Analytical estimation of acceleration/deceleration time in the flywheel battery system with slotless PMSM/G

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Abstract — This paper presents analytical estimation of acceleration/deceleration time in the flywheel battery system with slotless permanent magnet synchronous motor/generator (PMSM/G). Its estimation is very important for application of flywheel battery systems such as electric vehicle, aerospace and power quality improvement system. First, the circuit parameters of the PMSM/G are derived by space harmonic (SH) method, and the operating range of PMSM/G is decided using the circuit parameters by equivalent circuit (EC) method considering operating power. Finally, the acceleration and deceleration time of flywheel within the operating range can be estimated by the motion equation represented as s-domain according to electromagnetic torque obtained by SH method.

I. INTRODUCTION

Flywheel battery system is energy storage equipment which can be supplying the electrical energy when needed, after electrical energy is stored into the mechanical rotation energy. Within a flywheel battery system a rotating flywheel is mechanically connected to a motor-generator and all energy to and from the flywheel is transferred electrically via the motor-generator. Recently, the flywheel battery system is drawing attention as a substitute for electrochemical battery due to the lifespan and stability. This paper presents analytical estimation of acceleration/deceleration time in the flywheel battery system with slotless permanent magnet synchronous motor/generator (PMSM/G). Its estimation is very important for application of flywheel battery systems such as electric vehicle, aerospace and power quality improvement system. First, the circuit parameters of the PMSM/G are derived by space harmonic (SH) method, and the operating range of PMSM/G is decided using the circuit parameters by equivalent circuit (EC) method considering operating power. The operating range is for the purpose of keeping the system's temperature. Finally, the acceleration and deceleration time of flywheel within operating range can be estimated by the rotational motion equation represented as s-domain according to electromagnetic torque obtained by SH method. [5]

II. CIRCUIT PARAMETERS CALCULATION BY SH METHOD

The circuit parameters of the PMSM/G such as inductance, back-EMF constant and torque constant are derived by SH method which is one of the numerical analysis methods for field solution acquisition via magnetic vector potential in 2-D polar coordinate system. Fig. 1 shows the analysis model of PMSM/G which is composed of a 4-pole rotor with parallel magnetized NdFeB magnets and slotless stator with 3-phase winding. The back-EMF and torque constant are established by magnetic field solution due to permanent magnets, the inductance is established by magnetic field solution due to stator winding current. The governing field equations of analysis model using Maxwell's equation and coulomb gauge can be presented as follow [1] [3] [4]

$$\begin{cases} \nabla^2 \mathbf{A}^{I,III,V} = 0 & \text{airspace /iron} \\ \nabla^2 \mathbf{A}^{II,IV} = -\mu_0 (\nabla \times \mathbf{M}) & \text{magnet} \\ \nabla^2 \mathbf{A}^{II,IV} = -\mu_0 (\nabla \times \mathbf{J}) & \text{winding} \end{cases} \quad (1)$$

where $\boldsymbol{A}$, $\mu 0$, $\boldsymbol{M}$, $\boldsymbol{J}$ are magnetic vector potential, permeability of the air, magnetization of parallel magnetized PMs and current density. The governing field equations of (1) are represented as a quadric differential equation. Therefore, the solutions of equations are obtained by matrix calculation.[1][4]

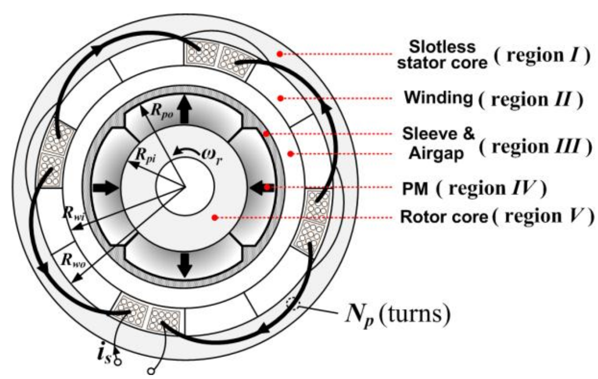

Fig. 1. Analysis model of slotless PMSM/G.

III. OPERATING RANGE ESTIMATION BY EC METHOD

The EC method has been used to model the nonlinear magnetic field in electromagnetic devices for steady-state and dynamic conditions. For the accurate analysis on generating characteristic of PMSM/G, the circuit parameters obtained by SH method are applied to the EC method. The single-phase equivalent circuit is composed of the circuit parameters such as inductance and back-EMF constant, the generating performance according to various rotation speeds is established by solving the circuit equation. Then, on the basis of the generating performance and maximum stator winding current, the operating range of PMSM/G is decided. Here, the maximum stator winding current is restricted to permitted current density according to cooling system of machine. [2]

IV. CALCULATION OF ACCELERATION AND DECELERATION TIME OF FLYWHEEL BATTERY SYSTEM

The acceleration and deceleration time of flywheel can be estimated within operating range by rotational motion equation represented as s-domain. The rotor dynamics equation is consist of the electromagnetic torque T_e, rotor inertia J_r, friction coefficient B and reverse torque T_r as shown (2).

$$T_e(s) = J_r\left[s\omega_r(s) - \omega_r(0)\right] + B\omega_r(s) + T_r(s) \qquad (2)$$

The electromagnetic torque is calculated as product of torque constant obtained by SH method and peak value of input phase current. The reverse torque includes load torque due to generating power and drag torque due to power loss such as core loss, rotor loss, copper loss and mechanical loss.

V. ANALYSIS RESULT

Fig. 2 shows a manufactured flywheel battery system with slotless PMSM/G. The PMSM/G is operated using hall sensor, the flywheel inertia is 0.0918 [kg·m^2]. Fig. 3 shows the line-to-line back-EMF characteristics at rotor speed 10,000[rpm] and 5,000[rpm] by SH method, finite element method and experiment. Fig. 4 shows the generating performance of the PMSM/G by EC method for operating range determination. The required power of flywheel battery system is given as 180[W], the peak value of maximum phase current considering maximum current density of the machine is 4[A]. Fig. 5 shows speed characteristic of flywheel by experiment.

In manuscript, the detailed process and result of analysis on acceleration/deceleration time will be presented. Also, the verification of generating performance will be performed by finite element method.

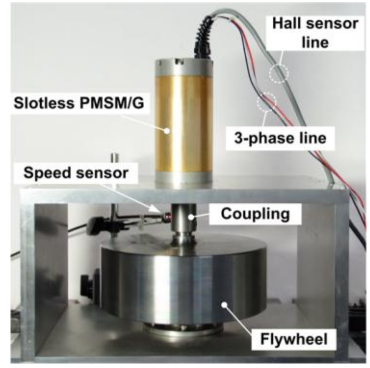

Fig. 2. A manufactured flywheel battery system with slotless PMSM/G.

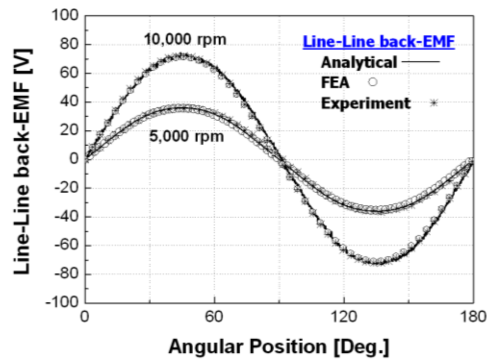

Fig. 3. The line-to-line back-EMF characteristics at rotor speed 10,000[rpm] and 5,000[rpm] by SH method.

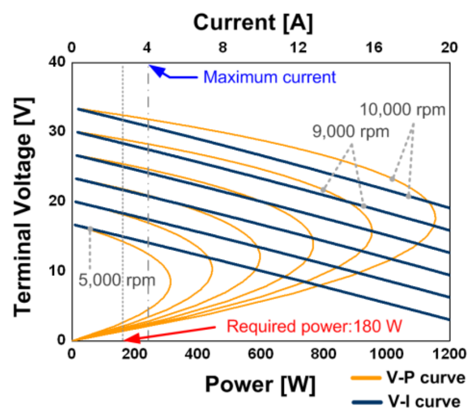

Fig. 4. The generating performance of PMSM/G by EC method for operating range determination.

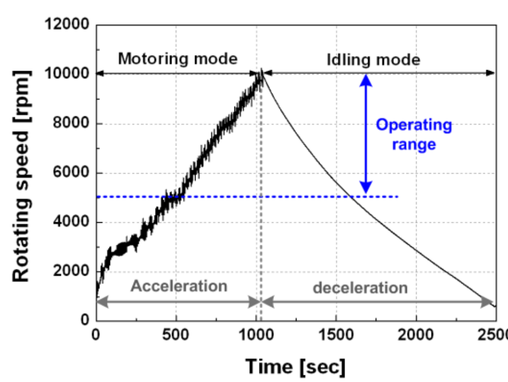

Fig. 5. Flywheel speed characteristic by experiment.

VI. REFERENCES

[1] Seok-Myeong Jang, Ji-Hoon Park, Dae-Joon You, and Sang-Ho Choi, "Analysis on operational power and eddy current losses for applying coreless double-sided permanent magnet synchronous motor/generator to high-power flywheel energy storage system," JOURNAL OF APPLIED PHYSICS 105, 07F116, March, 2009.

[2] Jang-Young Choi, Seok-Myeong Jang and Kyoung-Jin Ko, "Experimental verification and analytical approach to influence stator skew on electromagnetic performance of permanent magnet generators with multipole rotor," JOURNAL OF APPLIED PHYSICS 105, 07A327, March, 2009.

[3] K. Atallah, D. Howe, "The application of Halbach cylinders to brushless AC servo motors", IEEE Trans. on Magnetics vol. 34, 1998.

[4] Z. Q. Zhu, D. Howe, E Bolte, B. Ackermann, "Instaneous magnetis field distribution in brushless permanent magnet dc motors, Part I: open-circuit field," IEEE Trans. Magnetic., vol29, no.1, 1993.

[5] Mark Matthew Flynn, B.S., M.S., "A Methodology for Evaluating and Reducing Rotor Losses, Heating, and Operational Limitations of High-Speed Flywheel Batteries", The University of Texas at Austin, a doctoral dissertation, August, 2003.