DC Current Control Method of a Current Superimposition Variable Flux Reluctance Machine

Akira Kohara[1], Katsuhiro Hirata[1], and Noboru Niguchi[1]

[1]Osaka University, Suita, Osaka, Japan akira.kohara@ams.eng.osaka-u.ac.jp

We have proposed a current superimposition variable flux machine for traction motors. The torque-speed characteristics of this machine can be controlled by increasing or decreasing the DC current which is superimposed on the AC current. However, because of the change of coil resistances, the DC current was difficult to be controlled. In this paper, we propose a DC current control method and verify its effectiveness by using a coupled analysis of FEA and vector control. First, the structure and control method are described. Next, the torque-speed characteristics are computed using 2-D FEA. Finally, the computed characteristics are verified by carrying out measurements on a prototype.

Index Terms— Finite element analysis, Machine vector control, Rotating machines, Traction motors.

I. 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]-[2]. The VFRM is composed of 2 sets of windings: armature windings for generating a rotating magnetic flux, and field windings for controlling the magnetic field intensity. Due to this, the torque constant of the VFRM can be controlled and its power band can be increased. However, since two separate sets of windings are required, the size of the machine is large and it becomes more complicated to manufacture.

In order to solve these problems, a current superimposition variable flux reluctance machine (CSVFRM) has been proposed. The machine requires only a single set of windings that can perform both armature and field winding functions simultaneously [3]-[4]. By using a single set of coils, the winding structure is simplified.

However, the DC current is difficult to be controlled because the coil resistance changes according to coil temperature. In this paper, we propose a DC current control method and verify its effectiveness. First, the structure and control method are described. Next, the torque-speed characteristics are computed using 2-D FEA. Finally, the computed characteristics are verified by measurements using a prototype.

II. STRUCTURE AND CONTROL DIAGRAM

Fig. 1 shows the structure and winding pattern of the CSVFRM, which consists of a 10-pole rotor and a 12-slot stator. The specification is shown in Table I.

A 6-phase inverter is used to operate the CSVFRM. The coils consist of 6 phases (A, B, C, D, E, and F), which corresponds to 2 sets of 3 phases. 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) are applied to the A and D, B and E, and C and F phases, respectively, as shown in Fig. 1. DC voltages ($+V$ and $-V$) are superimposed onto the 3-phase AC voltages. 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.

Fig. 2 shows the control diagram. The CSVFRM is operated under vector control and DC current control. Applied DC
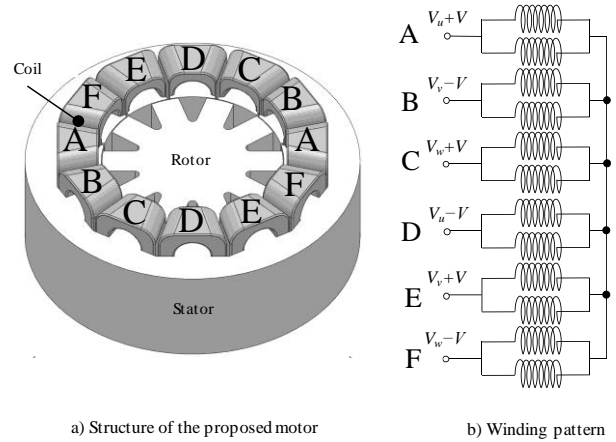

a) Structure of the proposed motor   b) Winding pattern
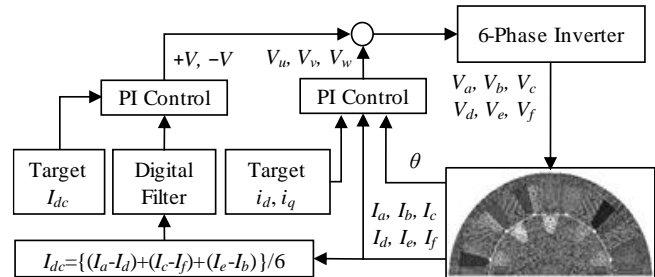
Fig. 1. Structure and winding pattern.

Fig. 2. Control diagram.

TABLE I
SPECIFICATIONS

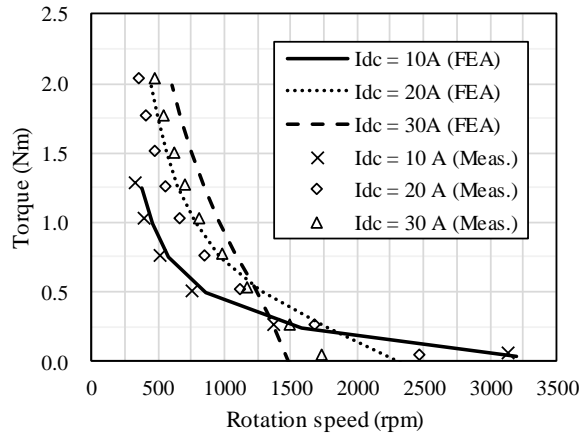| Machine size (mm)	$\phi110\times83$
Magnetic material	35A300
Number of coil turns	20
Coil resistance	0.032Ω /Phase
DC supply voltage (V)	12 (3rd harmonics injection)

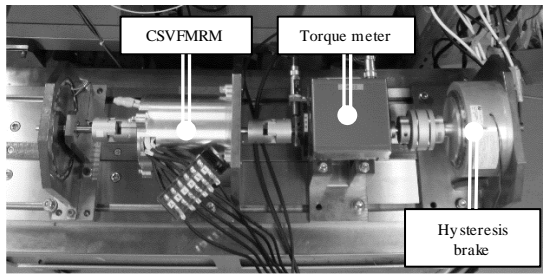Fig. 3. Torque-speed characteristics.
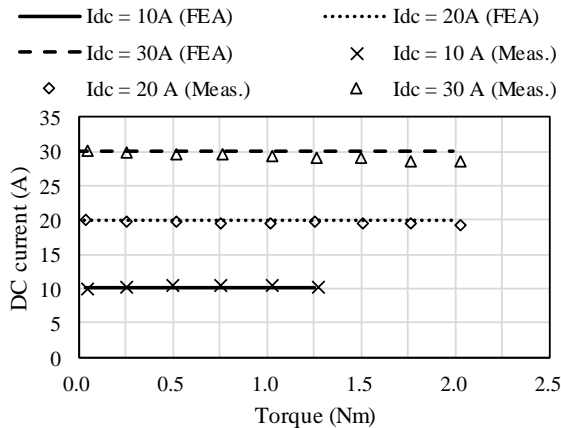

Fig. 4. Test bench.
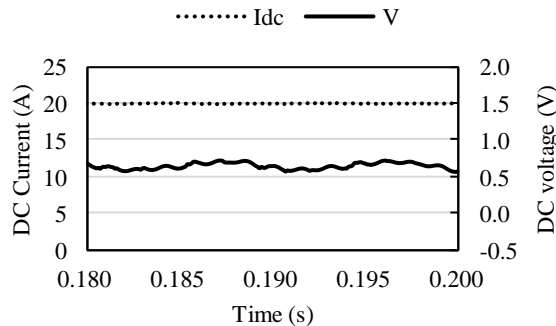

Fig. 5. DC current.

Fig. 6. DC voltage and current (FEA).

voltages are determined by using PI control. I_{dc} was calculated by an average DC current of 6 phases as shown in Fig.2. In this paper, the machine is operated using maximum torque control (I_d=0).

III. VERIFICATION OF THE EFFECTIVENESS

A. Analysis method

An electromagnetic analysis using 2-D FEA under vector control was conducted to evaluate the effectiveness of the proposed control method. In this analysis, JMAG-Designer 15.1 was used for the electromagnetic analysis and vector control was applied by MATLAB/Simulink. In this analysis, loads of 0, 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75 and 2 Nm were applied on the rotor.

B. Electromagnetic Analysis and Experiment Result

The computed torque-speed characteristics are shown in Fig. 3 with the measured torque-speed characteristics, where a test bench shown in Fig. 4 is used for measurements. The control period of the analysis and measurement are 0.1 ms and 50 μs, respectively. The computed and measured DC currents (I_{dc}) are shown in Fig. 5, where the target DC current is 10, 20, and 30 A.

From Fig. 3, it is observed that the difference between the computed and measured torque-speed characteristics increases as the DC current increases. This is because the difference between the computed and measured DC currents increases as shown in Fig. 5. The difference of the target and measured DC current is thought to be the PI gains and digital filter constant that are not completely tuned.

Fig. 6 shows the computed DC voltage and current when the target DC current and load are 20 A and 0.5 Nm, respectively. From Fig. 6, it is observed that the DC current is converged to 20 A although the DC voltage fluctuates.

IV. CONCLUSION

In this paper, we proposed a DC current control method of a current superimposition variable flux reluctance machine. The torque-speed characteristics are computed and measured through FEA and experiments using a prototype. The computed DC currents could be controlled. However, the difference between the target and measured DC currents increased as the target DC current increases.

REFERENCES

[1] F. Tadashi, M. Yoshitaka, S. Kazuo, M. Masatoshi, and K. Mitsuhiro, "A Multipole Synchronous Machine With Nonoverlapping Concentrated Armature and Field Windings on the Stator", *IEEE Trans. Industrial Electronics*, vol.59, No.6, pp. 2583-2591, 2012.
[2] X. Liu, and Z. Q. Zhu ,"Influence of Rotor Pole Number on Electromagnetic Performance of Novel Variable Flux Reluctance Machine With DC-Field Coil in Stator", *in Proc. ECCE Asia*, pp. 1108-1115, 2012.
[3] T. Fukami, Y. Ueno, and K. Shima : "Magnet Arrangement in Novel Flux-Modulating Synchronous Machines With Permanent Magnet Excitation", *IEEE Trans. Magnetics*, Vol. 51, No. 11, 2015.
[4] Z. Q. Zhu B. Lee and X. Liu : " Integrated field and armature current control strategy for variable flux reluctance machine using open winding", *Ecological Vehicles and Renewable Energies (EVER)*, pp. 1-7, 2015.
[5] Noboru Niguchi, Katsuhiro Hirata, Yuki Ohno, and Akira Kohara, "VARIABLE FLUX RELUCTANCE MOTOR USING A SINGLE SET OF COILS", *in Proc. ISEF 2015*, P2-JP009, 2015.
[6] A. Kohara, K. Hirata, N. Niguchi, Y. Ohno, "Finite-element analysis and experiment of Current Superimposition Variable Flux Machine Using Permanent Magnet", *IEEE Trans. Magnetics*, vol.52, No.9, 2016.