Implementation and Study of a Novel Doubly Salient Structure Starter/ Generator System

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Abstract: A new type of double salient starter/ generator is presented, which can be used in aircraft Low Voltage Direct Current (LVDC), Variable Speed Constant Frequency (VSCF) and High Voltage Direct Current (HVDC) systems. The operational theory of the motor and generator is analyzed, and corresponding control strategies are given. An 18kW prototype has been implemented to verify the system performance. It is shown that the DSM S/G system possesses simple structure, high efficiency and flexible control. It is appropriate to be used for aircraft application.

Key words: double salient motor; starter/generator; fielding winding; permanent magnetic

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摘 要: 介绍一种可以适应于航空低压直流、变速恒频、高压直流电气系统的新型双凸极起动/发电机系统, 并对其电动及发电机理进行了理论研究, 给出起动/发电机的相应控制策略, 在此基础上研制了 18kW 样机并进行了原理试验研究, 试验结果表明: 双凸极电机起动/发电系统的方案具有结构简单、可靠及控制方便等优点, 适合作航空用起动/发电机。

关键词: 双凸极电机; 起动/发电; 电磁式; 永磁式

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The aircraft integral starter/generator system operates not only as a starter but also as a generator according to the reversible operation of electric machines. When operating as an engine starter, the motor produces a torque to spin the engine up to its light-off speed. Following the light-off speed, it continues to produce the torque and assists the engine in accelerating to the idle speed. When the engine is running, the electric machine operates as a generator to supply vehicle loads. In short, the starter/generator system lessens a special starter and results in a lower system weight and higher system reliability, and it is a key technology in the More Electric Aircraft (MEA) for providing the engine start, and power to electric driven pump and other electrical loads and actuators. Therefore, it is a substantial aspect of advance in the aircraft power supply progress[1-3].

Traditionally, the motors used as a starter/ generator include Brush DC Motor(BDCM), Permanent Magnet Synchronous Motor(PMSM), Induction\| Motor(IM), Switched Reluctance Motor (SRM) and so on. With fast development of power electronics and microelectronics, the double salient motor (DSM) is a novel type AC driver which was first put forward by T. A. Lipo in 1990's. A lot of literature on DSM and its control system are reported in America, Europe and China. The major advantages of DSM are summarized as high efficiency, high density, high torque/current ratio, flexible control and so on[4~6]. According to different excitation patterns it can be divided into three types: permanent, fielding windings and hybrid motors. It possesses simple, rugged structure and is used in high temperature, high speed occasions due to no windings and permanent magnet on the

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rotor. DSM has the potential in aerospace applications.

This paper presents a new type starter/generator system —— Double Salient Starter/Generator (DSS/G), and analyzes its double-function operational theory, system design, control strategies and experimental results.

1 DS Starter/Generator Operational Theory

Fig. 1 shows the cross section of a three-phase, 6/4-pole DSPM. It can be noted that the structure of DSPM is similar to that of SRM; two pieces of PM are buried in the stator, and introduced into the main flux path of the stator windings. The stator pole arc is set to be $\pi/6$ mechanical radians. As configured, the airgap reluctance seen by the PM excitation is invariant of the rotor

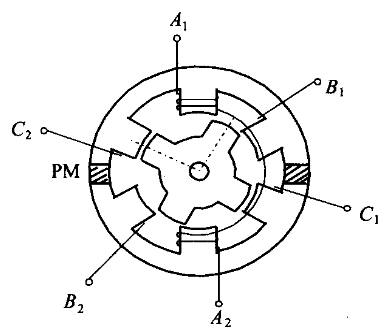

Fig. 1 The cross section of a three-phase, 6/4-pole DSPM

position if fringing is negligible. Therefore, there is essentially no cogging torque produced at no-load. A linear variation of the phase flux linkage and the inductance is induced in each of the stator windings as shown in the upper of Fig. 2. Homoplastically, the phase windings flux of double salient electric motor (DSEM) is provided by fielding windings in the stator instead of two pieces of PM. The torque expression derived below is based on a simplified linear model for the purpose of illustration. The variation of winding inductance and flux linkage of an active phase are assumed to be piece-wise linear and spatially dependent only. The terminal voltage equation for a phase winding is then

$$u = Ri + \frac{d\Psi}{dt} = L\frac{di}{dt} + i\frac{dL}{dt} + \frac{d\Psi_m}{dt} \quad (1)$$

The flux linkage Ψ is composed of the PM flux linkage Ψ_m and the armature reaction flux linkage (Li). The electrical power entering any of the windings is, neglecting ohmic and iron losses,

$$P_e = \frac{d}{dt}\left(\frac{1}{2}Li^2\right) + \left\{\frac{1}{2}i^2\frac{\partial L}{\partial\theta} + i\frac{\partial\Psi_m}{\partial\theta}\right\}\omega \quad (2)$$

Hence, the torque can be written as the sum of two components[5,6].

$$T = \frac{1}{2}i^2\frac{\partial L}{\partial\theta} + i\frac{\partial\Psi_m}{\partial\theta_r} = T_r + T_m \quad (3)$$

The following features of the DSPM are revealed through frontal analysis: The armature reaction field energy W_f, which is to be recovered during current commutation, is very small because of the small value of the stator inductance. Therefore, the energy conversion ratio is very high. The total torque of the motor consists of two components, the reaction torque T_m and the reluctance torque T_r according to Eq. (3). Because of the triangular-shaped variation of the stator winding inductance, T_r has a zero average value if the current amplitude is kept constant during one stroke as shown in the middle of Fig. 2. θ_{on}, θ_{off} are turning-on and turning-off angles of power switches respectively. The reaction torque T_m, which is the dominant torque component, can be produced by applying either a positive current to a phase winding when its flux linkage is increasing ($e_m > 0$) or a negative current when the flux linkage is decreasing ($e_m < 0$). It can output mechanical energy at two quadrants of the magnetization curve, which makes the volume of the motor smaller. The value

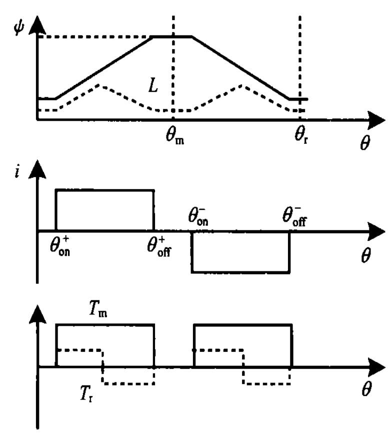

Fig. 2 Illustration of operating principles of DSPM

of the torque is adjusted to the threshold of the phase current and other parameters such as turning-on angle and turning-off angle. It is also realized by one-beating or two-beating in each cycle. Then operational modes between motoring and regenerating brakes are altered through varying the direction of the phase current. Four quadrants operation is readily achieved by changing the sequence of conduction and the polarity of the stator currents.

The torque of Double Salient Electric Motor (DSEM) is controlled through not only regulating the phase current but also varying the intensity of fielding flux linkage. Therefore, DSEM has a feature of flexible control and operation over a wide speed range.

2 The Configuration of DS Starter/Generator

DSM starter/generator system consists of a starter/generator, power converter, digital controller, generator control unit (GCU) and other adjuvant parts such as current sensor and position sensor, as shown in Fig. 3.

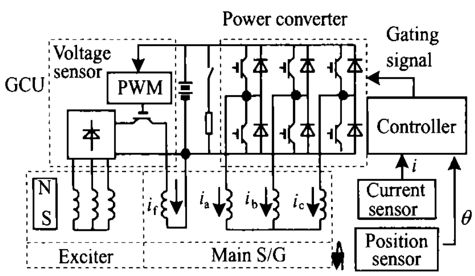

Fig. 3 Schematic diagram of DS Starter/Generator System

During the starting process, the storage battery powers up fielding windings and establishes fielding magnet energy. The different switches of the power converter are turned on or off according to the position signal, and the current flows in corresponding phase windings, and the starter produces a fixed direct torque and spins the engine up to work. All switches of the power converter are turned off during the generating process. Engine revolves the starter/generator in high speed, then fielding winding flow current to provide fielding energy. Three EMF are exported from three phase flux linkage varying with rotating of the rotor, and DC voltage is produced through diode rectifier. Regulation of DC voltage is realized through regulating fielding winding current by generator control unit (GCU).

The double salient starter/generator is constructed in two cascades, an exciter, main starter/generator and other accessories are packaged in configuration of DSS/G. It is shown in Fig. 4. Main motor is a 12/8-pole DSEM, the structures of its stator and rotor are salient poles. Concentrated phase and fielding windings are coiled in the stator. Each two faced winding of four stator teeth is linked in series; three phase windings are connected with star-shape. The cross section of the main generator is shown as Fig. 5. The pole arc is a half of the stator pole interval; the stator pole

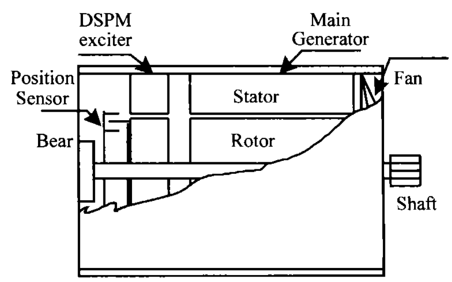

Fig. 4 Configuration of DS Starter/Generator

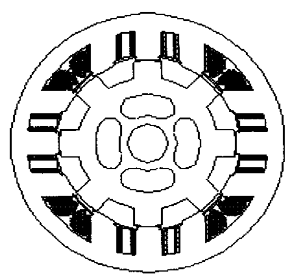

Fig. 5 The cross section of main S/G motor

arc is set to be $\pi/12$ mechanical radians. Therefore, the gap reluctance, seen by fielding excitation, is constant if fringing is negligible. A phase armature inductance varies with the overlop between the stator and rotor, and the rotor pole arc is selected to be slightly greater than the stator pole arc to allow for current reversal.

The exciter generator is also a 12/8-pole configuration. Four SmCo magnets are buried in the stator instead of fielding windings. The sizes of the exciter generator are similar to that of the main motor. Fig. 6 shows the cross section of PM exciter generator. The exciter generator provides electric energy for fielding windings to establish magnetic field without battery. The structures of the main motor and exciter generator are designed by Finite Element Analysis method. The part parameters of a 18kW prototype are provide in Table 1.

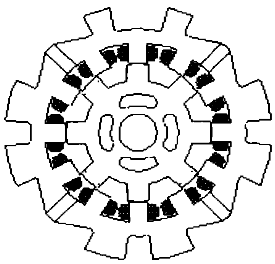

Fig. 6 The cross section of PM exciter generator

Table 1 Basic size of main generator and exciter

Material		Stator OD/mm	Stator ID/mm	Rotor OD/mm	Airgap /mm	Length /mm
M	1J21	180	116.6	116	0.3	160
E	D41	146	99	98	0.3	18

3 Control Strategy of Starter/Generator

3.1 Starting process

According to engine operation, the starting process is divided into three stages, soft starting stage, constant torque starting stage and constant power starting stage.

At initiative starting stage, a small starting torque is requested to eliminate the clearance of gearbox, and lessen impact to engine. The torque is limited by chopping phase windings current under constant fielding current. The chopping threshold of an 18 kW starter/generator prototype is set 200A at the soft starting stage. The threshold of the phase current is set 600A quickly after elimination of the gearbox clearance, the torque is increased quickly up to maximum to accelerate the engine, and the starter enters the constant torque starting stage. The back EMF of phase windings increases more and more with improvement of rotor speed, and the phase current chopping times are lessened because the back EMF restrains the phase current to rise. The value of the phase current continuous is almost kept constant. When the back EMF of phase winding is equal to the battery voltage, the chopping time is zero; the phase current can not be enhanced sequentially although power switches are turned on. The starter enters the constant power starting stage and the average torque begins to drop. Once the engine reaches its idle speed, the starting process is over. Otherwise, the fielding current is lessened to improve the system speed until the engine reaches its idle speed.

Fig. 7 shows the experimental phase current wave and control signal of the starter at 500r/min speed where the phase current is a 120° quasi-square waveform. At high speed, the current cannot be maintained constant due to the excessive EMF. In this case, the current peaks in the first half stroke drop rapidly due to a wide speed range. The experimental current wave is shown in Fig. 8. So turning-on angle θ_{on} and turning-off angle θ_{off} are required to optimize with variation of speed.

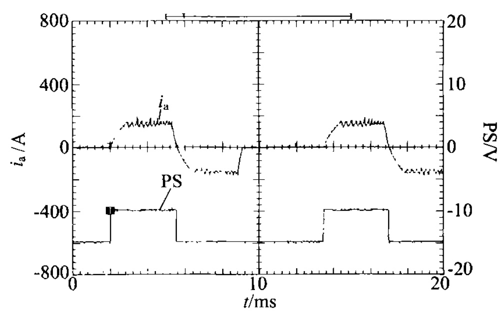

Fig. 7 Experimental wave of low speed motoring

Fig. 9 shows that the curves of the starting torque are tested between the fielding winding current and upper threshold of the phase winding current. The magnetization curve is located at saturation when i_f > 10A. It is effective to improve the starting torque by increasing the upper threshold of the phase current instead of fielding current. Fig. 10 shows torque/speed characteristics of the starting process with 5kg · m maximum torque. The output torque is almost constant, which is maintained by chopping during 0 ~ 2000r/min speed range. On the other hand, the output torque drops and output power is nearly constant during 2000～4000r/min.

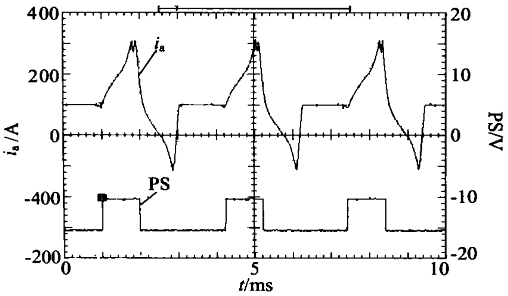

Fig. 8 Experimental wave of high speed motoring

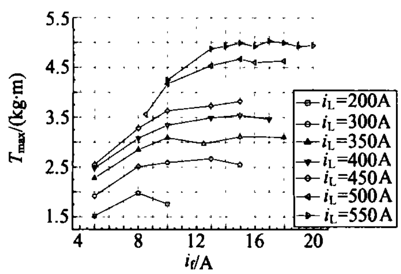

Fig. 9 Torque versus threshold of phase current and i_f

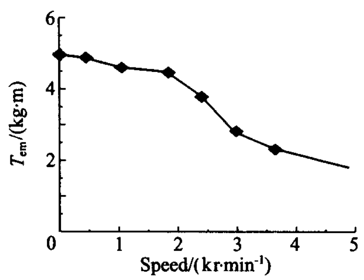

Fig. 10 Torque/speed characteristic of starting process

3.2 Generating process

After the starting process, DSEM works as a generator. Three AC electric energy flows through the rectifier to be converted into DC electric energy. Generator control relay (GCR) is closed and the exciter generator exports electric energy to fielding winding of the main generator. Output voltage of the generator is regulated through chopping the fielding current by GCU.

Fig. 11 shows a block diagram of GCU, which includes the voltage sensor, fielding current sensor, pulsed width modulation (PWM), power amplifier and protection parts. The bus voltage of POR detected by the sensor is compared with the reference voltage. PWM signal is produced between a changing error signal and a fixing frequency triangle waveform. Regulation of field winding current i_f can be implemented through variation of the duty ratio. A steady output DC voltage is carried out accordingly under different speeds and loads. The dynamic performance of the output voltage will be specially introduced in another paper.

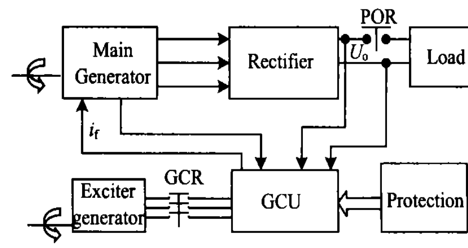

Fig. 11 Schematic diagram of generator system

Fig. 12 shows generating experimental waves of three phases voltage, and AC voltages are rectified into DC voltage for load. Characteristics of DC voltage/speed are shown in Fig. 13 under the condition of I_o = 0, 5, 10A; a favorable linear relation is obtained between the output voltage and speed because the back EMF is proportional to the variety ratio of phase flux linkage. Fig. 14 shows the curves of the output voltage versus i_f under no load. It is interesting to notice that a little effect on voltage is accompanied with saturation, when i_f is exceeding 6A. The control characteristic of the generator is shown in Fig. 15. Generating control performance at big fielding current is inferior to that at small fielding current, an 18kW rated output power is obtained under condition of 4200 r/min speed, i_f = 13A, and more generating power is produced at high speed.

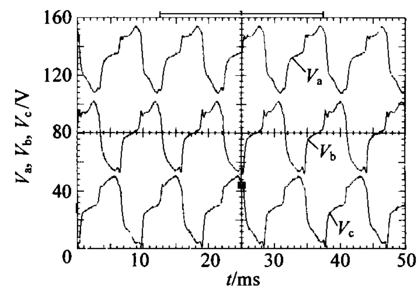

Fig. 12 Experimental wave of three phase voltage

4 Conclusions

This paper has laid the theoretical and experimental foundation for a new type double salient

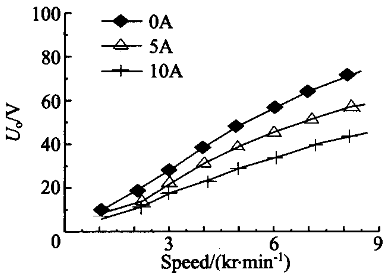

Fig. 13 Output voltage versus speed

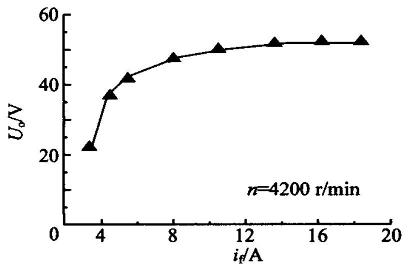

Fig. 14 Output voltage versus exciting current I_f under no load

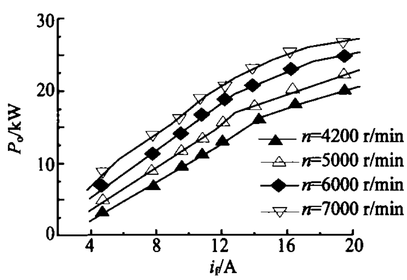

Fig. 15 Output power versus exciting current I_f

motor starter/generator system. The design and control strategies of this system have also been implemented although much research remains ahead to fully assess the potential of such systems. It is evident that this DS starter/generator possesses the following advantages:

The main starter/generator has simple, rugged structure and high speed capability owing to no permanent magnets and no windings on the rotor.

The starter/generator possesses power density and high efficiency, making VA rating of the power converter smaller as well as the motor.

The configuration of the motor is constructed in two cascades. It is convenient to achieve starting and generating functions. The exciter offers electric energy for fielding windings of the main generator. The quality of DC voltage is regulated by GCU. Furthermore, protection function is carried out through cutting between exciter and fielding windings. And the system can realize self-generating operation without external power supply. Neither power converter nor position sensor is required in the generating operation, which results in high reliability.

The brushless integral starter/generator is designed for LVDC system. Compared to other types of starter/generators it is shown that it possesses simpler structure and higher reliability. And it may be also used in high voltage direct current (HVDC) and variable speed constant frequency (VSCF) in the future.

References

[1] Richter E, *et al*. The integral starter/generator development progress[J]. IEEE AES Systems Magazine, 1996, (10): 17 – 23.

[2] MacMinn S R, Jones W D. A very high speed switched reluctance starter/generator for aircraft engine application [A]. In: Proc NAECON'89[C]. 1989, 1759– 1764.

[3] Ferreira C A, Jones S R, *et al*. Detailed design of a 30-kW switched reluctance starter/generator system for a gas turbine engine application[J]. IEEE IA, 1995, 31(3): 553–561.

[4] Blaabjerg F. New advanced control methods for doubly salient permanent magnet motor[J]. IEEE IA, 1995, 31(2): 222– 230.

[5] Yue F, Lipo T A. A new doubly salient permanent magnet motor for adjustable speed driver[J]. Electric Machines and Power Systems, 1994, 22(2): 258– 270.

[6] Yue F, Liao F L, Lipo T A. A novel permanent magnet motor with doubly salient structure[J]. IEEE Transactions on Industry Applications, 1995, 31(5): 1069– 1078.

[7] Cheng M, Zhou E. Analysis and control of novel split-winding doubly salient permanent magnet motor for adjustable speed drive[J]. Science in China(series E), 2001, 44(4): 353 – 364.

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