Self-Excitation and Energy Recovery of Air-Core Compulsators

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***Abstract*— As power supplies, compulsators are popular choices for high-end railgun power supplies. In order to increase power and energy density, air-core compulsators are proposed by using composite materials instead of traditional iron-core compulsators. Due to the absence of ferromagnetic material, the flux density in the air-core compulsator can reach to 4–6 T instantaneously, which is much higher than the saturation field strength in traditional iron-core machines. Therefore, self-excitation topology is essential for the air-core compulsator to obtain up to 100-kA field current. This paper carried out research on the key parameters of self-excitation efficiency first, and then focus on the large magnetic energy remained in the inductive field winding after one shot, an implementation scheme and control strategy of energy recovery of air-core compulsator was proposed and analyzed. By controlling the field rectifier working at active inverter state after one discharge process, the magnetic energy stored in the field winding can be converted to rotor kinetic energy again. The simulation results indicate that the energy recovery efficiency can reach to 70% for a reference air-core compulsator. The continuous discharge number of times increased from 3 to 4 during one kinetic energy charging, which means that the delivered energy density increases 33.3%.**

***Index Terms*— Compulsators, electromagneticlaunch, energy recovery, railguns, self-excitation.**

I. INTRODUCTION

COMPENSATED pulsed alternators (compulsators) can quickly convert rotational kinetic energy to high current electrical energy with very high energy density and flexible output pulse shape, which have been considered as popular choices for various high-power applications, such as electromagnetic railguns, electrothermal chemical guns, and electromagnetic coilguns [1].

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After nearly 40 years continuous research, several key technologies have been adopted into compulsators, such as the air-core machine, self-excitation, multiphase configuration, rotating field, hollow rotor structure, no compensation (d-axis compensation), instead of the original design of iron core, separate excitation, single-phase, rotating armature, solid rotor, and passive compensation. Both the theoretical research and engineering technology have been developed markedly. For theoretical research, the design methodologies of compulsators have been investigated, e.g., main dimension estimate [2], transient inductance calculation [3], magnetic field calculation [4], and analytical simulation modeling [5]. For engineering technology, focus on the issues from experiments, some researchers obtained some beneficial results from the high-voltage insulation, electric brush and slip ring, high-speed bearings, and high-power switches [6].

By applying fiber composites instead of the ferromagnetic material, which is mentioned as air-core instead of the traditional iron-core, the power density and energy density have been improved greatly, since both of the rotor linear speed and the air-gap flux density have opportunities to increase a lot (e.g., linear speed increased from 200 to 400–600 m/s, and airgap flux increased from 1 to 4–6 T) [7], [8]. However, due to the absence of ferromagnetic material in the flux path, the required magnetic voltage in air-core compulsators are much greater as compared with the iron-core designs, thus a self-excitation method is generally used to generate enough field ampere-turns. For the self-excitation topology, the armature winding itself is used to provide excitation power to the field coil by a positive feedback [9]. In order to obtain more continuous discharge times during once kinetic energy charging, as well as alleviate the heat issue of the field windings [10], air-core compulsator must have a high efficiency in self-excitation process.

Due to the large field current in the inductive field winding, there exists quite amount of magnetic energy after one discharge process, which is nearly the same or more than the energy delivered to the railgun. In most cases, these energies are not used and only dissipated by a resistor in the form of heat [11]. A novel pulse excitation by using capacitors is proposed to reclaim the magnetic energy into capacitor storage energy to achieve continuous discharge [12], and some beneficial conclusions were presented, but the field power is limited by the pulsed capacitor.

By controlling the field rectifier working at active inverter state, an energy recovery strategy of air-core compulsator was

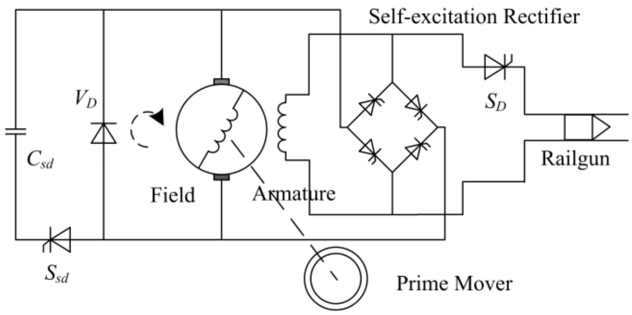

Fig. 1. Circuit diagram of a single phase air-core compulsator.

proposed in this paper. The magnetic energy stored in the field winding can be converted to rotor kinetic energy again after one discharge process, leading a higher delivered energy density (DED) of the electromagnetic launch system.

II. Self-Excitation

A. Operation Process of Air-Core Compulsators

Kinetic energy storage, self-excitation, discharge, and magnetic energy dissipation are the basic operation process of air-core compulsators. A single-phase rotational field direct-axis compensated air-core compulsator is used to illustrate this process for clarity, as shown in Fig. 1.

The prime motor system brings up the compulsator to the rated speed first, and then, an initial current (seed current) is injected into the field winding to start the self-excitation process by using an initiation capacitor C_{sd}. If the parameters in the circuit (including the self-excitation rectifier, field windings, and armature windings) meet the successful self-excitation condition [13], a positive self-excitation process will be achieved, and then, the field current increases exponentially. The rotor kinetic energy is converted to magnetic energy inside the field windings.

Once the field current reaches its rated value, the field rectifier will be stopped and the field current freewheels via the diode V_D. According to the fire angle, the armature winding output current into the railgun via the discharge rectifier S_D. Due to the magnetic coupling, the field windings induce current and provide a direct-axis compensation to reduce the effective inductance of the armature windings. After the discharge process, the field current in the freewheeling diode will be switched to a resistor in most cases, and the magnetic energy dissipated in the form of heat.

B. Self-Excitation Efficiency

During the self-excitation process, the kinetic energy is converted into the magnetic energy and Joule heat energy. Similar as the inductor charging efficiency, the self-excitation efficiency can be defined as follows [14]:

$$\eta_f = \frac{\frac{1}{2}L_f I_{\mathrm{fp}}^2}{\int_0^{t_{\mathrm{fp}}} i_f^2 R_f dt + \frac{1}{2}L_f I_{\mathrm{fp}}^2} \tag{1}$$

where L_f and R_f are the inductance and resistance of the field windings; i_f is the field current; I_{fp} is the final field current; t_{fp} is the duration to accomplish the self-excitation process.

TABLE I
General Specifications of the 2P2AC Compulsator

Description	Value
Energy Storage E_r	15 MJ
Rotor Speed n	10 000 rpm
Number of Phases	2
Number of Poles	4
Rotor Diameter D_r	0.6 m
Rotor Length L_r	0.95 m
Peak Current	800 kA
Field Current	45 kA

It can be seen that the magnetic energy is only determined by the final field current, while the Joule heat energy is determined by the self-excitation duration. Therefore, a fast self-excitation process is beneficial to increase the self-excitation efficiency.

The circuit equation in the field winding is shown as

$$L_f \frac{di_f}{dt} + R_f i_f = U_{\mathrm{df}} \tag{2}$$

where U_{df} is the rectified voltage of field winding, and can be rewritten as

$$U_{\mathrm{df}} = C_r U_a = C_r C_e n i_f \tag{3}$$

where U_a is the amplitude of the phase voltage of the armature winding; n is the rotor speed; C_r is the rectifier coefficient; and C_e is the electromotive force coefficient, which is a constant number due to no saturation characteristic in the air-core machine.

The solution of (1) is

$$i_f = I_{f0} e^{\alpha \cdot t} = I_{f0} e^{\frac{C_r C_e n - R_f}{L_f} \cdot t} \tag{4}$$

where I_{f0} is the initial current of field winding, determined by the initial circuit; α is the charging coefficient, and $\alpha > 0$ is the condition to achieve a positive self-excitation process.

The self-excitation time can be solved as

$$t_{\mathrm{fp}} = \frac{\ln\left(I_{\mathrm{fp}}/I_{f0}\right)}{\alpha}. \tag{5}$$

Substituing (4) and (5) into (1), self-excitation efficiency can be given by

$$\eta_f = \frac{\frac{1}{2}L_f I_{\mathrm{fp}}^2}{\frac{I_{\mathrm{fp}}^2 - I_{f0}^2}{2\alpha} R_f + \frac{1}{2}L_f I_{\mathrm{fp}}^2}. \tag{6}$$

Based on the design parameters of a two-phase two-axis-compensated compulsator (2P2AC compulsator, general specifications are shown in Table I) [15], and the co-simulation model between compulsators and railgun loads [16], key parameters of self-excitation efficiency will be described below.

C. Discussions of Initial Current

According to (5) and (6) the initial current I_{f0} has effects on both the self-excitation duration t_{fp} and the efficiency η_f. For the 2P2AC compulsator operating at 10 000 rpm, the comparison results of the self-excitation performance between $I_{f0} = 1$ kA and $I_{f0} = 6$ kA are plotted on Fig. 2.

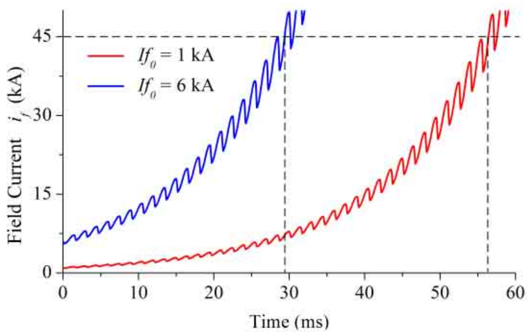

Fig. 2. Effects of initial current I_{f0} on self-excitation performance.

It can be seen that the self-excitations finished at 56.43 and 29.4 ms, respectively. The Joule heat energy can be calculated as 187.1 and 186.5 kJ according to the resistance of the field winding. The results indicated that I_{f0} has large effects on the self-excitation duration, but negligible effects on the heat energy loss and the efficiency, when the final field current I_{fp} is one order of magnitude higher than I_{f0}. Even so, a faster self-excitation process is expected to decrease the switching number of times of the field rectifier, thus increase the reliability of the system.

I_{f0} is determined by the initiation circuit, including the initiation capacitor, the resistance and inductance of the field winding. The initiation circuit is a second-order RLC serial circuit with zero input response, given by

$$R_f C_{\text{sd}} \frac{du_{\text{sd}}}{dt} + L_f C_{\text{sd}} \frac{d^2 u_{\text{sd}}}{dt^2} + u_{\text{sd}} = 0 \tag{7}$$

where C_{sd} is the capacity; u_{sd} is the voltage of the capacitor.

The initiation circuit is an oscillating circuit duo to the small resistance of field windings, then I_{f0} can be given as

$$I_{f0} = U_{\text{sd0}} \sqrt{\frac{C_{\text{sd}}}{L_f}} = \sqrt{\frac{2E_{\text{sd}}}{L_f}}. \tag{8}$$

Where U_{sd0} is the initial voltage of the initiation capacitor; E_{sd} is the initial stored energy.

For the 2P2AC compulsator, a pulsed capacitor of 12.5 kJ is used as the initiation capacitor, with capacity of 1 mF and initial voltage of 5 kV. It can provide about 7-kA initial current for the self-excitation process.

If the final field current I_{fp} is much higher than the initial current I_{f0}, (6) can be simplified as

$$\eta_f = 1 - \frac{R_f}{C_e C_r n}. \tag{9}$$

It can be seen that the self-excitation efficiency is determined by two aspects: the design parameters, including the resistance of field winding R_f and the electromotive force coefficient C_e; and operation parameters, including the rectifier coefficient C_r and the rotor speed n.

D. Discussions of Design Parameters

The best way to increase the self-excitation efficiency is to reduce the resistance of field winding R_f. Therefore, the cross-sectional area of the field coil of air-core compulsators is determined by the self-excitation performance in most cases, unlike the traditional consideration from thermal point of view. Because of limited space within the machine, R_f cannot be reduced excessively and still maintain the magnitude from 10–10^2 mΩ. The sectional area of the field winding is 10 mm × 20 mm, for instance, 48 turns with series connections under four poles have a resistance of 13 mΩ for an aluminum field winding.

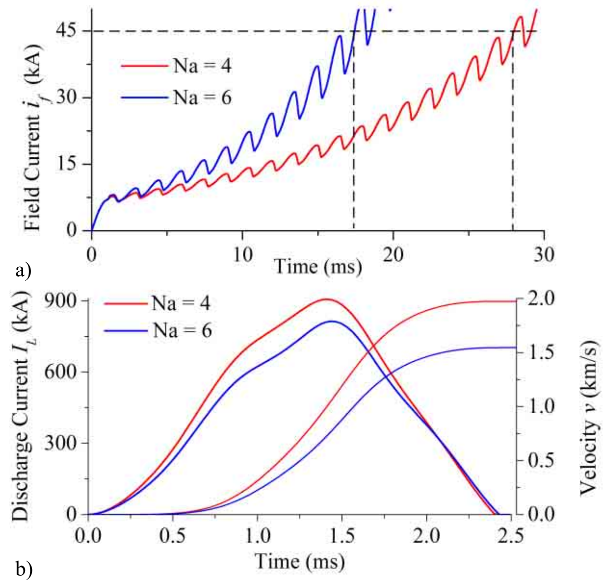

Fig. 3. Effects of N_a on the 2P2AC compulsator performance. (a) Field current during self-excitation process. (b) Output performance.

The electromotive force C_e is determined by the mutual inductance between armature windings and field windings M_{af}. For an air-core machine, M_{af} is given as [17]

$$M_{\text{af}} = \frac{2\mu_0}{\pi} \frac{(N_a k_{\text{wa}})(N_f k_{\text{wf}})}{p} \left(\frac{r_f}{r_a}\right)^p \cos(p\sigma) \tag{10}$$

where N_a and N_f are the total serial number of turns of armature windings and field windings; k_{wa} and k_{wf} are the fundamental winding factors; r_a and r_f are the radius of the position of each winding; p is the number of pole pairs; σ is the mechanical angle between the axis of both windings.

It shows that M_{af} (namely C_e) is direct proportional to the number of turns of armature windings N_a, field windings N_f, and to the ratio of r_f by r_a whole to the power of p. Since the spaces between armature and field windings are airgap and composited materials, the ratio of r_f by r_a cannot be increased a lot from the mechanical point of view. Besides, increasing N_f will also increase the R_f. Therefore, the increase of self-excitation efficiency is achieved by increasing N_a in most of cases.

However, since the internal impedance of the machine is direct proportional to the square of N_a, the output performance will be affected by increasing N_a [18]. As shown in Fig. 3, when the series number of turns per pole is increased from 4 to 6, the self-excitation efficiency increased 8.33% for the 2P2AC compulsator, whereas the muzzle energy reduced 38.74%. Therefore, the number of turns of armature

TABLE II
SELF-EXCITATION TOPOLOGY AND RECTIFICATION FACTOR C_r

Topology	Single phase full bridge	Two phases full bridge	Four phases half bridge	Four phases full bridge
C_r	0.64	0.9	0.9	1.8
Switch count	4	8	4	8

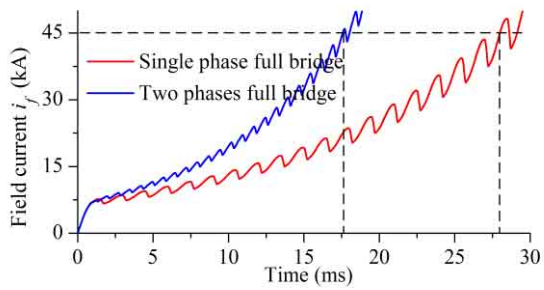

Fig. 4. Effects of rectification circuit on self-excitation performance.

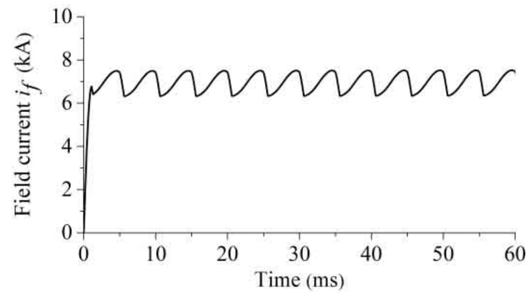

Fig. 5. Self-excitation simulation at rotor speed of 3000 rpm.

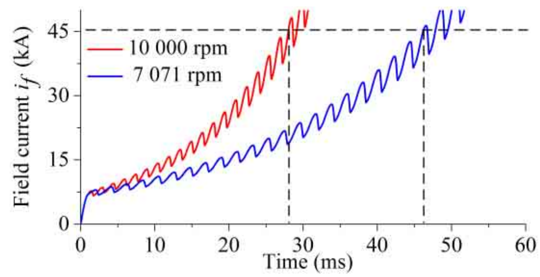

Fig. 6. Effects of rotor speed on self-excitation performance.

winding should be selected after a comprehensive consideration between discharge performance and self-excitation performance. When a good trade-off cannot be achieved in some cases, another specialized secondary armature winding is introduced to execute the self-excitation mission [19], [20], but also increasing the complexity level of the system.

E. Discussions of Operation Parameters

The rectifier coefficient C_r is determined by the number of phase of the compulsator and the adopted topology of rectifier circuit. To achieve the maximum average current, the trigger angle of the self-excitation rectifier should be 0°, and common used topologies and their coefficient are summarized in Table II. Since the switches of self-excitation rectifier are 10–10^2 kA level generally, and need to switch ON and OFF frequently during the 10–20 electrical periods of the machine, the effects of switch mass and heat on the energy density and efficiency of the whole system need to be considered during the design period. The self-excitation efficiency should be sacrificed a little, if necessary, to reduce the number of switches.

Under the same condition of 10 000 rpm and initial current, the simulation result of self-excitation process for the topology of single and two phases full bridge is plotted on Fig. 4. The two-phase topology spent 17.58 ms to accomplish the self-excitation process with 111.52-kJ Joule heat loss, while the single phase one used 27.99 ms with 176.8-kJ loss. The results show that the two-phase topology can reach the rated current faster than single phase one, thus consume less kinetic energy, which are consistent with the theoretical analysis. Considering the $L_f = 486\ \mu$H, $I_{\rm fp} = 45$ kA, the magnetic energy in the field winding is 490 kJ, then the self-excitation efficiency of two phases and single phase can be calculated as 81.46% and 73.49%, respectively.

During the continuous discharge period, the rotor speed decreases with the decrease of stored kinetic energy. From (9), the self-excitation efficiency will be affected a lot by speed decrease. When the rotor speed is lower than R_f/C_rC_e, the positive self-excitation cannot be maintained.

For the reference 2P2AC compulsator operating at 10 000 rpm, the field current i_f is 45 kA, and the amplitude of open circuit back EMF U_a is 3.5 kV, then a theoretical minimum speed of $n_{\min} = 2620$ rpm can be calculated. Considering the resistance of cables and switches in the self-excitation circuit, the practical minimum speed should be a little higher than the calculated value. The simulation of self-excitation process is carried out at 3000 rpm, and the result is shown in Fig. 5. It can be seen that the simulation result is coincident with the theoretical analysis. The self-excitation circuit enters into a balanced state, rather than a positive feedback state.

When the stored kinetic energy reduced to 50% of the initial stored energy, namely, the rotor speed decreased to 7071 rpm, the self-excitation process is shown in Fig. 6. It takes 46.2 ms to reach the rated field current, with RMS current of 21.89-kA and 287.79-kJ Joule heat energy loss. The self-excitation efficiency reduced to 63%, which is 10% decrease compared with rated speed of 10 000 rpm. The comparison results show that although the self-excitation can be achieved at this speed, the Joule energy loss have already been over 200 kJ, which is nearly the same amount of the output muzzle energy. If the speed continues to be decreased, the system efficiency will be reduced severely, and bring out the thermal problem to the field winding. Therefore, when design a continuous discharge compulsator, the kinetic energy loss ratio which is defined as the stored energy after the last shot by the initial stored energy need to be considered seriously. In 2P2AC compulsator design, the kinetic energy loss ratio is 0.5. According to the simulation results, this ratio design is reasonable.

III. ENERGY RECOVERY

Due to the large field current in the inductive field winding, there exists quite amount of magnetic energy after one

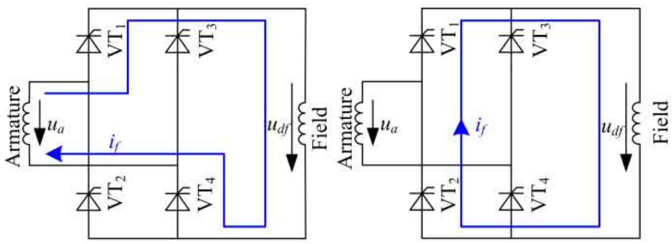

Fig. 7. Freewheeling of the field winding during discharge. (a) Rectification process. (b) Freewheel process.

discharge process, which is nearly the same or more than the energy delivered to the railgun. Currently, these energies are not used and only dissipated by a resistor in the form of heat, leading a lower N_s (continuous discharge times during once kinetic energy charging of the rotor), thus lower DED, defined as

$$DED = N_s E_m / M_{\text{system}} \tag{11}$$

where E_m is the muzzle energy and M_{system} is the system mass.

Since the field current is always positive, if we found a way to make the field winding voltage negative, the transient power of compulsators can be negative, then the magnetic energy in the field winding will be recovered automatically, and make the rotor speed increase. By using this theory, the trigger angle of self-excitation rectifier can be controlled to work at active inverter state after one discharge process, making the dc voltage of field winding negative, so as to obtain a negative power and recover the magnetic energy inside the field winding.

To achieve an active inverter state, the short-circuit upper and lower switches will take the place of the freewheeling diode V_D, as shown in Fig. 7. Assume that u_a is positive and VT_1 and VT_4 are ON at t_0, when u_a cross zero and becomes negative, VT_1 and VT_4 are still ON due to the inductance. Then, trigger VT_2 and do not trigger VT_3, VT_2 turns ON immediately due to the positive voltage, while VT_3 is still OFF. After VT_2 is ON, u_a forces negative voltage ON VT_4 and make VT_4 OFF. Finally, the field winding current i_f transferred to the short-circuit VT_1 and VT_2 freewheeling.

After discharge, using the first positive period of u_a as $\omega t = 0$, trigger VT_4 at $\omega t = \alpha_i$ ($0 \leq \alpha_i \leq \pi$), then VT_4 turns ON, and forces VT_2 OFF by providing negative voltage. The current in VT_1 and VT_2 switches to VT_1 and VT_4, and the self-excitation rectifier goes into the rectification state again (or inverter state). The average voltage of field winding can be given as

$$U_{\text{df}} = C_r U_a = 0.64 U_a \cos \alpha_i. \tag{12}$$

When $0 < \alpha_i \leq \pi/2$, the self-excitation circuit is still in rectifier state, and can make the field winding recharge again. Then the continuous discharge in millisecond can be achieved.

When $\pi/2 < \alpha_i \leq \alpha_{\max}$, the self-excitation circuit goes into an active inverter state, where $\alpha_{\max} = \pi - \beta_{\min}$, $\beta_{\min}$ is the minimum inverter angle, determined by the turn-OFF time of switches, overlap angle of commutation, and safety allowance angle. The recovery circuit still follows (4), but the rectifier coefficient C_r turns negative, so the field current decreases exponentially. To recover the field energy quickly, α_i should be close to $\alpha_{\max}$. Using the co-simulation model under the condition of $\alpha_i = 150°$, the simulation results of self-excitation, discharge, and energy recovery are shown in Fig. 8.

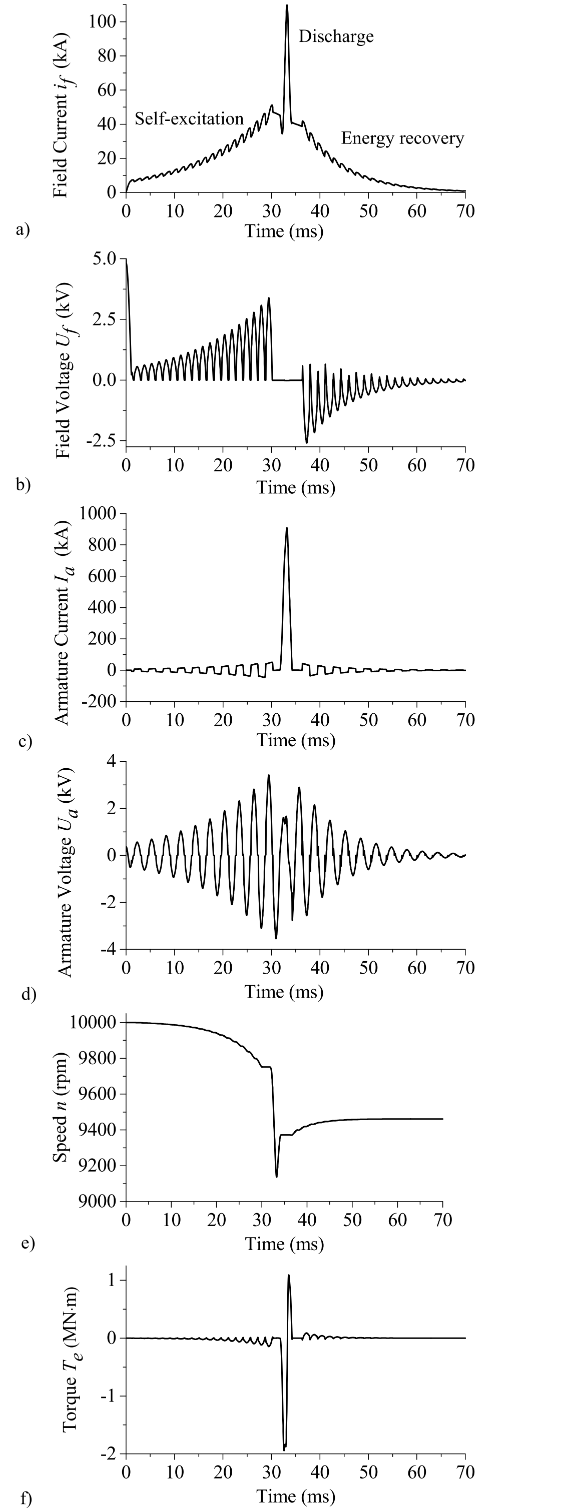

Fig. 8. Simulation results of one shot. (a) Current of field windings. (b) Voltage of field windings. (c) Current of armature windings. (d) Voltage of armature windings. (e) Machine speed. (f) Electromagnetic torque.

TABLE III
ENERGY TRANSFORMATION OF COMPULSATOR DRIVEN RAILGUN

	Self-excitation	**Discharge**	**Energy recovery**
n (rpm)	9751	9372	9462
ΔE_r (kJ)	737	1086	-254
E_{mag} (kJ)	537	228	-364
E_j (kJ)	200	858	110

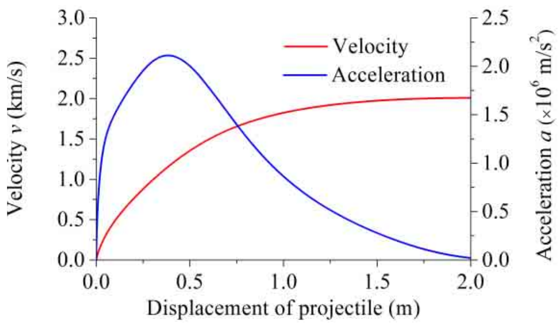

Fig. 9. Velocity and acceleration of projectile in the railgun.

The simulation results indicate that during the energy recovery process, the voltage of field winding is always negative by the rectifier under active inverter state. A positive torque with the same direction of rotation of the compulsator is generated, making the speed of compulsator increase, and the field current decreases, thus achieve the magnetic energy being recovered into rotor kinetic energy.

From the duration time and the current, voltage, torque and speed curves comparison before and after one shot, we can see that the self-excitation and energy recovery are approximate symmetrical process. Due to the resistances and their heat losses of the circuit, the magnetic energy cannot be recovered completely.

Before starting one shot, the prime motor brings up the 2P2AC compulsator to 10 000 rpm, and stores 15-MJ kinetic energy to the rotor. The compulsator goes through self-excitation, discharge, and energy recovery process in sequence, and accomplishes a whole driving railgun mission. The energy transformations in each stage are summarized in Table III, where n is the surplus speed, ΔE_r is the kinetic energy loss, E_{mag} is the magnetic energy, and E_j is the heat energy loss. The magnetic energy in the discharge process represents the railgun output energy of 228 kJ, driving a 100-g projectile with muzzle velocity of 2134 m/s on a 2-m railgun, as shown in Fig. 9.

By using the energy recovery, the rotor speed increase from 9372 to 9462 rpm, and 254 kJ-kinetic energy is recovered from 363-kJ magnetic energy of the field winding, with 70% of recovery efficiency.

Using the ratio of the muzzle energy by the kinetic energy loss as the delivered energy efficiency η_r, then η_r of 12.5% (228 / (737 + 1086)) can be increased to 15% (228 / (737 + 1086 − 254)) by introducing the energy recovery strategy. For the 2P2AC compulsator with the kinetic energy loss ratio of 0.5 (50%), the continuous discharge times N_s is 4 with energy recovery, comparing N_s is 3 without energy recovery, which means the DED increases 33.3%.

IV. CONCLUSION

This paper deduced the self-excitation efficiency of an air-core compulsator. The design parameters and operation parameters including the initial current, number of turns, rectifier circuit, and machine speed are simulated and analyzed. The requirements and constraints of machine design are proposed from the self-excitation point of view. By optimizing the topology and control strategy of the current self-excitation topology, the self-excitation rectifier can both provide the freewheeling circuit to the field winding during the discharge process, and operate at active inverter state after discharge. The magnetic energy stored in the field winding can convert to rotor kinetic energy again. The simulation results indicate that the energy recovery efficiency can reach to 70% for a reference air-core compulsator. The continuous discharge number of times increased from 3 to 4 during one kinetic energy charging, which means that the DED increases 33.3%.

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