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Research on the Control of Flywheel Battery

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Abstract: The control of flywheel battery is researched in this study. The motor/generator is three-phase Permanent Magnet Synchronous Motor (PMSM). Vector control method is used to control flywheel battery charge and Electrode Plate Control (EPC) is embedded in vector control. Through controlling the duty cycle of IGBT, the flywheel battery discharges with steady voltage. The experimental results have verified that this method was effective in flywheel battery storing energy and releasing energy processes.

Key words: Flywheel, electrode plate control, vector control

INTRODUCTION

Flywheel battery is now considered as enabling technology for many applications, including space systems (Christopher *et al*., 1997; Wagner *et al*., 2004), pulse power transfer for hybrid electric vehicles (Beno *et al*., 2002) and Uninterruptible Power Supplies (UPS) (Lawrence *et al*., 2003), telecommunications (Taylorand and Mistry, 1996).

There are some others alternative techniques for energy storage have been proposed, example for lead-acid batteries, superconductor, compressing air and capacitors (Jiancheng *et al*., 2002; Samineni *et al*., 2006). In comparison with others, the flywheel battery is a kind of clean energy storage system and has lots of advantages. It has high efficiency, high energy density, long serve life and no environmental pollution. It can improve the quality and reliability of the power network.

In this study, a kind of new control method, Electrode Plate Control (EPC) (Yongping and Shen-Yi, 2005), is introduced to control the flywheel battery charge and discharge processes. EPC is a kind of nonlinear control method, based on the physical model that a charge is between a pair of electrode plates.

SYSTEM OF FLYWHEEL BATTERY

The flywheel battery is an electro-mechanical approach to energy storage. To store electricity, a motor is used to convert the electricity from an external source into the rotational energy of a flywheel. Using the motor as a generator, then extracting energy retrieves the stored energy. In general, a complete system of flywheel battery consists of four parts (1) the flywheel that stores energy, (2) bearings that supports the flywheel, (3) a motor/generator and (4) power electronics and control electronics.

The amount of energy stored and released, E, is calculated by means of the equation:

$$E = \frac{1}{2}I(\omega_h^2 - \omega_l^2) \tag{1}$$

Where:

I = The moment of inertia of the flywheel.
ω_h = High operating speed.
ω_l = Low operating speed.

As shows in Fig. 1, the experiment flywheel battery system in this study consists of a digital controller, a three-phase rectifier, a intelligent inverter, a flywheel, a three-phase PMSM, a PC. The digital controller consists of a DSP control board based on TMS320LF2407 and interface board. The intelligent inverter is the 5th IPM,

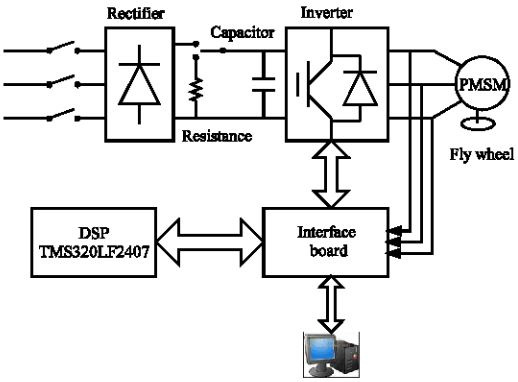

Fig. 1: Flywheel battery system

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PM25CLA120, made by MITSUBISHI. The power of PMSM is 1100W, the speed is 6000 r m^{-1}, the stator resistance is 3.5Ω (Chi and Xu, 2005).

FLYWHEEL CHARGE CONTROL

Mathematical model of permanent magnet synchronous motor: The mathematical model of PMSM is derived under the following assumptions (Pillay and Krishna, 1998):

- Saturation is neglected, although it can be taken into account by parameter changes.
- The back electromotive force is sinusoidal.
- Eddy currents and hysteresis losses are negligible.

With the assumption, the stator d, q equations in the rotor reference frame of the PMSM are:

$$pi_d = (v_d - Ri_d + \omega_r L_q i_q) / L_d \tag{2}$$

$$pi_q = (v_q - Ri_q + \omega_r L_d i_d - \omega_r \lambda_{af}) / L_q \tag{3}$$

where:

$$p\omega_r = (T_e - B\omega_r - T_l) / J \tag{4}$$

and

$$p\theta_r = \omega_r \tag{5}$$

The electric torque is expressed as:

$$Te = 3n\,[\lambda_{af}\, i_q + (L_d - L_q)\, i_d\, i_q]/2 \tag{6}$$

λ_{af} = The magnet mutual flux linkage (Web·turn).
i_d and i_q = The d and q axis stator currents (A).
v_d and v_q = The d and q axis stator voltages.
T_e = The electric torque (Nm).
L_d and L_q = The stator d,q inductances(H).
n = The number of pole pairs.
p = The derivative operator.
R = The stators resistance (Ω).
ω_r = The rotor speed (rad sec^{-1}).
B = Damping constant (N/rad/sec).

Electrode Plate Control (EPC): If a positive charge is between a pair of positive electrode plates, under the electric power, the charge will stay at the balance position. If the positive charge represents the control object, then electrode plates control model can be constructed in phase plane, as shows in Fig. 2.

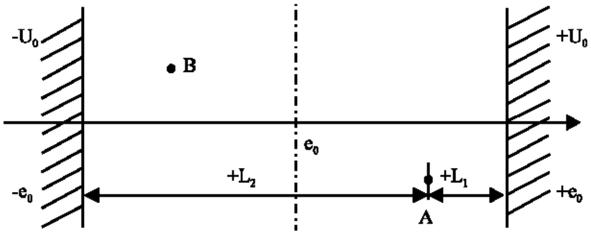

Fig. 2: Model of PEC

$+U_0$ and $-U_0$ are the control power to the control object. L_1 and L_2, are the distance between point A and the plates. When the control object is at position A, the control effect of $+U_0$ is strengther than of $-U_0$, because of the distribution of the field. So the control power u_A is positive and the control object move to the balance position of the electric field. When the control object is at position B, the condition is reverse.

The state function F of system can be expressed by L_1, L_2. The control power u_A is a function with F and $\pm U_0$. This is a negative feedback control system. When the control object in the position A. So the synthetical control power u_A can be expressed as:

$$\begin{aligned} u_A &= U_A^{+U_0} + U_A^{-U_0} \\ &= F(L_1, L_2)(+U_0) + F(L_2, L_1)(-U_0) \end{aligned} \tag{7}$$

$$\begin{cases} F(L_1, L_2) = \dfrac{L_1^{-m}}{L_1^{-m} + L_2^{-m}} \\ F(L_2, L_1) = \dfrac{L_2^{-m}}{L_1^{-m} + L_2^{-m}} \end{cases} \tag{8}$$

$$u(e) = \frac{L_1^{-m} - L_2^{-m}}{L_1^{-m} + L_2^{-m}} U_0 = \frac{(e_0 + e)^m - (e_0 - e)^m}{(e_0 + e)^m + (e_0 - e)^m} U_0 \tag{9}$$

e_0 is the distance between the plate and the balance position.

When m = 1, e_0 is a constant, then the EPC is the proportional controller. The error is e, then

$$u(e) = \frac{(e_0 + e)^m - (e_0 - e)^m}{(e_0 + e)^m + (e_0 - e)^m} U_0 = \frac{U_0}{e_0} e = Ke \tag{10}$$

The formula (10) is the proportional control.

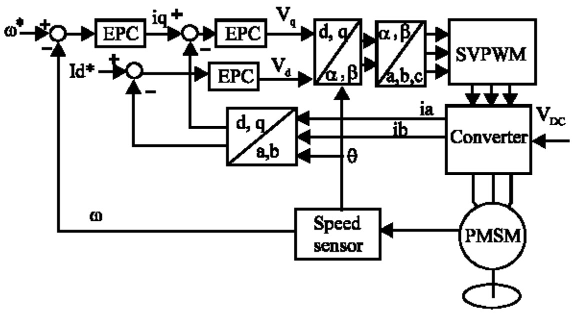

Fig. 3: Vector control of PMSM

There are three parameters: U_0, e_0, m in formular (10). These parameters play different roles.

The effect of U_0 is direct to u(e). When the parameter m and e_0 are certain values, u(e) is proportional to U_0. So U_0 can adjust the amplitude of u(e).

The parameter e_0 represents the ability of variable gain in EPC. With e_0 increasing, the control power u(e) decreases and the derivative of u(e) decreases too, So linearity of u(e) increases; otherwise, with e_0 decreasing, the control power u(e) increases, the derivative of u(e) increases, too. The changes of u(e) are drastic.

The parameter m reflects the stiffness of the EPC. The slope coefficient of u(e) is various with different value of m. When m is equal to 1, the derivative of u(e) with respect to e is constant; When m is unequal to 1, the derivative of u(e) with respect to e is a nonlinear function. So m can be changed in order to adapt for diverse conditions.

According to the principle of linear superposition, plates of accumulative error and differential of error can be constructed vertically to the plate of error. When m of all plates is equal to 1, this control modal changes into PID control, so PID control is a special case of EPC.

The vector control of PMSM: The vector control of PMSM is used in flywheel battery charge process, the controller in vector control is EPC. The control system shows in Fig. 3.

DISCHARGE OF FLYWHEEL BATTERY SYSTEM

The boost chopper principles are used in the flywheel battery's discharge process. According to the counter electromotive force of PMSM, the IGBT in IPM is opened and closed. Every IGBT works in 60° electrical angle. When one phases counter electromotive force amplitude reached 0.866 times of the maximum amplitude, one bridge arm will be open or close, which determined by the direction of counter electromotive force. When the amplitude of counter electromotive force declines to 0.866 times, then another bridge arm starts work. The three-phase bridge inverter and windings of PMSM show in Fig. 4.

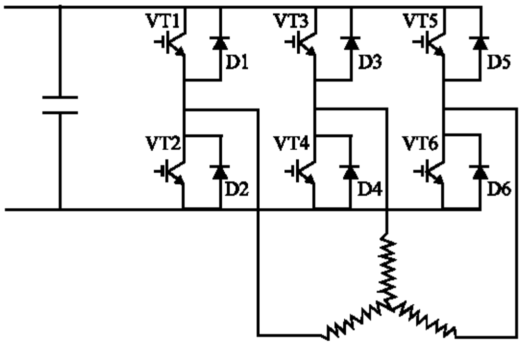

Fig. 4: Three-phase inverter bridge and windings of PMSM

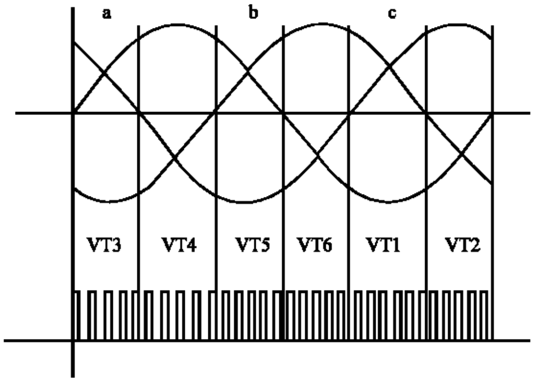

Fig. 5: Regenerative braking method

Takes VT4 for example. In the period of VT4 working, the three-phase voltage shows in Fig. 5. When VT4 is open, the windings of phase A, B, C and diodes D6, D2 construct a circuit. Because of the difference of three-phase electromotive force, there is electric current from winding A to winding B and C and the magnetic energy stored in three-phase inductors increases gradually. During this period, one part of the electric energy generated by PMSM translates into thermal power by the electric resistances, the other part translates into magnetic field energy stored in three-phase inductances. When VT4 is close in the same PWM period, the magnetic field energy flows into capacitor through diodes VD1, VD2 and VD3. So the energy received by capacitor includes the

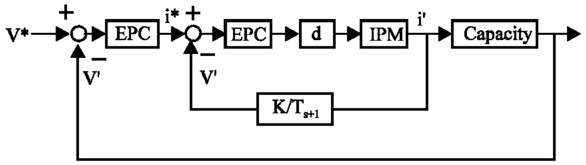

Fig. 6: Control method of regenerative braking

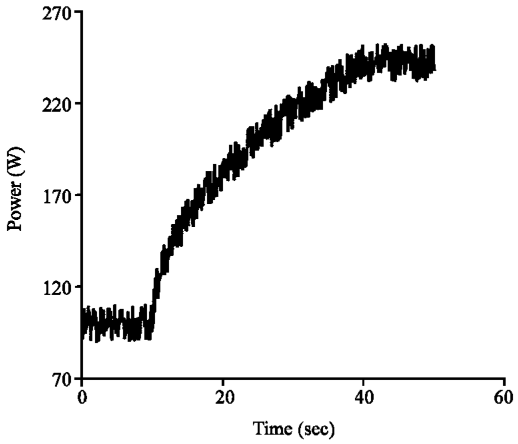

Fig. 7: Power change of flywheel battery for energy storage

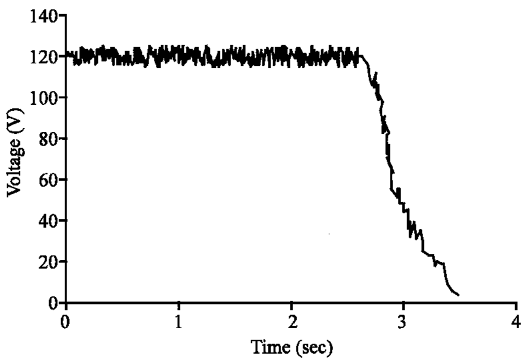

Fig. 8: Voltage change of flywheel battery in energy release

energy generated by PMSM when VT4 close and the energy in inductance. All energy generated by PMSM in one PWM period comes to DC bus, excluding the part converted into thermal power.

The control method of flywheel battery discharge shows in Fig. 6, EPC is used as controller.

V* is the specified voltage. V is the voltage of DC bus. i* is the specified current of DC bus; i is the current of DC bus. d is the duty cycle of IGBT.

Research on experiment: Based on mathematical model of PMSM, EPC controller is used to control charge and discharge processes. The power change of flywheel battery for energy storage shows in Fig. 7.

In the energy storage process, the power increased rapidly. This confirmed the advantage that flywheel battery can store energy at high power.

The voltage change of flywheel battery in energy release process shows in Fig. 8.

The voltage maintained 120V in 2.8 sec, then declined sharply. The flywheel battery can output stable voltage within a certain period of time.

The results of experiment verified that the energy storage and release processes of flywheel battery can be effectively controlled by the EPC controller.

CONCLUSION

In this study, Electrode Plate Control (EPC) was used in flywheel battery charge and discharge proceedings. In charge proceeding, EPC as a controller with vector control method made PMSM accelerate. In discharge proceeding, EPC controlled the current of DC bus in order to make the voltage of DC bus stable. The experiment results proved that this method was effective in flywheel battery storage and release energy proceeding.

REFERENCES

Beno, J., R. Thompson and R. Hebner, 2002. Flywheel batteries for vehicles. Proceedings of the 2002 Workshop on Autonomous Underwater Vehicles, pp: 99-101.

Chi, S. and L. Xu, 2005. Development of sensorless vector control for a PMSM running up to 60,000 rpm: Electric machines and drives. IEEE Int. Conf., pp: 834-839.

Christopher, D.A., R.F. Beach and J.R. Barton, 1997. A flywheel energy storage system test on the International Space Station. Energy Conversion Engineering Conference, IECEC-97. Proceedings of the 32nd Intersociety, pp: 1762-1766.

Jiancheng, Z., H. Lipei, C. Zhiye and W. Su, 2002. Research on flywheel energy storage system for power quality: Power system technology, 2002. Proceedings International Conference on Power, 1: 496-499.

Lawrence, R.G., S.L. Craven and G.D. Nichols, 2003. Flywhed UPS. Industry Applications Magazine. IEEE., 9: 44-50.

Pillay, P. and R. Krishnan, 1988. Modeling of permanent magnet motor drives: Industrial electronics. IEEE Trans., 35: 537-541.

Samineni, S., B.K. Johnson, H.L. Hess and J.D. Law, 2006. Modeling and analysis of a flywheel energy storage system for voltage sag: Correction industry applications. IEEE Trans., 42: 42-52.

Taylorand, T. and K. Mistry, 1996. Power, the broad band challenge. Telephony, pp: 52-54.

Wagner, R.C., D.R. Boyle and K. Decker, 2004. Commercialization of flywheel energy storage technology on the international space station. Energy Conversion Engineering Conference, 2002. IECEC '02. 2002 37th Intersociety, pp: 146-150.

Yongping, R. and L. Sheng-Yi, 2005. Design method of a kind of new controller. Control and Decision, 4: 471-477.