Design and Control of a Two-Phase Brushless Exciter for Aircraft Wound-Rotor Synchronous Starter/Generator in the Starting Mode

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***Abstract*—The structure and control strategy of a novel two-phase brushless main exciter (ME) are proposed in this paper to solve the excitation problem of the main generator (MG) when the aircraft brushless wound-rotor synchronous starter/generator start up as a motor. Two-phase symmetrical winding is adopted as the field winding of the ME and is supplied with two-phase ac by a two-phase inverter in the starting mode and dc by the traditional generator control unit in the generation mode. In order to make the field current of the MG remain constant during the start-up process, the excitation control method for the two-phase ME in the starting mode is proposed, which contains the feedback control for the two-phase field currents and speed reference control for the excitation frequency. The proposed two-phase ME and excitation control method have the advantages of capability for higher and constant field current for the MG in the starting mode and unchanged structure and control methods in the generation mode. A two-phase ME prototype, based on an original single-phase ME, is designed, manufactured, and tested. Finite-element analysis (FEA)-based simulation and experimental results verify the feasibility and advantages of the novel two-phase brushless ME and excitation control method.**

***Index Terms*—Aircraft starter/generator, excitation control method, two-phase brushless exciter, wound-rotor synchronous machine.**

I. Introduction

INTEGRATED starter/generator (ISG) system is becoming increasingly popular due to its less weight and volume in modern aircrafts [1]–[4]. A simple and efficient method to achieve the ISG system from a traditional separated starter and generator system is removing the special starter and making the generator also operate as a motor to start the aero engine in the starting mode. Various types of electric machines can be considered to operate as an ISG, such as switched reluctance machine [5], [6], permanent-magnet machine [7], [8], induction machine [9], [10], and wound-rotor synchronous machine [11]–[13]. Because of advantages such as high safety (possibility of canceling of the field current in case of short-circuit and high voltages in the generation mode) and low cost in maintenance, wound-rotor synchronous machine becomes an attractive candidate for ISG in aircrafts.

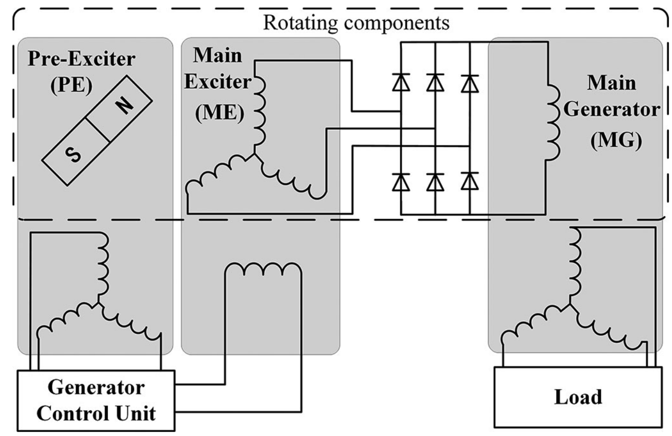

Fig. 1. Structure of the traditional three-stage brushless wound-rotor synchronous generator.

Three-stage brushless wound-rotor synchronous machine is generally used as the generator in aircrafts [11], [12]. This generator, illustrated in Fig. 1, mainly consists of three stages (corresponding to three electric machines): the pre-exciter (PE), the main exciter (ME), and the main generator (MG). The PE is a small-power-level permanent-magnet synchronous generator, and the ME is a rotating-armature electrically excited generator with single-phase field winding and three-phase armature winding. The armature winding of PE is connected to the field winding of ME through the generator control unit (GCU), which rectifies three-phase ac to dc and also adjust the dc voltage applied to the ME to obtain the required output of the MG. The MG is a wound-rotor synchronous machine, with its field winding connected to the armature winding of ME through a rotating diode rectifier. All of the rotors of these three electric machines and the rotating diode rectifier are mounted in the same shaft, constituting the rotating parts of this system.

When this three-stage electric machine system operates as the traditional generator, the PE provides dc excitation for the ME through the GCU and then the induced three-phase armature voltages of the ME are rectified by the rotating diode rectifier into the field winding of MG, providing dc excitation for the MG. However, when this three-stage electric machine system is in motor operation to start the engine in the starting mode, there is no electromotive force induced in the armature winding of ME if the ME is still excited by dc when the machine is

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stationary in the beginning. As a result, the MG cannot produce electromagnetic torque to start the aero engine since there is no field current in the field winding of the MG. Even when the machine starts rotating, if the speed is low, the induced electromotive force in the armature winding of the ME cannot be sufficient to provide the required field current for the MG to start with large load. Therefore, the field current problem of the MG in the starting mode, especially in the stationary and low-speed statuses, is the key problem to solve in order to achieve the ISG from a three-stage brushless wound-rotor synchronous generator.

As for the aforementioned field current problem in the starting mode, there are mainly two traditional solutions: One is the single-phase ac excitation strategy [14]–[17], and the other is the three-phase ac excitation strategy [11], [18]–[20].

The basic principle of the single-phase ac excitation strategy is that the structure of the original ME keeps unchanged, and the field winding of the ME is excited by single-phase ac in the stationary and low-speed statuses. So even when the rotor speed is zero, as the ME works as a transformer, there will be electromotive force induced in the armature winding, which can supply dc field current for the MG through the rotating rectifier. When the machine approaches a certain speed, the ME is excited by dc instead of single-phase ac since dc excitation is easy to control and can provide bigger and better (meaning less ripple) field current for the MG. The single-phase ac excitation strategy has the advantages of simple control and no change in the structure of the original ME. However, due to poor energy transfer from the stator to the rotor related to pulsating field operation, single-phase ac excitation strategy can hardly provide enough field current for the MG to start with large load [11].

In the three-phase ac excitation strategy, the original single-phase field winding of the ME is replaced by a three-phase winding. The ME is excited by three-phase ac in the stationary and low-speed statuses, so rotating magnetic field will be generated even when the rotor is stationary. And then sufficiently large three-phase electromotive force will be induced in the armature winding of ME, which can provide large field current for the MG. When the machine reaches a certain speed, different excitation strategies can be used. In [18] and [19], the three-phase field winding was reconnected into a single-phase winding and supplied with dc excitation by reasonable control of a dual three-phase inverter, since the three-phase field winding was constructed by three open-winding field windings. The structure and manufacture of these three open-winding field windings are relatively complicated, and the dual three-phase inverter needs 12 IGBTs, which will increase the weight and volume of the controller. In [11] and [20], three-phase ac excitation for the ME was used in the whole process, including the starting and generation modes. This method does not require switch from ac excitation to dc excitation; therefore, the problems during the switch can be eliminated. However, the control of three-phase ac excitation for the ME in the generation mode is more complicated compared with dc excitation control, and the structure and mature control methods for the traditional three-stage brushless wound-rotor generator can no longer be used in the generation mode of this ISG system.

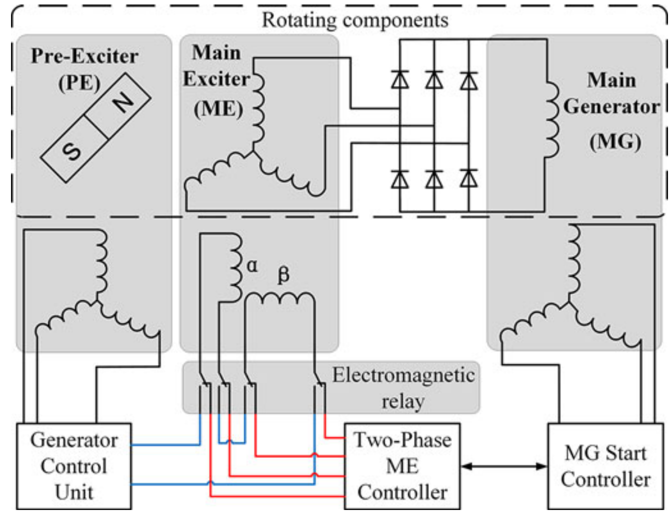

Fig. 2. Structure of the proposed wound-rotor synchronous starter/generator with two-phase brushless ME.

In order to solve the field current problem of the MG in the starting mode, meanwhile keeping the original structure and control methods unchanged in the generation mode, a novel brushless ME with two-phase field winding and two-phase ac excitation control method for three-stage ISGs were proposed in this paper. Two-phase winding is generally used in two-phase induction motors [21] and two-phase stepper motors [22] but rarely applied in brushless exciters. A four-leg two-phase inverter [23], [24] was adopted in this paper to supply two-phase ac excitation voltage to the proposed two-phase ME during the start-up process, because it can provide the highest two-phase ac voltage for the ME compared with the two-leg two-phase inverter [25], [26] and three-leg two-phase inverter [27]–[29] under the same dc-bus voltage [12]. A two-phase ME prototype and excitation control method in the starting mode were designed and tested based on an original single-phase ME of a traditional three-stage brushless wound-rotor generator. This new two-phase ME and excitation control method have the advantages of capability for higher and constant field current for the MG in the starting mode and unchanged structure and control methods in the generation mode.

The worst situation for the three-stage wound-rotor synchronous ISG in the starting mode is when the rotor is stationary. And after the rotor starts spinning, things will get better. In the generation mode, as the two-phase ME will be converted into the traditional single-phase ME, mature control methods for the traditional three-stage wound-rotor generator can be used, and that is not the focus of this paper. So in this paper, we will pay much more attention to the stationary status, and of course, the whole start-up process will be considered as well when the research of the excitation control method for two-phase ME is carried out.

II. Operation Principle of Wound-Rotor Synchronous Starter/Generator with Two-Phase ME

The structure of the proposed three-stage wound-rotor synchronous starter/generator with a two-phase ME is shown in Fig. 2. Compared with the traditional three-stage wound-rotor generator system (shown in Fig. 1), the main differences are that the field winding of the novel ME is a two-phase symmetrical winding (spatial difference of 90° electrical angle), and a two-phase ME controller is adopted to supply field currents for the ME in the starting mode.

A. Operation Principle in the Starting Mode

In the starting mode, the two-phase field winding of the ME is connected to the two-phase ME controller through the electromagnetic relay. Two-phase symmetrical ac excitation (90° phase difference) is supplied to the two-phase field winding ME by the ME controller. As the electrical angle difference of this two-phase field winding is also 90°, rotating magnetic field will be generated and the speed corresponds to the frequency of the two-phase ac. In this situation, the two-phase ME works as an induction generator and three-phase electromotive force will be induced in the armature winding of the ME, which will provide dc field current for the MG through the rotating rectifier. As the energy transfer from the stator to the rotor in the ME is related to rotating field operation, the efficiency is fairly high. So the two-phase ME can provide big enough field current for the MG to start with large load in the starting mode, even in the stationary status.

In order to keep the field current of the MG constant in the starting mode for simpler start control of the MG, the frequency and magnitude of the two-phase excitation voltage supplied to the ME should be adjusted with the rotor speed. The detailed excitation control method will be given in part IV.

B. Operation Principle in the Generation Mode

After the engine has been started, the two-phase field winding of the ME will be connected in series into a single winding and connected to the GCU through the electromagnetic relay. In this situation, the two-phase ME is converted into the traditional ME with single field winding, and the whole system and its working principle will be the same as the traditional three-stage wound-rotor generator. As a good result, mature control methods for the traditional three-stage wound-rotor generator system can be used in the generation mode of this new proposed ISG system. Details about the control methods in the generation mode can be found in [30] and [31] and will not be repeated in this paper.

III. Design and Finite Element Analysis of a Two-Phase ME

Design of a two-phase ME was carried out based on an original single-phase ME of a traditional three-stage wound-rotor generator. The structure of the original single-phase ME is illustrated in Fig. 3(a): The stator field winding was formed from individual coils wound around each of the 12 stator teeth, and the rotor used 12-pole three-phase distributed winding, which was connected to the rotating diode rectifier. In order to reduce the redesigned section and get better comparison between the original single-phase ME and proposed two-phase ME, reconfiguration was only undertaken for the stator while the rotor structure and armature winding remained unchanged. Besides, the main dimensions of the stator, such as the active diameter and active length, were constrained to the existing mechanical envelope. So the key point of the design lay in the reconfiguration of stator slots and the two-phase field winding.

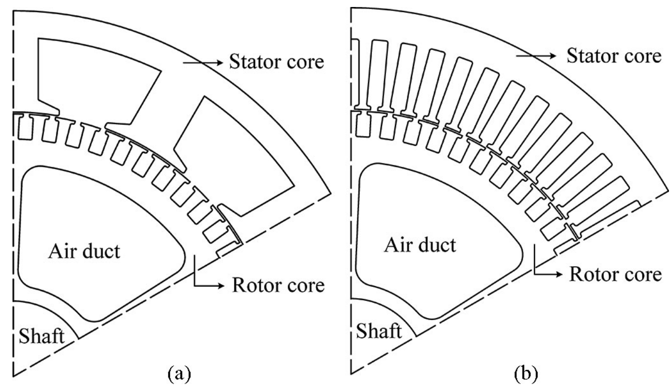

Fig. 3. Structure of the MEs: (a) original single-phase ME; (b) proposed two-phase ME.

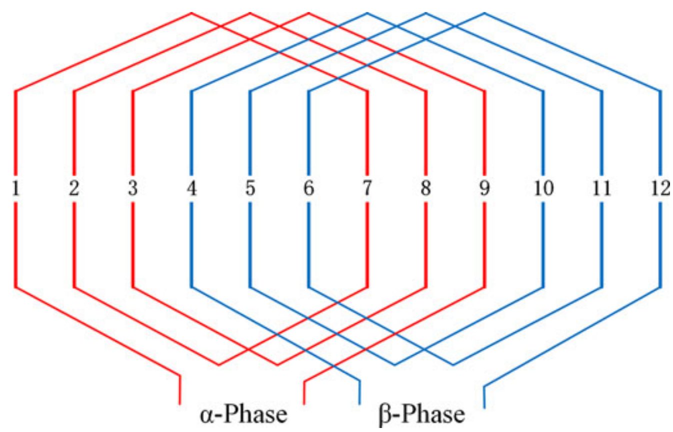

Fig. 4. Connection diagram of the two-phase field winding (one pair of poles).

Because the rotor winding structure, containing 12 poles, was kept unchanged, the stator should also have 12 poles after reconfiguration. And in order to reduce harmonic components of the rotating magnetic field generated by the two-phase ac excitation, distributed winding structure was selected for the two-phase field winding. Taking into account the structural strength of the stator and the flux density in stator teeth, 72-slot was selected for the stator, as illustrated in Fig. 3(b). The two-phase field winding had a spatial difference of 90° electrical angle, and the connection diagram is shown in Fig. 4 (only for one pair of poles). The number of coils of the two-phase field winding was chosen to make the two-phase ME have the same output capacity for the MG in the generation mode when excited by the same dc field current as the original single-phase ME. So in

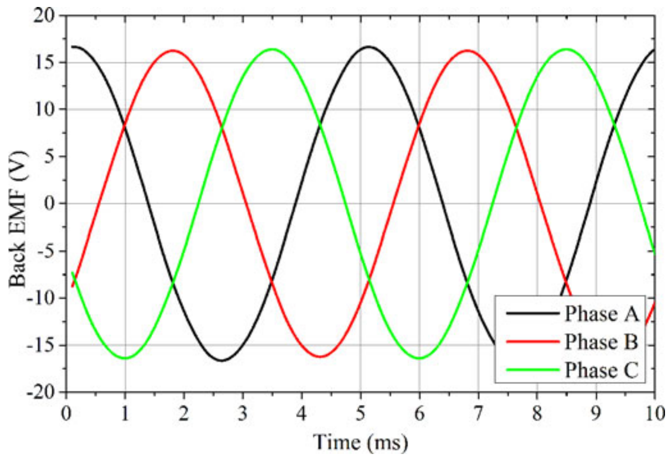

Fig. 5. Back EMF of the ME using two-phase ac excitation in the stationary status.

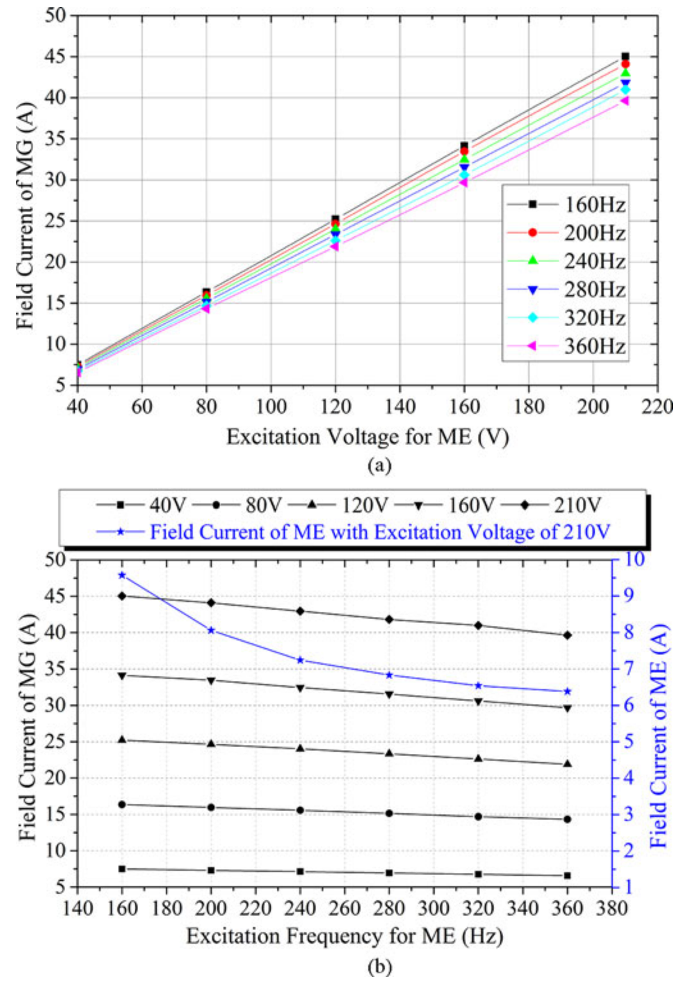

Fig. 6. Simulation results about the field currents of the MG and ME with different excitation voltages and frequencies for the proposed two-phase ME in the stationary status.

the generation mode, the original GCU can be still used and the characteristic of the MG will be the same as the original one.

Finite element analysis (FEA) model of this designed two-phase ME was built in MagNet software. In the stationary status, 5 A RMS two-phase ac was supplied to the two-phase field winding, and the back EMF of this two-phase ME was obtained and shown in Fig. 5. A good rotating magnetic field generated by the two-phase ac excitation can be inferred from the waveforms of the back EMF in Fig. 5.

A three-phase full-bridge diode rectifier circuit and a series of an inductor and a resistor, representing the rotating rectifier and the field winding of MG, respectively, were added and connected properly in the FEA model of the two-phase ME. In order to get the maximum field current for the MG in the stationary status, the relationship between the field current of the MG and the frequency and magnitude of the excitation voltage for the two-phase ME was FEA analyzed and obtained by supplying different excitation voltages to the two-phase ME and measuring the corresponding field currents of the MG. The FEA simulation results are shown in Fig. 6: Fig. 6(a) shows the relationship between the field currents of the MG and the excitation voltages for the ME under different excitation frequencies; Fig. 6(b) shows the relationship between the field currents of the MG and the excitation frequency for the ME under different excitation voltages, and the field currents of the ME under the excitation voltage of 210 V RMS with different frequencies are also provided in Fig. 6(b). It can be seen clearly from Fig. 6(a) that, in the stationary status and under the same frequency, the field current of the MG rose substantially linearly with the increase of the excitation voltage for the ME. So, in order to get the maximum field current for the MG, the excitation voltage for the two-phase ME should be as high as possible. In Fig. 6(b), as the frequency of the excitation voltage get smaller, the field current of the MG only increased a little, but the field currents of the two-phase ME increased a lot, which will cause a serious heating problem. The experimental tests for the field currents of the MG when different excitation types are used for the two-phase ME are carried out in Section V of this paper, and the same results can be obtained from the experimental results. So considering the field currents of the two-phase ME and the fact that 210 V RMS is the maximum two-phase ac (with a little overshoot) that the two-phase inverter can provide under the dc-bus voltage of 270 V (aircraft dc supply), we chose 210 V/200 Hz as the best excitation type for the proposed two-phase ME in the stationary status.

Early study on the original single-phase ME using single-phase ac excitation strategy showed that the best excitation type for the original single-phase ME in the stationary status was also 210 V/200 Hz. And in this situation, the maximum field current of the MG was only 21.7 A. Whereas when the proposed two-phase ME was excited by 210 V/200 Hz in the stationary status, the field current of the MG reached 43.7 A, as shown in Fig. 7. It can be seen clearly that the proposed two-phase ME can provide almost double field current for the MG as the original single-phase ME under the same condition.

The dc field current of the original single-phase ME was 6 A when the original three-stage wound-rotor generator operated in the rated generation mode. In order to compare the output capacity of the proposed two-phase ME and the original single-phase ME in the rated generation mode, both of these two MEs

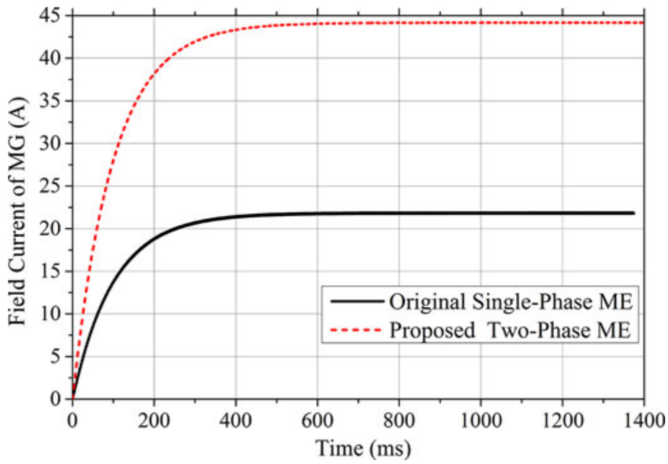

Fig. 7. Comparison of field currents of the MG supplied by the proposed two-phase ME and original single-phase ME in the stationary status.

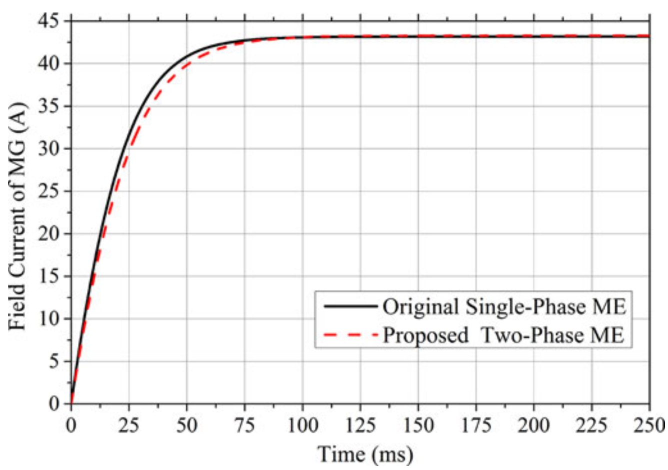

Fig. 8. Comparison of field currents of the MG supplied by the proposed two-phase ME and original single-phase ME in the rated generation mode.

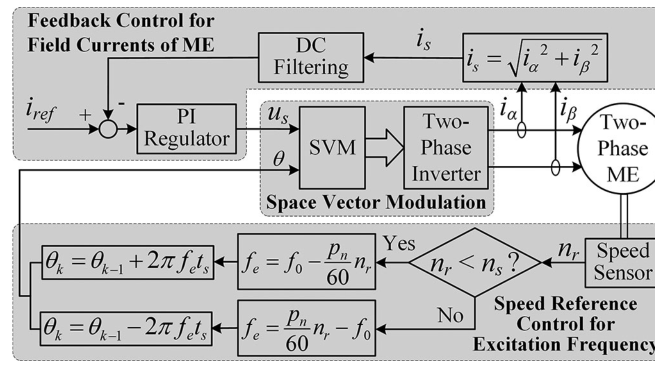

Fig. 9. Block diagram of the proposed excitation control method for the two-phase ME.

were excited by 6 A dc, and speeds were both set at 8000 r/min. FEA simulation results for the field currents of the MG are shown in Fig. 8, and it can be observed that, with the same dc field current, the proposed two-phase ME can provide almost the same field current for the MG as the original single-phase ME.

As a summary, on the premise of the same output characteristics in the generation mode, the proposed two-phase ME can supply almost double field current to the MG as the original single-phase ME in the beginning of the start-up process, which enables the MG to start with large load from the stationary status.

IV. Excitation Control Method for the Two-Phase ME

Constant field current for the MG during the start-up process can result in a relatively simple control algorithm for the start control of the MG. However, as the field winding of the MG is mounted in the rotor part, the field current of the MG cannot be measured directly when the starter/generator is rotating. As a result, closed-loop feedback control for the field current of the MG, which can keep the field current constant, cannot be achieved. Besides, if 210 V/200 Hz (the best excitation type in the stationary status) or other fixed excitation type is supplied to the two-phase ME during the whole start-up process, the field current of the MG cannot remain constant due to the change of the rotor speed.

As the load of the two-phase ME and rotating rectifier, the resistance of the field winding of the MG do not change very much during the start-up process. So constant dc voltage output of the rotating rectifier can make the field current of the MG remain approximately constant. To make the dc voltage output of the rotating rectifier constant during the start-up process, an easy and effective way is to keep the induced voltages in the armature winding of the ME "constant." (For ac and rotating variables in this paper, "constant" means the magnitude and frequency or speed is constant.)

Induced three-phase voltages in the armature winding of the two-phase ME mainly relies on the magnetic field intensity and relative speed of the rotor and magnetic field. Therefore, in the proposed excitation control method for the two-phase ME, the magnetic field intensity and relative speed of the rotor and magnetic field were kept constant to obtain "constant" induced voltages in the armature winding of the ME, and hence approximately constant dc field current for the MG, during the start-up process.

The block diagram of the proposed excitation control method for the two-phase ME is shown in Fig. 9. It contains feedback control for the field currents of ME, speed reference control for the excitation frequency, and space vector modulation (SVM) for the excitation voltage vector.

The feedback control for the field currents is used to keep the magnetic field intensity constant and it determines the magnitude of the excitation voltage vector for the ME (denoted by u_s). The speed reference control for the excitation frequency is aimed to make the relative speed constant, and it determines the phase angle of the excitation voltage vector (denoted by θ). Knowing the magnitude and phase angle of the excitation voltage vector, SVM method is used to control the four-leg two-phase inverter to drive the ME. Details about the SVM of the two-phase voltage vector using four-leg two-phase inverter can be seen in [20] and will not be repeated here. Details about feedback control for the field currents and speed reference control for the excitation frequency were analyzed later.

A. Feedback Control for Field Currents

Magnet field intensity is mainly related to the field currents of the two-phase ME when the armature currents are supposed to be constant. So closed-loop feedback control for field currents of the two-phase ME can make the magnetic field intensity inside the ME remain "constant."

For simpler implementation, the two-phase field currents were first processed as

$$i_s = \sqrt{i_\alpha^2 + i_\beta^2} \tag{1}$$

where i_α and i_β are the instantaneous values of the two-phase field currents. Because i_α and i_β had the same amplitude and a phase difference of 90°, after processing of (1), i_s was a constant value equaling the amplitude of i_α and i_β. After a dc filtering process, i_s was used as the measured current in the closed-loop feedback control for field currents of the two-phase ME.

The reference value of the field currents in this control loop can be decided by measuring and processing the two-phase currents response when supplying 210 V/200 Hz to the two-phase ME in the stationary status. With the error of the reference value and measured value, a PI regulator was used to determine the magnitude of the excitation voltage vector for the two-phase ME.

B. Speed Reference Control for Excitation Frequency

The rotating direction of the magnetic field generated by the two-phase field currents can be the same or opposite with that of the rotor. When they have the same rotating direction in the beginning, in order to keep the relative speed constant, the frequency of the field currents, corresponding to the speed of the rotating magnetic field, should become higher and higher as the rotor speed increases. In this situation, the magnitude of the excitation voltage for the two-phase ME should also increase to keep the amplitude of the two-phase field currents constant as a PI-control result. However, the excitation voltage supplied to the ME in the stationary status has already been chosen to be the highest value that the two-phase inverter can provide, so there is no chance to increase the excitation voltage as the rotor speed increases. Therefore, it is very difficult to make both the relative speed and magnetic field intensity constant during the start-up process when choosing the rotating direction of the magnetic field same as that of the rotor in the beginning.

Whereas when the magnetic field and the rotor have the opposite rotating directions in the beginning, in order to keep the relative speed constant, the frequency of the field currents should decrease as the rotor speed increases. In this situation, the excitation voltage for the ME will become smaller by the PI control for constant field currents, which is, of course, realizable. After the excitation frequency approaches zero as the rotor speed reaches a certain value, in order to keep the relative speed still constant, the rotating direction of the magnetic field should be the same as that of the rotor, and the excitation frequency should increase as the rotor speed gets higher. As already analyzed before, in this situation, the excitation voltage for the ME will also increase. If the excitation voltage has not reached its maximum value when the engine accelerates to its self-sustain speed, the starting mode just finishes and switches to the generation mode. However, if the excitation voltage has reached its maximum value before the self-sustain speed, the excitation voltage cannot go higher as the rotor speed keeps increasing. A simple and efficient way to continue supplying excitation to the two-phase ME is just keeping the magnitude and frequency of the excitation voltage constant, which cannot guarantee the constant field current for the MG any more. Fortunately, in general application, the engine usually gets its self-sustain speed before the excitation voltage reaches its maximum value, and this paper will focus on this situation.

To state clearly, the rotating direction of the rotor is set to be clockwise. The stage before the excitation frequency decreases to 0 is denoted as "the first stage," and the stage after that is denoted as "the second stage." So in the first stage, the rotating direction of the magnetic field generated by two-phase field currents is anticlockwise, and in the second stage, the rotating direction is clockwise. When the rotating direction is clockwise, the speed is marked as a positive value, otherwise a negative value.

The relationship between the frequency of the two-phase field currents and the speed of the rotating magnetic field in different stages can be written as

$$n_{fm} = \begin{cases} -\dfrac{60 f_e}{p_n}, & \text{in the first stage} \\ \dfrac{60 f_e}{p_n}, & \text{in the second stage} \end{cases} \tag{2}$$

where f_e represents the excitation frequency, n_{fm} the rotating speed of the magnetic field, and p_n is the number of pole pairs of the two phase ME.

If the rotor speed is denoted by n_r, then the relative speed between the rotor and magnetic field, denoted by n_w, can be calculated as

$$n_w = n_r - n_{fm}. \tag{3}$$

In the stationary status, the rotor speed is zero, and the frequency of the field currents is denoted by f_0. Then the relative speed is calculated as

$$n_w = 0 - n_{fm} = 0 - \left(-\frac{60 f_0}{p_n}\right) = \frac{60 f_0}{p_n}. \tag{4}$$

Therefore, during the start-up process, the relative speed should be kept constant at $60 f_0 / p_n$.

Substituting (2) and (4) into (3), one can calculate the frequency of the two-phase field currents from the rotor speed in different stages as

$$f_e = \begin{cases} f_0 - \dfrac{p_n}{60} n_r, & \text{in the first stage} \\ \dfrac{p_n}{60} n_r - f_0, & \text{in the second stage.} \end{cases} \tag{5}$$

When the frequency of the two-phase field currents decreases to 0, the switch from the first stage to the second stage occurs.

So, by setting the frequency to 0 in (5), one can obtain the switch speed, denoted by n_s, as

$$n_s = \frac{60 f_0}{p_n}. \tag{6}$$

In order to generate anti-clockwise-rotating magnetic field in the first stage, the rotation of the excitation voltage vector for the ME should also be anticlockwise. So as for the clockwise-rotating magnetic field in the second stage. As a result, the phase angle of the excitation voltage vector should increase in the first stage and decrease in the second stage.

The frequency of the excitation voltage for the ME is the same as that of the field current. And the phase angle of the excitation voltage vector can be calculated by the integral of the angular frequency. In order to make the voltage vector rotate anticlockwise in the first stage and clockwise in the second stage, the phase angle of the voltage vector should be calculated using different equations in different stages as

$$\theta = \begin{cases} \int 2\pi f_e(n_r)dt, & \text{in the first stage} \\ \int -2\pi f_e(n_r)dt, & \text{in the second stage.} \end{cases} \tag{7}$$

In digital implementation, the integral of the angular frequency can be converted into discrete expression as

$$\theta_k = \begin{cases} \theta_{k-1} + 2\pi f_e t_s, & \text{in the first stage} \\ \theta_{k-1} - 2\pi f_e t_s, & \text{in the second stage} \end{cases} \tag{8}$$

where θ_k is the phase angle of the current voltage vector, θ_{k-1} is the phase angle in the previous calculating period, and t_s is the calculating period time.

As a summary for the speed reference control for the excitation frequency, the rotor speed is obtained from the speed sensor first and then compared with the switch speed. If the rotor speed is smaller than the switch speed, the ME is in the first stage. Then the excitation frequency is calculated by $f_e = f_0 - (p_n/60)n_r$, and the phase angle of the excitation voltage vector is calculated by $\theta_k = \theta_{k-1} + 2\pi f_e t_s$. If the rotor speed is larger than the switch speed, the ME is in the second stage. Then the excitation frequency is calculated by $f_e = (p_n/60)n_r - f_0$, and the phase angle of the excitation voltage vector is calculated by $\theta_k = \theta_{k-1} - 2\pi f_e t_s$.

C. Simulation Results

The proposed two-phase ME model and excitation control system were built in MATLAB/Simulink, and the two-phase ME model was connected with a resistance in series with a inductance, representing the field winding of the MG, through a three-phase diode rectifier.

The start-up process of the starter/generator in this research was from 0 to 3500 r/min. In the simulation model, the excitation type for the two-phase ME in the stationary status was chosen as 210 V/200 Hz, and the rotor speed increased from 0 at 0.5 s to 3500 r/min at 4 s, imitating the start-up process. The proposed excitation control method for the two-phase ME was used in the simulation. The field currents of the MG and two-phase ME were observed and shown in Fig. 10. One can see that during the start-up process, the field current of the MG remained constant at 43 A.

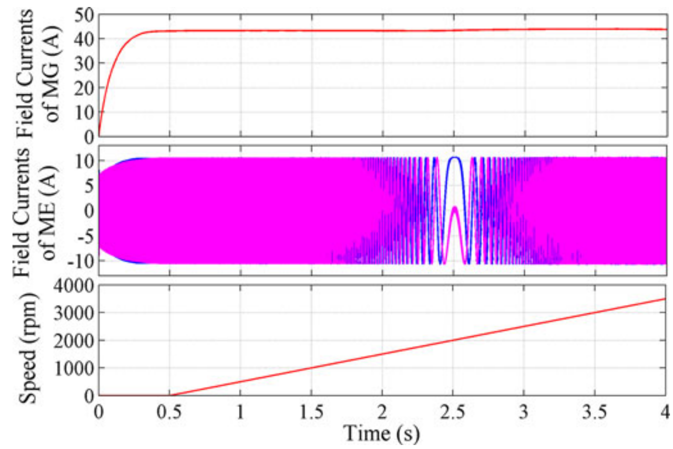

Fig. 10. Simulated field currents of the MG and the two-phase ME during the start-up process.

V. Experimental Results

A prototype of the proposed two-phase ME was manufactured based on an original single-phase ME of a traditional brushless wound-rotor generator. And a two-phase ME controller was established, including a four-leg, two-phase inverter and TMS320X2812-based DSP control module. Then static tests and rotating tests were carried out to verify the feasibility and advantages of the proposed two-phase ME and excitation control method.

A. Statics Tests

When the starter/generator was stationary, by extending the field winding of the MG with a long wire and leading it out, the field current of the MG can be measured directly. Different excitation types were supplied to the two-phase ME in the stationary status, and field currents of the MG and ME were measured and shown in Fig. 11. A good agreement can be noticed between the FEA simulation results [see Fig. 6(b)] and experimental tests results. So, same as the simulation result, 210 V/200 Hz was chosen as the best excitation type for the two-phase ME prototype in the stationary status.

The same static tests were also implemented for the original single-phase ME using single-phase ac excitation, and the results showed that the field current of the MG also rose substantially linearly with the increase of the single-phase voltage magnitude and changed weakly with the change of frequency. Static tests results of the original single-phase ME and the proposed two-phase ME under the same frequency of 200 Hz are illustrated in Fig. 12. One can see clearly that under the same excitation voltage, the proposed two-phase ME can provide almost double field current for the MG as the original single-phase ME. The test waveforms of the field currents of the ME and MG when the proposed two-phase ME and original single-phase ME were both excited by 210 V/200 Hz are shown in Fig. 13.

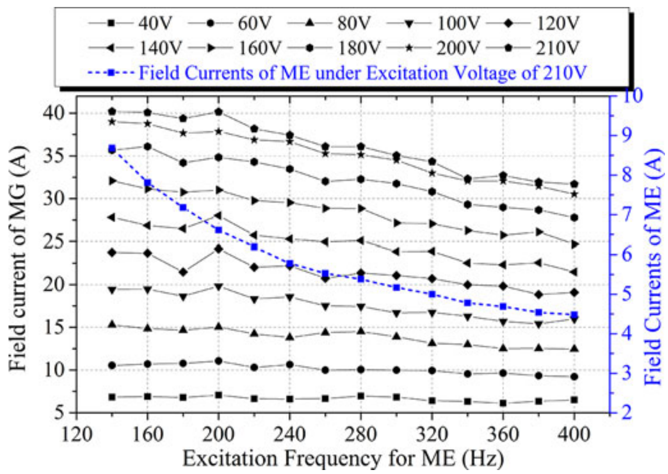

Fig. 11. Experimental results about the field currents of the MG and ME with different excitation voltages and frequencies for the two-phase ME prototype in the stationary status.

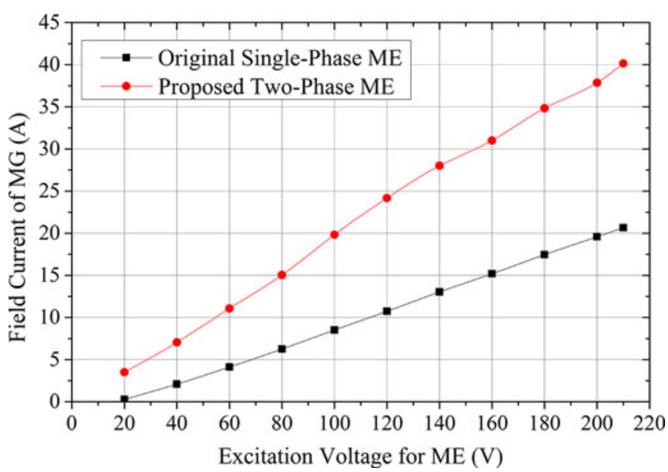

Fig. 12. Comparison of field currents of the MG supplied by the original single-phase ME and proposed two-phase ME under excitation frequency of 200 Hz in the stationary status.

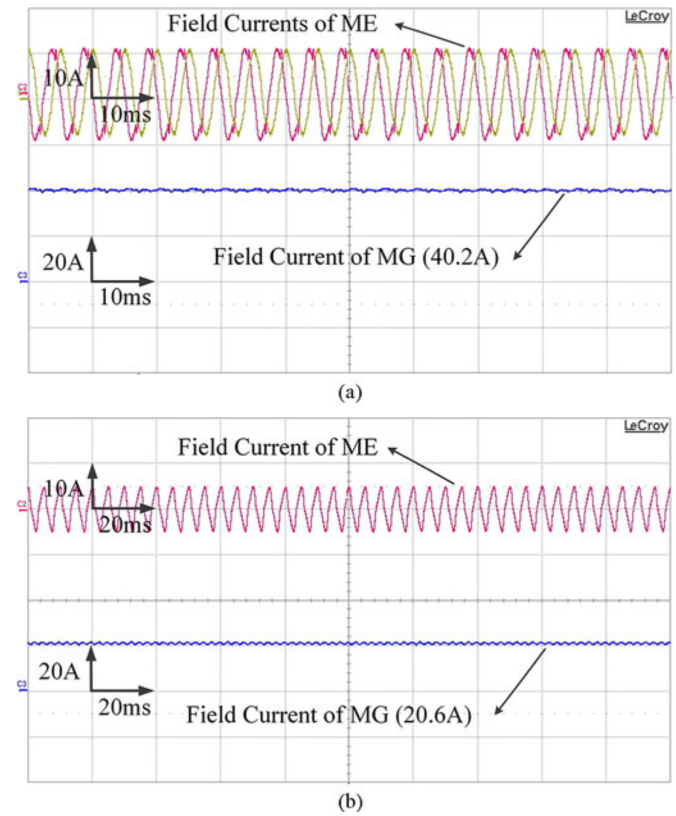

Fig. 13. Field currents of the ME and MG in the static tests: (a) proposed two-phase ME and (b) original single-phase ME.

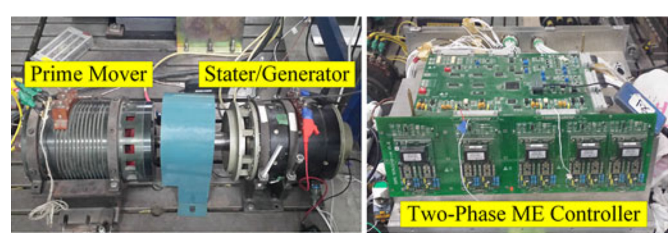

Fig. 14. Test platform for the back-EMF measurement.

B. Rotating Tests

When the rotor rotates, the measurement method for the field current of the MG in the static test cannot be used any more as the field winding of the MG also rotates. As a result, the field current of the MG in the rotating tests cannot be measured directly. However, the back EMF of the MG contains the information of the field current at certain speeds, so the back EMF of the MG can be measured and analyzed to verify the constant field current for the MG during the start-up process when the proposed excitation control method was used for the two-phase ME.

In the rotating tests, the armature winding of the MG was disconnected, and a prime motor was used to drag the wound-rotor starter/generator to accelerate to the self-sustain speed, imitating the start-up process. During the start-up process, the two-phase ME was driven by the controller using the proposed excitation control method, and the back EMFs of the MG were measured at different speeds. If the field current of the MG remains constant during the start-up process, the back EMF will rise linearly with the increase of speed. The test platform for the back-EMF measurement is shown in Fig. 14.

From the simulation and static test results, the best excitation type for the two-phase ME prototype in the stationary status was 210 V/200 Hz. And in this situation, the field current of the ME was 6.6A RMS. So during the start-up process, the field current of the ME was kept constant at 6.6A RMS, and the proposed excitation control method for the ME was used. To imitate the start-up process, the rotating tests were carried out from standstill to 3500 r/min. The measured back EMFs of the MG at different speeds and the linear fitting result are shown in Fig. 15. It can be seen clearly that the back EMF rose linearly with the increase of speed, which reflected that the field current of the MG was constant during the start-up process.

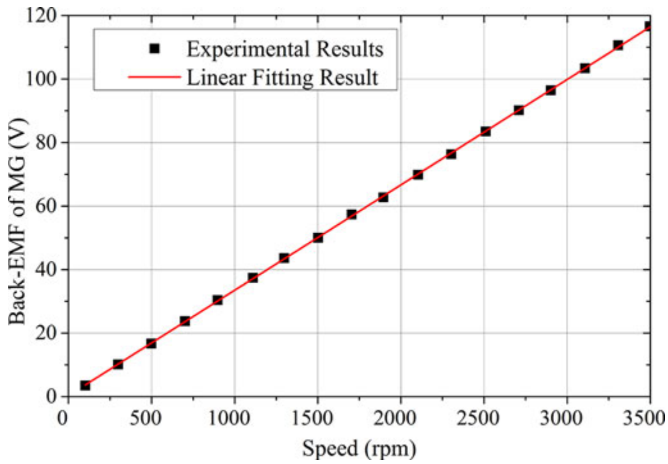

Fig. 15. Measured back EMFs of the MG at different speeds and the linear fitting result.

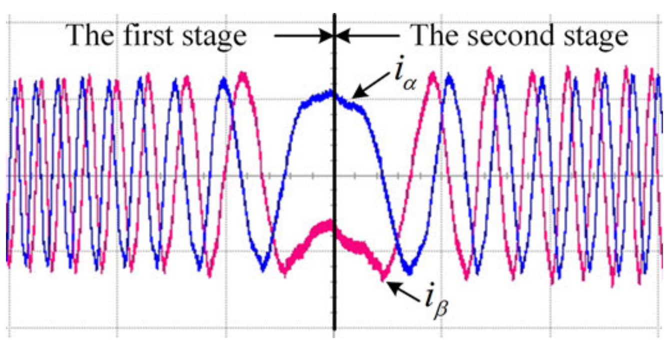

Fig. 16. Waveforms of the two-phase field currents of the ME around the switch speed.

The waveforms of the two-phase field currents of the ME from the first stage to the second stage are shown in Fig. 16. One can see that, in the first stage, phase α current lead phase β current, and in the second stage, phase β current lead phase α current. Also, the switch from the first stage to the second stage was smooth.

VI. Conclusion

A novel two-phase brushless ME and excitation control method for the aircraft three-stage wound-rotor synchronous starter/generator have been presented in this paper. The two-phase ME was excited by two-phase ac in the starting mode. And in the generation mode, the two-phase ME was converted into traditional single-phase ME and excited by dc. The design of a two-phase ME was carried out based on an original single-phase ME of an existing wound-rotor synchronous generator. Then the characteristic of the designed two-phase ME was analyzed using two-dimensional (2-D) FEA method. The excitation control method for the two-phase ME was proposed in order to make the field current of the MG keep constant during the start-up process. This excitation control method contained the feedback control for the two-phase field currents and speed reference control for the excitation frequency. A prototype of the proposed two-phase ME was manufactured and a two-phase ME controller was established. Then static tests and rotating tests on the wound-rotor synchronous starter/generator with this proposed two-phase ME were carried out. Simulation and experimental results have verified that, on the premise of the same output characteristics in the generation mode, two-phase ME can supply almost double field current for the MG as the original single-phase ME in the stationary status. And the excitation control method for the two-phase ME can make the field current of the MG keep constant during the start-up process.

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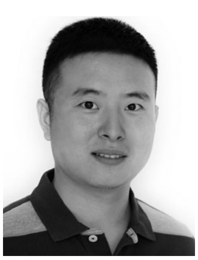

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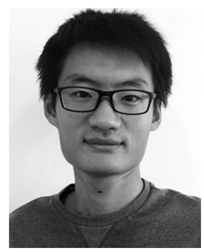

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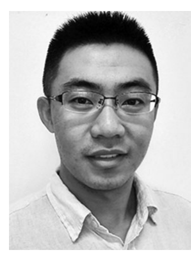

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