Power Distribution Optimization of Parallel Hybrid Excitation Generator with Active Rectifier

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Abstract: The power distribution characteristic of a parallel hybrid excitation generator (PHEG) is studied and optimized. The PHEG consists of a permanent magnet machine part (PMMP), a flux modulation machine part (FMMP), and a rectifier. The winding coupling relationship and inductance characteristic of PMMP and FMMP are illustrated. By introducing the controllable devices, the internal power factor angle of the PHEG can be adjusted, which provides the possibility to optimize the power distribution between PMMP and FMMP. Based on the analysis of the phasor diagrams, it is found that the output capacity of PMMP in PHEG with an active rectifier is improved. Therefore, PHEG can output constant power and voltage over a wider speed with the lower loss, which verifies that PHEG with an active rectifier is a promising candidate in the aircraft DC power generation system.

Key words: active rectifier; internal power factor; power distribution optimization; parallel hybrid excitation generator (PHEG)

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0 Introduction

The hybrid excitation machine (HEM) which combines the permanent magnet (PM) source and the wound field (WF) source, has the advantage of good flux regulation capability[1-2]. Compared with the series HEM, the parallel HEM has a superior flux regulation capacity since the WF flux does not pass through the PMs, and thus, it avoids the disadvantages that the PMs suffer from a risk of demagnetization in the series HEM[3-4].

The structural parallel HEM (PHEM) is an important branch of the parallel HEM[5]. It inherits the advantage of the natural brushless structure of reluctance motors by locating the permanent magnets in the rotor and the field winding in the stator. The independent structure of the flux modulation machine part (FMMP) and the PM machine part (PMMP) allows for a flexible pole-slot combination and length ratio design[6-7].

The high inductance of the FMMP in a PHEM brings a guarantee for short-circuit current limitation which is the primary concern for the application in aircraft DC power systems[8]. However, the high inductance characteristic of the FMMP also brings about a severe armature reaction that limits the output capacity of the PMMP, especially at low speeds[9]. Aircraft generators need to achieve a constant voltage output over a wide speed range. Therefore, the required excitation power rises significantly when the speed is decreased, bringing additional excitation losses and increasing the size and weight of the exciter and regulator, which seriously affects the efficiency and stability of the power generation system.

Replacing the diode rectifier in the existing parallel hybrid excitation generator (PHEG) with fully controlled power devices can effectively regulate the armature reaction characteristics, thereby optimizing the power distribution between the two parts of

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the PHEG, releasing the output capacity of PMMP at low speeds.

The active rectifier in a parallel hybrid excitation flux switching machine effectively filters out high-frequency harmonics and DC bias in the back-EMF, contributing to the improvement of dynamic performance[10]. Based on this, a power angle linear control algorithm is proposed to reduce flux linkage ripple and current THD while improving the dynamic performance of a parallel hybrid excitation flux switching DC generation system[11]. The active rectifier can distribute power output between different energy sources in an open-winding hybrid excitation power generation system through cooperative control of armature current and field current[12].

In this paper, the winding coupling relationship and inductance characteristic of the PMMP and FMMP are illustrated. Then, the power distribution characteristics of the PHEG with a diode rectifier is revealed. The internal power factor angle of PHEG is adjusted by introducing the controllable devices. Based on the analysis of the phasor diagrams, the output capacity of the PMMP in the PHEG with an active rectifier is improved. The comparison of the power distribution between the PHEG with active and diode rectifier verifies the optimization effect of the active rectifier on the power distribution of the PHEG.

1 Structure and Operating Principle

The explosion diagram of PHEM is shown in Fig.1. It consists of two parts, a 12/10-pole FMMP and a 48-slot/20-pole surface-mounted PMMP. The armature windings of the two parts are connected in series, and the rotors are installed on the same shaft. The combination of a PHEM and rectifier can form a brushless PHEG. The basic machine parameters are given in Table 1.

The PHEGs equipped with diode rectifier and active rectifier are shown in Fig.2, respectively. The diode rectifier is more common in the existing PHEG.

The self-inductance of the two parts is shown in Fig.3. The self-inductance of the FMMP is approximately 10 times higher than that of the PMMP. This high inductance characteristic of the FMMP brings a guarantee for short-circuit current limitation while leading to a strong armature reaction at load.

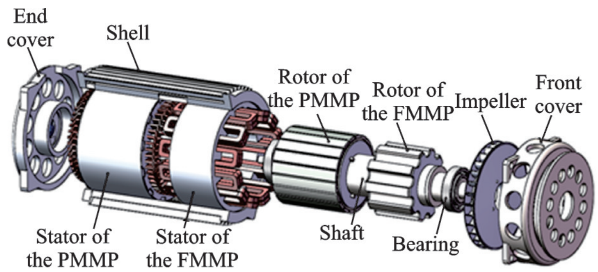


Fig.1 Explosion diagram of PHEM

Table 1 Parameters of parallel hybrid excitation machine

Parameter	PMMP	FMMP
Stator outer diameter/ mm	140	150
Stack length/ mm	40	72
Air-gap length/ mm	1.2	0.4
Number of pole-pairs	10	10
Number of slots	48	12

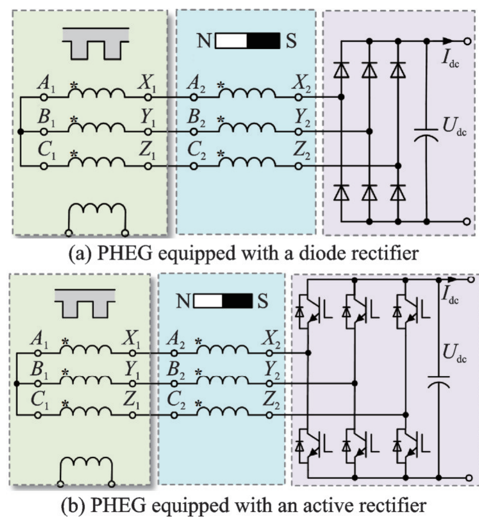


Fig.2 PHEG with different rectifier topologies

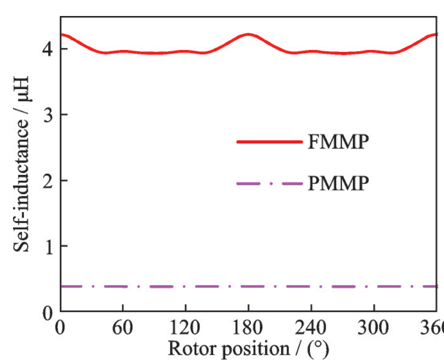
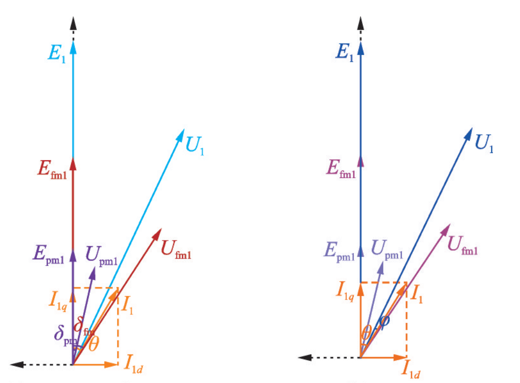


Fig.3 Self-inductance of FMMP and PMMP

Fig.4 shows the fundamental wave phasor diagrams of the PHEG with a diode rectifier. The output voltage is 30 V and the output power is 6 kW at 6 000 r/min. E_{pm1}, E_{fm1}, E_1 are the no-load back-EMF of PMMP, FMMP and PHEG, respectively. U_{pm1}, U_{fm1}, U_1 are the phase voltages of the PMMP, FMMP and PHEG, respectively. I_1, I_{1d}, I_{1q} are the phase current, d-axis current and q-axis current of PHEG, respectively. The angle between the no-load back-EMF and the phase voltage of PMMP, FMMP and PHEG is called the power angle, denoted as δ_{pm}, δ_{fm}, δ, respectively. The angle between the phase voltage and the phase current is called the power factor angle, denoted as φ_{pm}, φ_{pm}, φ, respectively. The angle between the no-load back-EMF and the phase current is called the internal power factor angle, denoted as θ_{pm}, θ_{fm} and θ, respectively. Since the armature winding of the PMMP and the FMMP is connected in series, the internal power factor angles of PMMP, FMMP and PHEG are equal, i. e. $\theta_{pm}=\theta_{pm}=\theta$, where $\varphi_{pm}=\theta_{pm}-\delta_{pm}$, $\varphi_{fm}=\theta_{fm}-\delta_{fm}$, $\varphi=\theta-\delta$. The reactive power Q_{pm}, Q_{fm} and active power P_{pm}, P_{fm} of the PMMP and the FMMP are calculated as

$$\begin{aligned} P_{fm} &= 3U_{fm} \cdot I \cdot \cos\varphi_{fm} \\ Q_{fm} &= 3U_{fm} \cdot I \cdot \sin\varphi_{fm} \\ P_{pm} &= 3U_{pm} \cdot I \cdot \cos\varphi_{pm} \\ P_{fm} &= 3U_{fm} \cdot I \cdot \cos\varphi_{fm} \end{aligned} \tag{1}$$

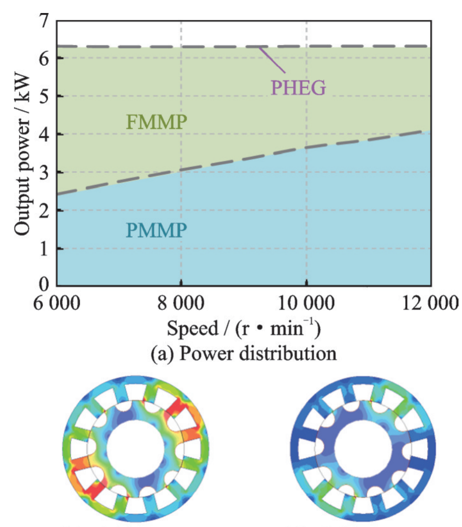


(a) PMMP and FMMP (b) PHEG

Fig.4 Fundamental phasor diagram at rated output voltage(I_f =32 A, n=6 000 r/min, P_o=6 kW)

The magnetic circuits of the FMMP and the PMMP are decoupled. The no-load back-EMF of the PMMP is almost constant at different field currents and speeds. At the same time, the low inductance of the PMMP leads to a weak armature reaction at load, so the power angle of PMMP δ_{pm} is small. The power factor angle θ is large in the PHEG under the influence of the strong armature reaction of the FMMP, and the power factor angle of the PMMP $\varphi_{pm}=\theta_{pm}-\delta_{pm}=\theta_{pm}-\delta$. Therefore, the power factor angle of the PMMP is large. According to Eq.(1), the PMMP generates large reactive power, which suppresses the effective output capacity of the PMMP. Therefore, the output power of the FMMP needs to be increased by increasing the field current at low speed, which brings additional copper losses. In the diode rectifier, the phase displacement characteristics of the PHEG cannot be adjusted, so the power distribution between the PMMP and the FMMP cannot be controlled.

The power distribution characteristic of PHEG with diode rectifier at different speeds is shown in Fig.5, where the output voltage and output power are constant. The field currents at different speeds are also given in Fig.5. As the speed decreases, the output power of the PMMP is restricted and to achieve constant voltage and power output, the power output of the FMMP needs to be increased by adding the field current. The flux density of the FMMP becomes saturated as the speed decreases, which affects the iron loss and efficiency.



(a) Power distribution

(b) Field current (6 000 r / min) (c) Field current (12 000 r / min)

Fig.5 Power distribution and field current at different speeds with diode rectifier(U_o=30 V, P_o=6 kW)

2 Comparison of Power Generation Characteristics Under Different Rectification Methods

2.1 Optimization of power distribution

The control block diagram of PHEG with an active rectifier is shown in Fig.6. The d-axis current i_d can be controlled by the PI regulator. The q-axis current i_q varies with different speeds and field currents I_f, thus adjusting the internal power factor angle θ. The power distribution between the FMMP and the PMMP can be changed by regulating i_d.

As shown in Fig.7, the internal power factor angle θ differs at the same field current under diode rectifier and active rectifier, where the armature currents have the same RMS values under the same field current. In the active rectifier, as the field current is reduced, the no-load back-EMF of the PHEG decreases. Therefore, the required i_d decreases and the q-axis current i_q increases at a certain output voltage. As a result, the internal power factor angle θ of the PHEG decreases. The smaller the field current is, the smaller the internal power factor angle θ is.

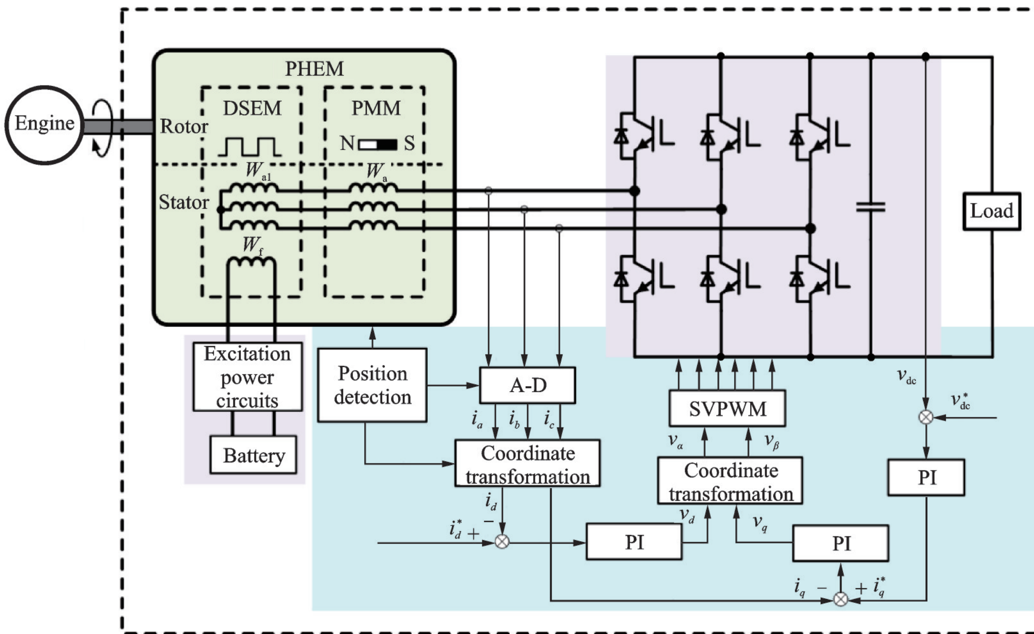


Fig.6 Curve of internal power factor angle changing with excitation current

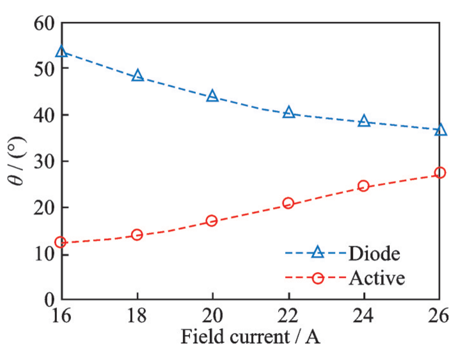


Fig.7 Curves of internal power factor angle changing versus field current

The power factor angle of the PMMP versus the field current is shown in Fig.8. Since the power factor angle of PMMP $\varphi_{pm}=\theta_{pm}-\delta_{pm}=\theta-\delta_{pm}$, the power factor angle φ_{pm} of the PMMP varies similarly to the internal power factor angle θ, which gradually decreases as the field current decreases.

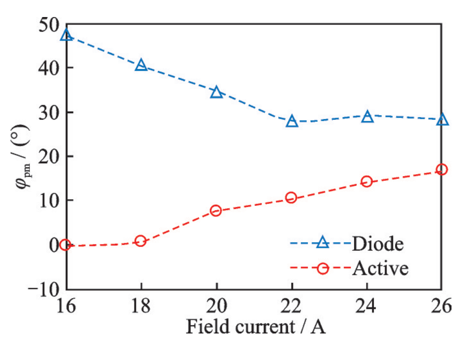


Fig.8 Curves of power factor angle changing versus field current

The power distribution characteristic of PHEG with a diode rectifier is shown in Fig.9. The output power of the PMMP keeps almost constant when the field current changes. As the field current decreases, the output power of the FMMP decreases significantly, thus the output power of PHEG decreases. The power distribution characteristic of PHEG with an active rectifier is shown in Fig.10. The power distribution is also compared between active rectifier and diode rectifier at the same output voltage and output power in Fig.10. As the field current decreases, the output power of the PMMP is released by adjusting the internal power factor angle. Therefore, the required voltage and power can still be output as the field current decreases. The PHEG with a diode rectifier can only generate the same output power by adding the field current to 32 A to increase the output power of the FMMP.

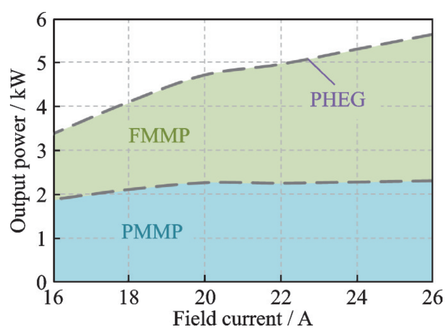


Fig.9 Power distribution characteristic with diode rectifier

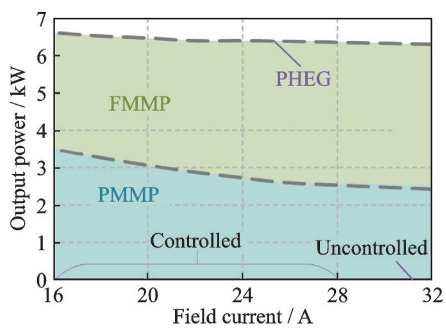


Fig.10 Power distribution characteristic with active rectifier

The fundamental phasor diagram with diode rectifier and active rectifier at the same field current and RMS value of armature current is compared in Fig.11. E_1, E_2, U_1, U_2, I_1, I_2, I_{1q}, I_{2q}, I_{1d}, I_{2d} are the no-load back-EMF, phase voltage at load, phase current, q-axis and d-axis current of the PHEG under the diode rectifier and the active rectifier, respectively. Due to the reduction of the d-axis current i_d, the phase current I_2 in the PHEG with an active rectifier exceeds the phase current I_1 in the PHEG with a diode rectifier. The phase voltage in the PHEG with an active rectifier is much larger than that in the diode rectifier if the RMS values of I_1 and I_2 are the same. Therefore, the output power of the PHEG with an active rectifier is higher than the PHEG with a diode rectifier at the same copper loss.

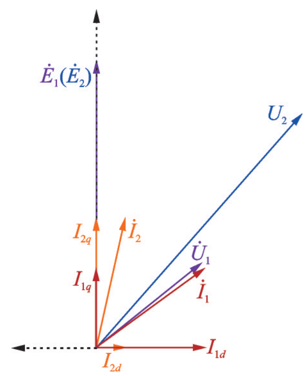


Fig.11 Comparison of fundamental phasor diagram ($I_f = 16$ A, $n = 6\,000$ r/min)

2.2 Comparison of output power and losses

Fig.12 shows the output power versus output current of the PHEG with a diode rectifier at 16 A. The maximum output power is approximately 3.5 kW, which is much less than the output power of the PHEG with an active rectifier. With the same field current, the active rectifier enhances the output capacity of the PHEG.

The variation of the field current affects the

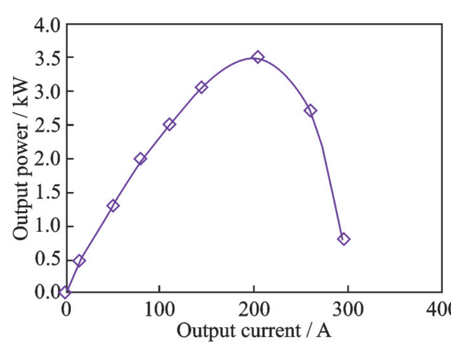


Fig.12 Output power of PHEG with diode rectifier ($I_f = 16$ A)

losses of the machine, especially at low speeds, and the field copper loss occupies a larger proportion of the losses of PHEG, which have a crucial impact on the efficiency of the generator.

Fig.13 shows the loss of PHEG versus the field current. Fig.14 compares the loss distribution of the PHEG with different rectifiers at the same output voltage and power. The field current of PHEG with an active rectifier is 16 A, while the field current of PHEG with a diode rectifier is 32 A. The copper loss of the PHEG with an active rectifier is much smaller than that of the PHEG with a diode rectifier because of a smaller field current. The loss of the PHEG with active rectifier is reduced by approximately 45% compared to the diode rectifier at the same output.

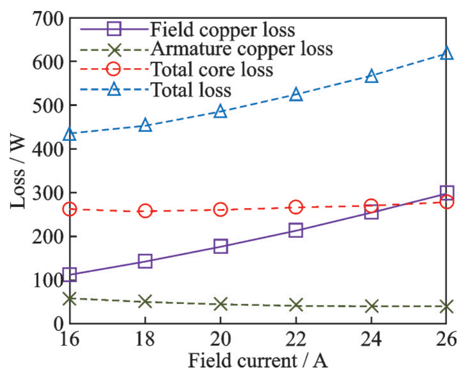


Fig.13 Loss of PHEG with active rectifier versus field current

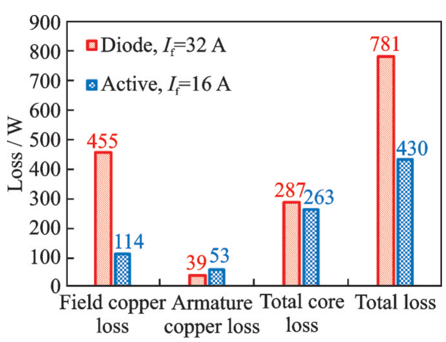


Fig.14 Comparison of loss of PHEG under different rectifier power generation modes

3 Conclusions

The power distribution characteristic of PHEG at different rectifiers is analyzed. The controllable devices are introduced to optimize the power distribution between the FMMP and the PMMP. The following conclusions are obtained by comparison.

(1) In the PHEG with a diode rectifier, the high inductance characteristic of the FMMP leads to a strong armature reaction at load, which inhibits the power output capability of the PMMP in the PHEG.

(2) In the PHEG with an active rectifier, the output capacity of the PMMP can be released by adjusting the power factor angle in the PHEG, allowing for optimal power distribution.

(3) Compared to the PHEG with a diode rectifier, the loss of the PHEG with an active rectifier is significantly reduced at the same output power by decreasing the field current.

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Author contributions Ms. **YU Shijia** designed the study, complied the models, conducted the analysis, interpreted the results, and wrote the manuscript. Dr. **GU Xiangpei** guided the research, designed the article structure. Prof. **ZHANG Zhuoran** contributed to the discussion and background of the study. All authors commended on the manuscript draft and approved the submmission.

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采用可控整流器的并列式混合励磁发电机的功率分配优化

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摘要: 研究并优化了并列式混合励磁发电机(Parallel hybrid excitation generator, PHEG)的功率分配特性。PHEG包括永磁电机部分(Permanent magnet machine part, PMMP),磁场调制电机部分(Flux modulation machine part, FMMP)和整流器。阐述了PMMP和FMMP的绕组耦合关系和电感特性。通过引入可控器件,调整了PHEG的内功率因数角,为PMMP和FMMP之间的功率分配提供了可能。通过分析基波相量图,可以发现PHEG中的PMMP的输出能力增强了。因此,PHEG可以在减少损耗的条件下在更宽的转速内恒压恒功率输出,这也验证了采用可控整流器的PHEG在飞机直流电源系统中具有应用潜力。

关键词: 可控整流器;内功率因数;功率分配优化;并列式混合励磁发电机