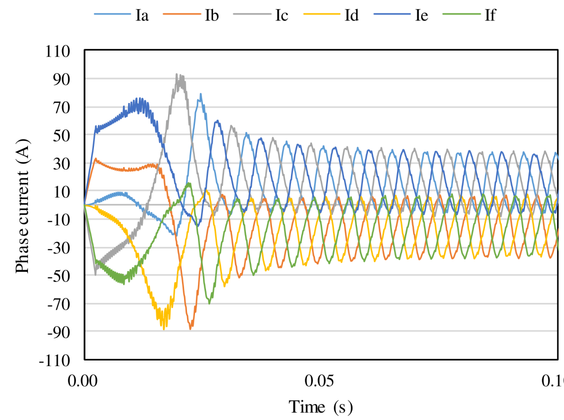

Figure 7: Phase current waveform (n = 0.7)

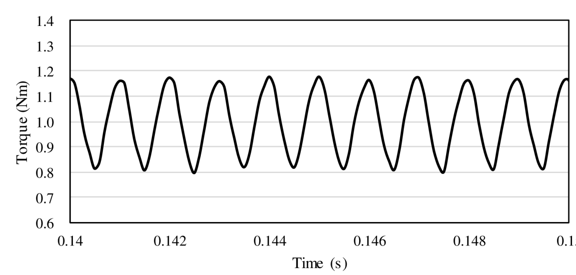

Figure 8: Torque waveform (n = 1.0)

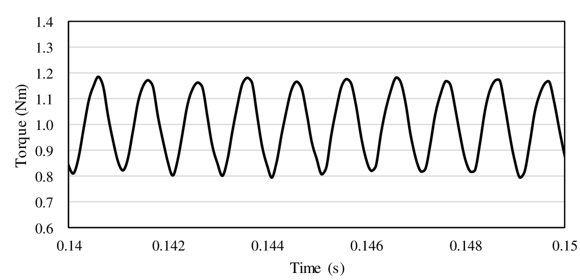

Figure 9: Torque waveform (n = 0.7)

The effective values of the phase currents are 20.9Arms and 20.3Arms, respectively. The phase current waveform under a current ratio of 1.0 crosses zero in the transient state, and does not cross zero in the steady state.

The torque waveforms when the current ratio are 1.0 and 0.7, are shown in Figures 7 and 8. The torque ripple are about 17.8 and 18.6%, respectively.

4 Unipolar drive characteristics

In this section, the characteristics when the current direction is restricted assuming the unipolar drive are described. As aforementioned, it is difficult to prevent zero crossing of the current in a transient state by controlling only the current ratio. Therefore, the current is controlled not to cross zero by giving an initial DC voltage within the current density limit. Where, applied DC voltage is 2.0V.

The phase current waveform and torque waveform, when the current ratio is 1.0, are shown in Figures 9 and 10, respectively. From Figure 9, it can be observed that the phase current does not cross zero in the transient state. The torque ripple is about 17.7%. Because of a unipolar drive, the same current waveforms in the steady state, the output power and torque ripple are also the same.

Figure 11 shows the phase current waveform when the current ratio is 0.7. Because of the current direction restriction, sinusoidal wave cannot be obtained in each phase. The effective value of the phase current is 20.4Arms. The

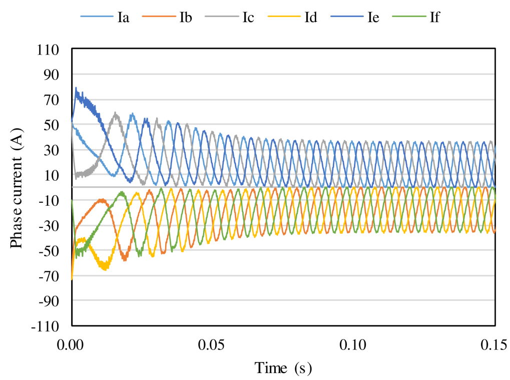

Figure 10: Phase current waveform (n = 1.0)

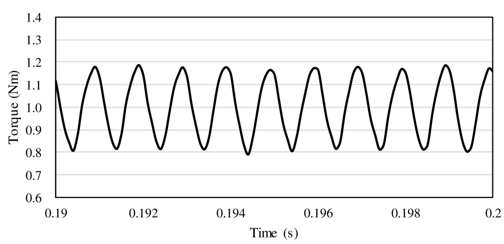

Figure 11: Torque waveform (n = 1.0)

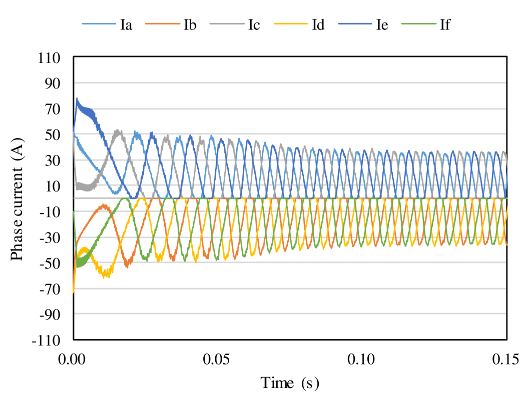

Figure 12: Phase current waveform (n = 0.7)

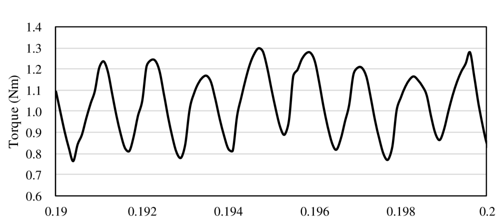

Figure 13: Torque waveform (n = 0.7)

torque waveform is distorted as shown in Figure 12. In addition, the rotation speed in the steady state is 830 rpm, and the output power decreases with that of the bipolar drive.

5 Conclusion

In this paper, the effect of AC/DC current ratios in a current superimposition variable flux machine was described. From the results of the analysis, the phase current was minimum when the current ratio is 0.7, and the efficiency was maximum. The power factor increased along with the current ratio was increasing. However, the efficiency decreased as the current ratio was increasing. In addition, the machine can be driven with unipolar currents by controlling the AC/DC current ratio. Namely, the same driving circuit as a switched reluctance machine can be used, and there is a possibility of reducing the inverter cost.

References

[1] Kashitani Y., Shimomura S., Novel Slipring-less Winding-Excited Synchronous Machine, ICEMS, 2011, 1-6.

[2] Fukami T., Matsuura Y., Shima K., Moriyama M., Kawamura M., A Multipole Synchronous Machine With Nonoverlapping Concentrated Armature and Field Windings on the Stator, IEEE Trans. Industrial Electronics, 2012, 59, 6, 2583-2591.

[3] Di Wu, Jun Tao Shi, Z. Q. Zhu, Xu Liu, Electromagnetic Performance of Novel Synchronous Machines With Permanent Magnets in Stator Yoke, IEEE Trans. Magn., 2014, 50, 9.

[4] Fukami T., Ueno Y., Shima K., Magnet Arrangement in Novel Flux-Modulating Synchronous Machines With Permanent Magnet Excitation, IEEE Trans. Magn., 2015, 51, 11.

[5] Niguchi N., Hirata K., Ohno Y., Kohara A., VARIABLE FLUX RELUCTANCE MOTOR USING A SINGLE SET OF COILS, ISEF, 2015, P2-JP009.

[6] Kohara A., Hirata K., Niguchi N., Ohno Y., Finite-element analysis and experiment of Current Superimposition Variable Flux Machine Using Permanent Magnet, IEEE Trans. Magn., 2016, 52, 9, 8107807.

[7] Kohara A., Hirata K., Niguchi N., Ohno Y., Study on a current superimposition variable flux reluctance machine with distributed winding, ICEM, 2016, 2498-2503.

[8] Niguchi N., Hirata K., Kohara A., Characteristics of a wide power band variable flux reluctance motor, ICEM, 2016, 180-185.

[9] Kohara A., Hirata K., Niguchi N., DC Current Control Method of a Current Superimposition Variable Flux Reluctance Machine, COMPUMAG, 2017, PD-M3-3.