Design and Simulation of a Two-Phase Air-Core Compulsator

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Abstract. A two-phase four-pole air-core compulsator is designed and its basic electromagnetic characteristics are analyzed. The absence of specific compensation components simplifies the compulsator structure design and increases the reliability and pulse current versatility. A new self-excitation circuit structure is proposed for two-phase compulsator, which can improve the excitation efficiency and reduce the excitation loss. The experimental results show that the 5g projectile can be accelerated to approximately 2km/s. simultaneously, the effect of series inductance in waveform regulation is verified.

Introduction

In 1978, the concept of Compensated Pulsed Alternator (Compulsator & CPA) was proposed by University of Texas [1]. Compulsator is a kind of special synchronous generator in nature, which can reduce the armature inductance greatly and realize high power output by special magnetic compensation structure [2]. Adopting flywheel inertial energy storage form, compulsators can achieve extremely high energy density and power density, which makes it the most promising technology to provide pulse power for the electromagnetic rail gun, electric chemical gun, high-energy laser weapons and other new concept weapon [3]. High-performance compulsator is usually air-core structure. The absence of ferromagnetic materials can eliminate the limits of magnetic field intensity and rotor speed, and significantly improve the energy density and power density.

Based on current development trend of advanced compulsator technology, a small air-core compulsator is designed. It’s an external stator, inner rotor, rotating field, two-phase four-pole generator without any compensation structure.

Design Scheme of Air-Core Compulsator

The use of rotating field structure can reduce the requirements of the brush and slip ring requirements, thus improve system stability [5]. Adopt slot-less patch winding to reduce the coil inductance.

In theory, fewer poles number results in wider discharge pulse. However, when two-pole generator discharge, the lateral force on the winding and rotor is not symmetrical, which is easy to cause the rotor vibration, so the design of four-pole compulsator is adopted. Orthogonal two-phase structure can minimizes the flux coupling between the two smallest, to eliminate the phase to phase inductance. In addition, multi-phase structure overcomes the contradiction between discharge pulse width and rotor speed, and is conducive to the regulation of discharge waveform [6].

“Uncompulsator” refers to compulsator without specific compensation structure (compensation tube, compensation coil, etc.), whose actual compensation function is completed by the short circuit field winding [7]. Reference [8] points out that no compensation structure is more suitable for air-core compulsator based on detailed analysis.

The rotor is made of high-strength composite material and comprises five layers: an inner support layer composed of glass fiber resin matrix composite material, three field winding layers and an outer
reinforcement layer composed of carbon fiber resin matrix composite material. The field-winding wire gauge is QZYSBEFB/3.8mm×6mm (JB-652-68) flat aluminum wire (F class insulation), with 39 turns on each pole. The armature winding wire gauge is QZYSBEFB/1mm×6.5mm(JB-652-68) flat copper wire(F-class insulation), using 10 wires abreast, 4 turns each pole. The basic parameters of the compulsator are shown in Table 1, and the sectional view is shown in Fig. 1. Air gap thickness is 1mm.

Table 1. The main parameters of the compulsator.

| Overall Performance | Energy storage | 389.2[kJ] (20000[rpm]) |
|---------------------|----------------|------------------------|
|                     | Rated speed   | 20000[rpm]             |
|                     | Peak power    | 238[MVA]               |
|                     | Peak voltage  | 2.2[kV](phase A); 2.6[kV](phase B) |
|                     | Peak current  | >100[kA]               |
|                     | Pulse width   | >2[ms]                 |
| Bearing             | Types         | 2 radial hybrid active control magnetic bearings, 1 axial thrust bearing. |
|                     | maximum radial bearing capacity | 2400[N](5g) |
|                     | Maximum axial bearing capacity | 1200[N](3g) |
| Size and Mass       | Stator outer diameter | 285[mm] |
|                     | Rotor outer diameter | 204[mm] |
|                     | Rotor Axial length | 625[mm] |
|                     | Rotor Mass    | 40[kg]                 |
|                     | Stator and base mass | 90[kg] |
|                     | Electronic circuits, switching devices and a pulse capacitor | 30[kg] |
|                     | Moment of inertia | 0.177[kgm²] |
|                     | Total mass    | ≤160[kg]               |
|                     | Overall dimensions | <300[mm]×300[mm]×750[mm] |

Figure 1. The sectional view of the compulsator.

Electromagnetic Characteristics Simulation

The electromagnetic field distribution of the compulsator directly affects its no-load as well as with-load characteristics. In general, the electromagnetic field of the air-core compulsator can be
solved analytically by appropriate simplification, such as the equivalent rectangular method [9], the vector magnetic potential distribution method [10] and so forth. Analytical method is complex to solve, but can be used for the electromagnetic design and structure selection. The finite element method is the most accurate method to analyze the electromagnetic field characteristics, but its disadvantage is the large amount of calculation. This work will use the finite element software Ansys Maxwell to conduct a comprehensive electromagnetic simulation analysis.

**Steady State Characteristics**

Consider an ideal steady state in which the field current remains constant at 7.5kA and the rotor speed is maintained at 20,000rpm to analyze the basic performance of the compulsator. Magnetic field distribution and other simulation results are shown in Fig. 2~4. Once the excitation current reaches 7.5kA, the magnetic flux density of air gap can reach about 2.5T, and the open-circuit voltages of phase A and B are 2.22kV and 2.6kV respectively. Winding self-inductance and mutual inductance calculated results are shown in Table 2. It is thus clear that the armature winding inductance is very small, and there is no electromagnetic coupling between the two phases. Furthermore, the mutual inductances between the armature windings and excitation winding change in a sinusoidal manner following the relative position.

![Magnetic field distribution](image1)

Figure 2. Magnetic field distribution.

![Magnetic flux density of air gap](image2)

Figure 3. Magnetic flux density of air gap.

![Open-circuit voltage](image3)

Figure 4. Open-circuit voltage.
Table 2. Inductance calculated by Maxwell.

|                | Field Winding | Winding A     | Winding B     |
|----------------|---------------|---------------|---------------|
| Field Winding  | 987[μH]       | 70sin(θ)[μH] | 84sin(θ)[μH] |
| Winding A      | 70sin(θ)[μH] | 16[μH]        | 0             |
| Winding B      | 84sin(θ)[μH] | 0             | 17[μH]        |

**Self-Excitation System**

Because there is no ferromagnetic material, air-core compulsators need much stronger magnetic field than iron-core compulsators. The use of high-power external excitation circuit will make the air-core compulsator’s high energy density and power density advantage gone, therefore a self-excitation mode is adopted [11], whose basic principle is as follows: firstly, charge the field winding with a small external capacitor to obtain a seed current, subsequently the armature windings obtain the induced electromotive force. Then make armature windings to charge the field winding after rectification, which can increase the excitation current and enhance the magnetic field. This results in a positive feedback process where the excitation current increases exponentially as long as certain conditions are met [12]. When the excitation current reaches requirement, the main switch is turned on to discharge the load.

Although the excitation time is very short (millisecond), but the excitation loss and field winding temperature rise cannot be ignored [13], therefore excitation circuit topology optimization is necessary. For two-phase compulsators, the two phases are usually rectified to the excitation winding separately [14]. This paper designed a special self-excitation circuit structure, in which the two-phase armature windings are connected through switch circuit. This circuit can ensure the field winding always get the highest voltage, thus shorten the excitation time and reduce the excitation loss. Two excitation schemes are shown in Fig. 5, 6.

![Figure 5. Self-excitation scheme 1.](image1)

![Figure 6. Self-excitation scheme 2.](image2)

Use a 4000V/250μF capacitor as the charging capacitor, whose charging time is set to 2ms. The rotor initial speed is 20000rpm, and its kinetic characteristic is considered. The excitation current and loss are compared under two self-excitation schemes, as shown in Fig. 7~9. To reaches 7.5kA excitation current, the two schemes needs 10.79ms and 8.25ms respectively, and the energy loss is... KJ. Respectively. The excitation scheme designed in this paper can reduce the armature zero current time, improve the excitation efficiency and reduce the excitation loss.
Self-Excitation System

Different kinds of load have various requirements for discharge pulse shape. For instance, electromagnetic rail guns need flat-top pulse [15] while flashing lamps require a sharply peaked pulse [16]. In the beginning of compulsator design, designers usually choose different compensation forms according to the demand of pulse waveform: passive compensation generates sine wave, passive compensation produces flat-top wave, and active compensation generates spike pulse [17]. In other words, once the structure is determined, only the external circuit and control method can be used for pulse shaping.

Air-core compulsator’s single-phase pulse is sine wave, which is difficult to get flat-top pulse [18]. The pulse shaping methods include combining multi-phase pulse, controlling ignition angle mode modulation wave and so on [19]. In this paper, an additional inductance is connected in series with the load circuit, which can reduce the peak pulse waveform, increase the pulse width and improve the projectile exit speed.

Consider the simplest electromagnetic gun model, ignoring the friction, air resistance and ablation resistance. Set the mass of projectile as 5g, the gradient of the inductance of the electromagnetic gun as 1μH/m, and the resistance gradient as 0.5mΩ/m. Then, during the CPA driving projectile, the electromagnetic thrust is:

\[
F = \frac{1}{2}LI^2. \tag{1}
\]

Using excitation scheme 2, the excitation current reach 9kA at time 9.1ms. Meanwhile, the rotor speed declines to 18393rpm. Then turn on the main switch to drive the EM gun. The discharge waveform is shown in Fig. 10. Without additional inductance, the projectile can be accelerated to 1814m/s. With different inductance in series, the discharge pulse can be widened, the pulse peak will drop and the projectile velocity has a certain increase, as Fig. 11 shows.
Summary
This paper designed a simple and reliable air-core compulsator. A novel self-exciting circuit is proposed, which can improve the excitation efficiency and reduce the loss. The role of series inductance in waveform regulation is studied preliminarily. The work can provide a reference for the design of small and lightweight compulsator.

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