Influence of Load on Discharge Performance of High-speed Flywheel Energy Storage System

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***Abstract*--High-speed and high-capacity flywheel energy storage system with high-performance is a research focus in the energy field. A 200kW, 15000rpm high-speed permanent-magnet machine that used in flywheel energy storage system is investigated in this paper, and its discharge performance is analyzed through establishing a field-circuit coupling model. The relationship between the load and the performance of uncontrolled discharge process of the flywheel system are studied, and the computational results is compared with the experimental ones, which prove the model is correct. On the basis of the above study, the influence of the load and the control circuit on the constant voltage discharge performance of system is analyzed. The results could provide a reference for the design of high performance flywheel energy storage system.**

***Index Terms*--constant voltage discharge, discharge performance, flywheel energy storage system, uncontrolled discharge.**

I. Introduction

The energy issue is one of the significant issues for human being. While developing new energy constantly, in order to make more efficient use of existing energy, advanced energy-saving technologies and energy storage technologies are needed to be developed[1]-[3]. As a new and efficient mechanical energy storage technology, flywheel energy storage has the advantages of high energy storage density, high power density and high energy conversion efficiency, etc. Thus, it has a wide application prospect in the fields of peak regulation of power network, power quality control and vehicle regenerative braking, etc [4]-[7].

Discharging efficiency and rate are important indexes of flywheel energy storage system. The indexes are closely related to the load and the performance of machine. Therefore, it is of great value to study the effect of load on the discharge performance of flywheel system.

In this paper, a 200kW, 15000rpm high-speed permanent-magnet machine that used in flywheel energy storage system is investigated, the influence of the load on uncontrolled discharge and constant voltage discharge performance of system are analyzed through establishing a field-circuit coupling model.

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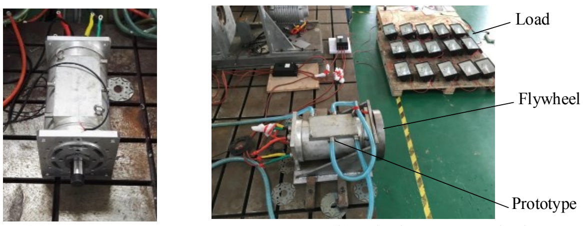
II. 2-D Finite Element Model of Electric Machine

The prototype and discharge test platform of 200 kW, 15000r/min permanent magnet motor which used in high-speed flywheel system are shown in Fig. 1. Some basic parameters are listed in Table I.

TABLE I
BASIC PARAMETERS OF THE PROTOTYPE

Rated power (kW)	200	Pole number	2
Rated voltage (V)	380	Stator outer diameter(mm)	238
Rated torque (N•m)	127.3	Stator inner diameter (mm)	156
Rated speed(rpm)	15000	Rotor outer diameter (mm)	144
Stator slots number	36	Core length (mm)	300



(a) Prototype (b) Discharge test platform

Fig. 1. Prototype and discharge test platform of electric machine.

Considering the high-speed permanent magnet machine is an elongated structure and the length of the winding end is short, therefore, in this paper, the 2-D cross section of the machine perpendicular to the axial direction is selected as the analysis model, as shown in Fig. 2.

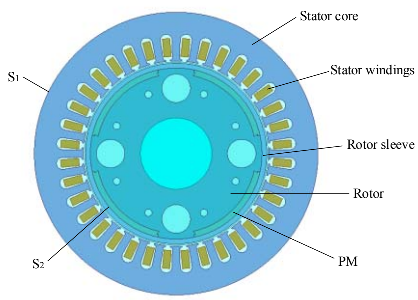


Fig. 2. Two-dimensional finite element model of electric machine.

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The following assumptions are made in this calculation[8]-[10]:

1) The effects of displacement current is ignored.

2) Considering that the diameter of the strands of the paralleled wire is very small, the eddy-current in the stator windings are ignored.

3) Hysteresis effect in permanent magnets is ignored.

4) The leakage fluxes outside machine core are ignored.

5) The variation of material permeability with the temperature is neglected.

The transient mathematical model for the 2-D electromagnetic field calculation is given in (1), where Ω is the calculation region, A_z and J_z are the magnetic vector potential and the source current density in the z-axial component, J_s is the equivalent face current density of PM, and σ is conductivity. S_1 is the parallel boundary condition, S_2 is the PM-region boundary condition, μ_1 and μ_2 are the relative permeability of the two different regions, and n is the normal direction of PM-region boundary.

$$\begin{cases} \Omega : \dfrac{\partial}{\partial x}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial x}\right)+\dfrac{\partial}{\partial y}\left(\dfrac{1}{\mu}\dfrac{\partial A_z}{\partial y}\right)=-\left(J_z-\sigma\dfrac{dA_z}{dt}\right) \\ S_1 : A_z = 0 \\ S_2 : \dfrac{1}{\mu_1}\dfrac{\partial A_z}{\partial n}-\dfrac{1}{\mu_2}\dfrac{\partial A_z}{\partial n}=J_s \end{cases} \quad (1)$$

III. INFLUENCE OF LOAD ON UNCONTROLLED DISCHARGE PERFORMANCE OF FLYWHEEL SYSTEM

When the machine is in the state of discharging, it is worked as a generator, voltage drop would be produced in the stator end windings resistance and end windings leakage reactance, so the field-circuit coupling analysis method is adopted in order to simplify the analytical modeling. The stator end windings resistance and end windings leakage reactance are considered by adding a resistance and an inductance in the power circuit.

A. The Voltage Equations of the Machine During The Discharge Process of Flywheel System

The machine works as a generator during the discharge process of flywheel energy storage system, ignoring the magnetic saturation, the voltage equation for the steady state operation of the machine is:

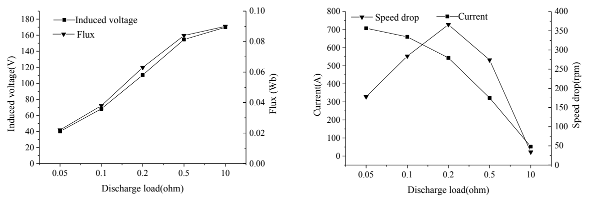
$$\begin{aligned} \dot{E}_0 &= \dot{U}_L + \dot{I}R_a + j\dot{I}_d X_d + j\dot{I}_q X_q \\ &= \dot{I}Z_L + \dot{I}R_a + j\dot{I}_d X_d + j\dot{I}_q X_q \end{aligned} \quad (2)$$

Where $\dot{E}_0$ is the induced electromotive force of the machine, $\dot{U}_L$ is the phase voltage of the load, $\dot{I}$ is the armature current of the machine, $\dot{I}_d$ and $\dot{I}_q$ is the direct-axis and quadrature-axis component of armature current, respectively. R_a is the phase resistance of the stator windings, X_d and X_q is the direct-axis synchronous reactance and the quadrature-axis synchronous reactance of the machine. Z_L is the load impedance, Z_L equals to R_L for the pure resistor load, and Z_L equals to R_L+jX_L for the resistor-inductance load, where R_L and X_L is the load resistance and reactance, respectively.

When the load of the machine is the pure resistor load and the resistor-inductance load, it can be seen that the armature reaction is a direct axis demagnetization reaction and the strength of demagnetizing reaction is directly related to the load by using the vector diagram. If the armature current is too large, the main magnetic field could be weakened by the strong demagnetization reaction, and the discharge efficiency of flywheel system would be affected at the same time. If the armature current is too small, the discharge time of flywheel system would be longer. Therefore, the choice of load has an important impact on the discharge process of the flywheel system.

B. Effect of the Pure Resistance Load on Discharge Performance of Flywheel Energy Storage System

The uncontrolled discharge process of flywheel system with different pure resistor load are calculated by using the field-circuit coupling model, where the initial speed of the machine is 9000rpm and the load is 0.05Ω, 0.1Ω, 0.2Ω, 0.5Ω and 10Ω, respectively. The flywheel energy storage system researched in this paper is a system with high-speed and high-capacity, which discharge time of the uncontrolled discharge is long. On the premise of the accuracy of calculation results, the discharge process from 0s to 0.2s are calculated. The simulation results are shown in Fig. 3.



(a) Relationship between induced voltage, flux and load

(b) Relationship between current, speed drop and load

Fig. 3. Relationship between discharge performance of the pure resistance load on induced voltage, winding flux, current and speed drop.

With the discharge process proceeding, the speed of machine will decrease from the initial speed to a certain value after 0.2s, where the initial speed of machine is 9000rpm. For the convenience of analysis, the difference between the initial speed and the speed at 0.2s is defined as the value of the speed drop, and the speed drop is greater, the discharge time is shorter.

Fig. 3 (a) shows that the single-phase winding flux and induced voltage of the machine increase with the increasing of the load resistance. When the load resistance is 0.05Ω, the induced electromotive force of machine is 40V. The impedance angle of machine's equivalent circuit is large and the total impedance of circuit is very small, which can be easily known from equation (2), the armature current is very large, and the direct-axis component of the armature current is greater than the quadrature-axis component of the armature current, so the demagnetization reaction is strong and the magnetic flux is seriously weakened, the single-phase winding flux of the machine is 0.022Wb. Most of the power in the circuit is reactive power, the active power on the load side is small, and the discharge efficiency is extremely low.

With the increase of the load resistance, the impedance angle of the circuit decreases, and the total impedance increases so that the armature current becomes smaller, the direct-axis demagnetization reaction is weakened and the single-phase winding flux and induced electromotive force are increased. The reactive power is reduced and the discharge efficiency is improved.

Fig. 3 (b) shows that the armature current decreases with increasing load resistance, but the discharge time is not linearly related to the load resistance. The speed drop is the most as the load is 0.2Ω, the discharge time of flywheel system is the shortest, when the load is greater than 0.2Ω, the discharge time increases with increasing of the load resistance.

The relationship between single-phase flux and discharge time is shown in Fig.4. With the discharge process proceeding, the demagnetization effect of machine is weakened, the single-phase flux increases gradually. The reason is that the induced voltage, the direct-axis synchronous reactance and the quadrature-axis synchronous reactance of the machine decreases with the slowdown of speed, which result in the decrease of the armature current and the demagnetizing current component.

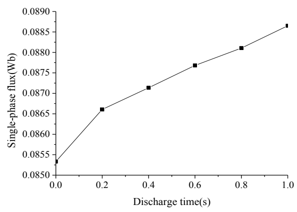


Fig. 4. Relationship between single-phase flux and discharge time.

The calculated waveform and measured waveform of load voltage when the uncontrolled discharge process of flywheel system with a pure resistor load are shown in Fig. 5 and Fig. 6, respectively, where the speed of machine is 9000rpm and the load resistance is 9.68Ω.

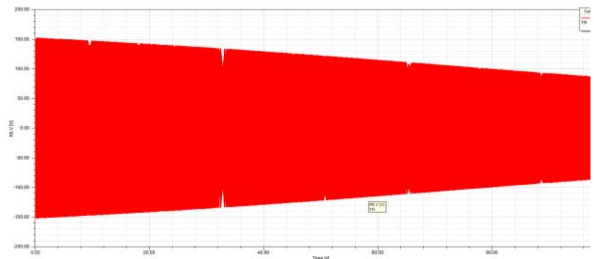


Fig. 5. Calculated waveform of load voltage

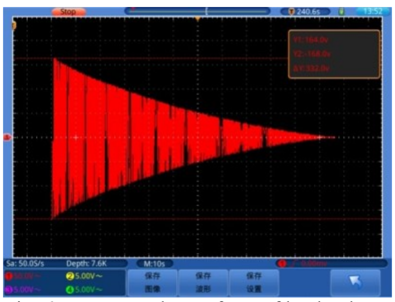


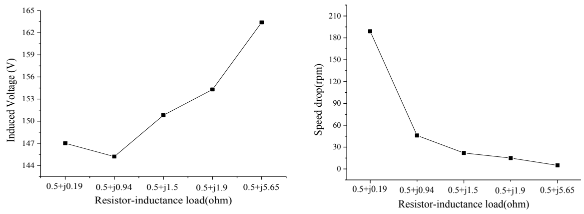
Fig. 6. Measured waveform of load voltage

Fig. 5 and Fig. 6 show that the calculated result is consistent with the measured waveform, and the load voltage decreases with the discharge process proceeding. The calculated value and measured value of the load voltage amplitude are 154V and 164V at the initial time of discharge, compared with the measured value, the error of the calculated result is within the engineering permissible range, the correctness of the analysis model is verified.

C. Effect of the Resistor-inductance Load on Discharge Performance of Flywheel Energy Storage System

When the uncontrolled discharge process of flywheel system with the resistor-inductance load, the principle of which is similar to the pure resistance load, changing of the load can change the impedance of circuit, and then the strength of demagnetization reaction is changed, thus affecting the induced electromotive force at initial time and the discharge time of flywheel energy storage system.

For the convenience of the study, the initial speed of the machine is set to be 9000rpm, and the resistor-inductance load is combined with a constant resistor and different reactance. The uncontrolled discharge process of flywheel system with different resistor-inductance load, 0.5+j0.19Ω, 0.5+j0.94Ω, 0.5+j1.5Ω, 0.5+j1.9Ω and 0.5+j5.65Ω, are calculated by using the field-circuit coupling model. As the same as the flywheel system with pure resistor load, the discharge process from 0s to 0.2s is calculated, the results are shown in Fig. 7.



(a) Relationship between induced voltage and load

(b) Relationship between speed drop and load

Fig. 7. Effect of the resistor-inductance load on induced voltage, and speed drop.

Fig. 7 shows that the discharge time is increased with the increasing of the load reactance, but change of the induced voltage at the initial time is nonlinear with the change of the load. When the load reactance is 0.94Ω, induced voltage of the machine at the initial time is the least, the armature demagnetization reaction is the strongest, and the efficiency of discharge is extremely low. When the load reactance is set to be more than 0.94Ω, with the increase of the load reactance, the armature demagnetization reaction is weakened, the induced voltage of the machine at the initial time and the efficiency of discharge are increased.

From the analysis above, when the resistance of resistor-inductance load is constant, the induced voltage of the machine at the initial time does not change linearly with the increase of the load reactance, and exists a minimum value, which are related to the impedance parameter of machine and the load.

IV. INFLUENCE OF DEMAGNETIZATION REACTION ON CONSTANT VOLTAGE DISCHARGE PERFORMANCE OF FLYWHEEL SYSTEM

From the analysis above, the voltage of load is decreased as the speed of the machine decreases in the uncontrolled discharge process of the flywheel system. So the actual application of flywheel energy storage system often takes constant voltage discharge as its discharge method, in which, the three-phase AC voltage of the machine is rectified by three-phase uncontrolled rectifier to DC, and then the DC is adjusted by the Boost circuit to ensure that the voltage of the load is a constant. The relationship between the output voltage U_0 and the input voltage E of the Boost circuit is:

$$U_0 = \frac{1}{1-\alpha} E \tag{4}$$

In the equation (4), α is the duty cycle of the Boost circuit. With the discharge process proceeding, E decreases as the speed of the machine decreases. In order to ensure that the load voltage U_0 is a constant, the duty cycle of the Boost circuit should be increased when E is decreased.

From the results of uncontrolled discharge analysis, the magnetic field in the machine can be affected by the change of load. Therefore, it is necessary to study the influence of the change of the magnetic field on the constant voltage discharge circuit during the discharge process. For the convenience of analysis, the initial speed of the machine is set to be 9000rpm, taking the pure resistance load as an example, the discharge process when the IGBT in the circuit turns on and turns off are calculated by using the field-circuit coupling model, which is shown in Fig. 8.

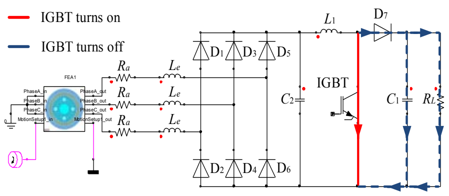


Fig. 8. Constant voltage discharge circuit of flywheel system.

In Fig. 8, the load R_L is 9.68Ω, and the inductance L_1 in the Boost circuit is 0.5mH.

When the IGBT is turned on, the inductor L_1 in the Boost circuit is charged by the machine, while the through the inductance L_1 is a pulse DC, the reactance of the inductance in the DC circuit is almost zero, the three-phase windings of the machine work in short state. The impedance of the circuit is consist of the winding resistance, the direct-axis reactance and quadrature-axis reactance of the machine, so the impedance angle of the discharge circuit is large, the direct-axis component of the armature current is a high value, demagnetization reaction is obvious, Most of the power generated by the machine is reactive power, only a small part of power for the L_1 charge, the discharge efficiency of the system is very low.

The induced voltage of the machine is 16V, the single-phase winding flux is 0.007Wb, which compared with 0.1Wb, the rated single-phase winding flux, is very low. It can be seen that demagnetization reaction is obvious, so the induced voltage of machine is very small and the discharge efficiency is very low.

When the IGBT is turned off, the machine and inductance $L1$ supply power to the load R_L and the capacitor C_1 together, the machine discharges with a pure resistive load, the induced voltage of the machine is 167V, the single-phase winding flux is 0.094Wb. Compared with the IGBT turns on, the induced voltage and the single-phase winding flux are increased obviously, this is because the large load resistance, the armature current of machine and its direct-axis component are very small, demagnetization reaction is weak, so the discharge efficiency of system is higher.

From the analysis above, if the turn-on time of the IGBT is too long, the three-phase windings of the machine would work in a short state, while the machine energy is the braking energy, so the discharge efficiency is very low. Therefore, in the practical application, in order to improve the discharge efficiency of the system during constant voltage discharge process, the duration of the armature current can be reduced by increasing the switching frequency of the IGBT, thus, the influence of the demagnetization reaction on the magnetic field in the machine can be reduced, which can ensure the value of the output active power.

V. CONCLUSION

In this paper, a 200kW, 15000rpm high-speed permanent-magnet machine that used in flywheel energy storage system is investigated in this paper, and its discharge performance is analyzed through establishing a field-circuit coupling model. The influence of load on discharge performance of high-speed flywheel energy storage system are studied, some conclusions are achieved as following:

1) In the uncontrolled discharge process of flywheel system with different pure resistor load, the single-phase winding flux and induced voltage of the machine increase with the increasing of the load resistance. The discharge time does not change linearly with the increase of the load resistance, and exists a minimum value, then the discharge time increases with increasing of the load resistance.

2) In the uncontrolled discharge process of flywheel system with the resistor-inductance load, when the resistance of resistor-inductance load is constant, the discharge time is increased with the increasing of the load reactance, but the induced voltage of the machine at the initial time does not change linearly with the increasing of the load reactance, and exists a minimum value.

3) In the constant voltage discharge process of flywheel system, in order to reduce the influence of the demagnetization reaction on the magnetic field in the machine, a method that the discharge efficiency of the system could be improved by increasing the switching frequency of the IGBT is presented.

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