Overview and Development of Variable Frequency AC Generators for More Electric Aircraft Generation System

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Abstract: With the development of more electric aircraft (MEA), higher demands for electrical energy are put forward in generation systems. Compared to constant frequency AC (CFAC) generation systems, the constant speed drive (CSD) is eliminated and integrated starter/generator (SG) can be realized in variable frequency AC (VFAC) generation systems. In this paper, an overview of VFAC generators for safety-critical aircraft applications is presented, with a particular focus on the key features and requirements of candidate generators and the starting control strategies. Wound rotor synchronous machines (WRSMs) are typical generators used in VFAC generation systems so far. Meanwhile, hybrid excitation synchronous machines (HESMs) and cage-type induction machines are promising candidates for VFAC generation systems. The generation operation of WRSM is relatively mature, however, the SG technology of WRSM is still full of challenges. As one of the most important issues, the starting excitation methods of WRSM are summarized. An HESM-based VFAC SG system is proposed and developed in this paper. The experimental results show that the starting mode, transition mode and generating mode of the VFAC SG system are realized. The continuous progress of VFAC generation system makes great contributions to the realization of MEA.

Keywords: Brushless starter/generator, generation system, hybrid excitation synchronous machine, more electric aircraft, variable frequency AC generator, wound rotor synchronous machine.

1 Introduction

Up to now, the power of conventional aircraft, initially generated by fuel, can be divided into two parts. The main part, namely primary power, is converted to propulsive power by the engine; the other critical part, namely secondary power, has four different integrated energy vectors: mechanical power, hydraulic power, pneumatic power and electrical power[1]. The secondary power is distributed around the engine and airframe to supply all the on-board systems, for example landing gear, braking and flight control, air conditioning, pressurization, de-icing and avionics, etc.[2]. On conventional aircraft, either civil or military, the secondary power system has complex architecture, and is distributed by complex power distribution nets aboard with an appropriate redundancy system. What's more, interactions among different categories of equipment reduce the efficiency of the whole system. As for pneumatic and hydraulic systems, they also have a risk of leaks which are generally difficult to be located and accessed[3].

In order to reduce the complexity of conventional aircraft, and to improve efficiency and reliability, aircraft manufacturers are laying greater emphasis on the application of technologies that can lower both the overall costs and fuel consumption. Furthermore, future legislation with respect to climate change demands a radical change on the entire aircraft, as it is not sufficient to optimize the current aircraft sub-systems and components individually to achieve these goals[4]. The trend is to use the electrical power for extracting and distributing the non-propulsive powers, defined as More Electric Aircraft (MEA). The MEA concept is based on utllizing electric power to drive aircraft subsystems which historically have been driven by a combination of hydraulic, electric, pneumatic, and mechanical power transfer systems[5-6]. The key driver behind the development of MEA, is to reduce fuel burn and air pollution[7].

With the increasing electrical power capacity in an MEA, it is possible to use the original electrical machine to start the engine, namely starter/generator (SG) system. In starting mode, the electrical machine operates as a starter to start the engine, where the customized air turbine starter(ATS) can be removed. In generating mode, the electrical machine operates as a generator to supply electrical energy. The weight and reliability of generation system are improved effectively by the SG system. Compared to constant frequency AC(CFAC) generation systems, variable frequency AC(VFAC) generation systems are perferred since the constant speed drive(CSD) is eliminated and the SG system is likely to be realized. VFAC generation systems have been implemented in B787 Dreamline with SGs to replace intergrated drive generators (IDGs).

This paper presents an overview of VFAC generators for safety-critical aircraft applications,

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with a particular focus on the discussion of candidate generators and the starting control strategies. Wound rotor synchronous machines (WRSMs) are the most widely used generators in AC generation systems for aircraft applications so far. Meanwhile, hybrid excitation synchronous machines (HESMs) and cage-type induction machines (IMs) also enjoy benefits when applied in VFAC generation systems if the technical barriers are overcome. A new HESM-based VFAC SG system is proposed and investigated.

2 Development, features and applications of VFAC generation systems

2.1 From CFAC to VFAC generation systems

With significant development of aircraft in the 20th century, the generation system has made great advancements and tremendous progress[8]. The generation system has been developed through low voltage DC (LVDC), CFAC, VFAC and high voltage DC(HVDC) generation systems. The CFAC generation systems are widely used in aircrafts. As can be seen in Fig.1(a), the constant speed constant frequency (CSCF) generation system includes a CSD and a generator. Another kind of CSCF generation system illustrated in Fig.1(b) is based on the IDG which consists of the CSD and the generator. As the development of electronics power converter, the variable speed constant frequency (VSCF) comes true, as shown in Fig.1(c).

The CSCF generation system with a CSD, which was introduced by Sundstrand in 1946, is the most popular power system and its commercial operation is extensive, for instance, the Boeing B777 and Airbus A340[9]. However, the VSCF generation systems with cycloconverter or DC-link are mainly used in several military aircrafts including the F-18, AV-8B, TR-1, and F-117, just to name a few[10].

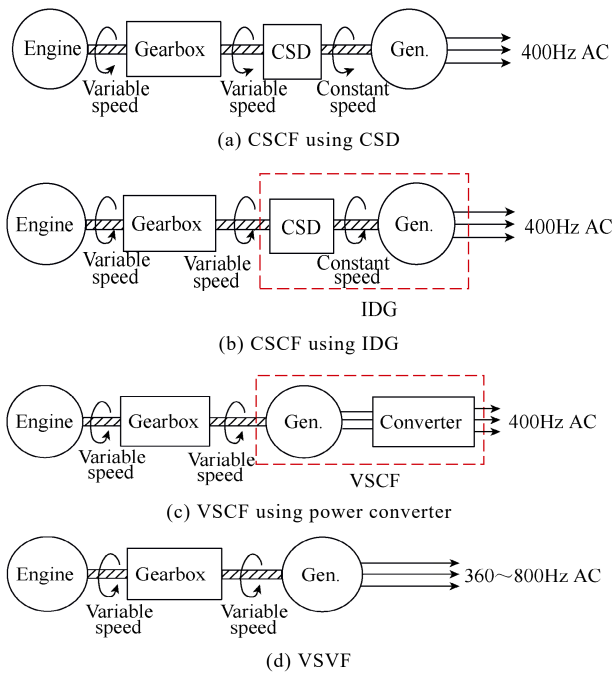


Fig.1 AC generation system

However, a CSD, which is a complex hydro-mechanical unit, has low energy conversion efficiency when transforming power from engine to generator. In addition, the CSD is not inherently highly reliable[11]. What's more, as the CSCF generation system with CSD cannot constitute an SG system, there is no choice but to develop ATS, which results in a complex, heavy and large engine.

Over the past 50 years, although the reliability and power density of CFAC generation systems have been increased, considerable interest is still kept in VFAC generation systems without CSD, as shown in Fig.1(d).

2.2 Development, features and applications of VFAC generation systems

In order to further improve energy conversion efficiency, reliability and power density by eliminating the CSD and to constitute SG, the variable frequency generators(VFGs) are preferred, as shown in Fig.1(d), which is directly coupled to the engine by a gearbox with constant gear ratio. Due to the speed variations of engine over approximately 2:1 range, the output electric frequency of VFG may typically range from 360Hz to 800Hz.

Actually, early in 1940's, VFAC generation systems had been implemented on some military aircrafts, as like F-104, F-5A, for which the electric frequency is varied from 320Hz to 480Hz. It is called 115V narrow VFAC generation system with a narrow speed range of engine. The VFAC power supplies electric energy to galley heaters, deicing equipment, lighting and avionics, which are frequency insensitive loads.

With the increasing demand of electrical power and the continuous development of power electronics, an advanced VFAC generation system, namely wild VFAC with frequency varied between 360 and 800Hz, has been favored by aircraft designers, as on the A380 and B787, for which the voltage standard is 230/400VAC or 115/200VAC[12-14]. This VFAC generator and its associated generation system have some main features as follows:

- Compared to CFAC generation systems, the weight and reliability of VFAC generation systems are improved for CSD is eliminated.
- The VFG operates easily as a starter to accelerate main engine to self-sustaining speed. Eliminating the main engine starters, such as conventional DC starter and ATS, is also a trend[15].
- Since the design point of the VFG with fixed power must be in the lowest frequency, a tradeoff should be taken between high magnetic flux with respect to the lowest frequency and high mechanical strength at the highest speed.
- Due to the frequency variations of VFGs, the parallel generation system is impossible to implement. The rated power of VFG should be improved.
- The AC impedance of VFGs is relatively larger at high speed than that of constant frequency

generators, resulting in the voltage drop and unbalance value increasing.

- High power auto transformer rectifier units (ATRUs) and DC/AC inverters are needed for conditioned AC power driven equipment, such as braking and hydraulic pumps motors[16-17].
- The parameters of VFG, such as voltage and frequency, vary greatly with wide speed range and load condition. As a result, it will be added with extra burden and difficulty to develop a generator control unit (GCU), especially a voltage regulator (VR). Thus, the coordination control of VFG and GCU should be carefully designed.
- Overvoltage protection unit (OPU) is important for the VFAC generation system, especially at the highest speed. A voltage magnitude of 360V can be developed in highest speed, since VFAC generation systems suffer from speed variations over a 2:1 range. For CFAC generation systems, however, the voltage is not exceed to 180V generally[18].

As mentioned above, the architecture of VFAC generator and its associated generation system are significantly different from CFAC generation system.

The A380 is the first application of VFAC generation systems on large commercial aircrafts. There are four 120/150kVA VF generators with the conventional rating voltage 115/200Vrms and normal speed range varied from 11,100r/min to 23,100r/min, resulting in variable frequency changed from 370Hz to 770Hz[17]. In addition, two 120kVA constant frequency generators (nominal 400Hz), are both driven by auxiliary power unit (APU). What's more, four external power connections are used in ground. However, the bleed air from the APU still exists in environment control system and main engine start.

The B787, the first aircraft using VFAC SG system as a key technology in MEA, conforms to most of the characteristics of the MEA electrical system. The characteristics of the main power generation systems are:

- Four 250kVA variable frequency SGs with three-phase, 230VAC, 360~800Hz driven by two main engines
- Two 225kVA constant frequency SGs with three-phase, 230VAC, 400Hz driven by the APU
- Four external power connections for ground power
- Four 150kW ATRUs converting 230VAC power to ±270VDC power for large motors with adjusted speed
- Two 90kVA auto transformer units(ATUs) converting 230VAC to 115VAC for conventional sub-systems
- Four transformer rectifier units(TRUs) converting 230VAC power to 28VDC power with 240Amps each channel

Furthermore, it's worth noting that B787 adopts a bleedless system by a set of compressors utilizing electric power, which is simpler and more efficient than bleed air system[19].

3 State-of-the-art and key technologies of VFAC generators for MEA

With the development of MEA, higher demands for generators are put forward in generation systems. In order to make MEA more competitive with existing systems in terms of weight and reliability, the industry has seen the start of fundamental developments in the generation of electricity, especially the generator technology[20]. The generator should satisfy the key requirements for VFAC generation systems, which are described as follows:

- High reliability (integrated rotating rectifier assembly, high mechanical strength and robust rotor).
- High efficiency, especially at low speed.
- High power quality.
- High voltage to reduce the weight of power cables and large capacity to supply electrical energy in MEA .
- High power density with efficient oil-cooled system.
- Preferred SG integrating the starter and generator into one machine to simplify the generation system and the accessory gearbox of engine.

Different generators should be selected and optimized to satisfy the key requirements. WRSM is widely used in aircraft generation systems for its mature generator technology. Meanwhile, HESM and cage-type IM are the promising candidates for VFAC generation systems.

3.1 Wound rotor synchronous machine

WRSM is a compact and integrated unit which includes three separate generators, namely, permanent magnet generator (PMG), main exciter (ME), and main generator (MG) mounted on one shaft. WRSM can be used as a generator which is connected to consumers and keep a constant voltage by a GCU. It is utilized as a generator in A380. Furthermore, WRSM may be used as a SG which is powered in starting mode by a high power DC/AC converter and starts main engine in the ground or in the air, which has been realized in B787.

WRSM mainly operates in generating mode for powering electrical loads on-board. The PMG supplies DC field current to ME stator winding via a buck converter. As shown in Fig.2, a chopper controlled by GCU is used to control the input of ME stator winding. With the rotating of the rotor, the ME's rotor windings generate AC current which is rectified by a rotating rectifier into the field winding of MG. Finally, three phase AC current of MG stator windings can be provided to an AC load. It can be seen that the MG field current I_f is regulated by I_{ef} directly. In order to keep constant output voltage, the field current I_{ef} must be regulated by GCU to compensate the frequency and load variations.

The ephemeral but important function of WRSM is to produce motive power on the shaft in starting mode. When WRSM is in stationary mode or at low speed, AC power should be supplied to the ME stator

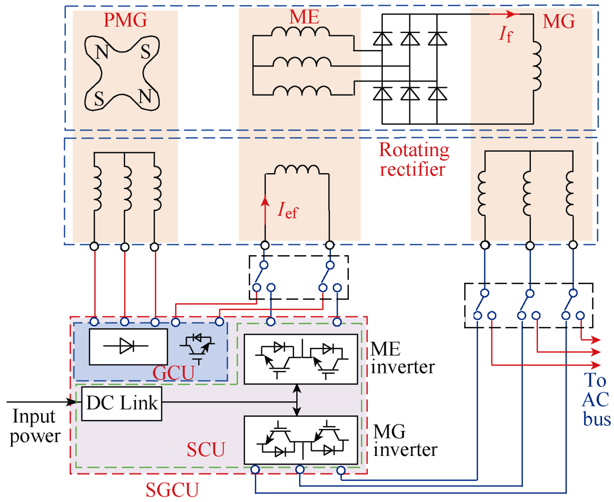


Fig.2 SG system diagram block of WRSM

winding via a ME inverter, as shown in Fig.3. As a result, DC current I_f produces a static magnetic field. Meanwhile, variable-frequency variable-voltage AC power generated by a MG inverter is supplied to MG stator windings. The 3-phase conditioned AC power creates a rotating magnetic field in the air gap of MG. The static magnetic field of the rotor of MG follows the rotating magnetic field of the stator. Hence, the rotor turns and supplies adequate mechanical torque to start the engine.

However, the starting control strategy determines the implementation of WRSM working as a SG which is difficult to realize, especially in the excitation method of ME stator winding. When WRSM is in stationary or at low speed, the sufficient field current I_f of MG is difficult to obtain.

Many excitation methods or ME structures have been developed. In [21-24], a single-phase ac excitation of ME has been proved to furnish effective field current for SG. As shown in Fig.3, during the starting mode, the single-phase AC field current flows into ME stator winding. Whether ME rotor rotates or not, 3-phase AC voltage is induced in the ME rotor armature windings due to the oscillating magnetic field effect. The three-phase AC current is rectified by rotating rectifier to DC current I_f and fed to MG field winding. This is the simplest excitation technology, but the redesign of ME field winding is necessary.

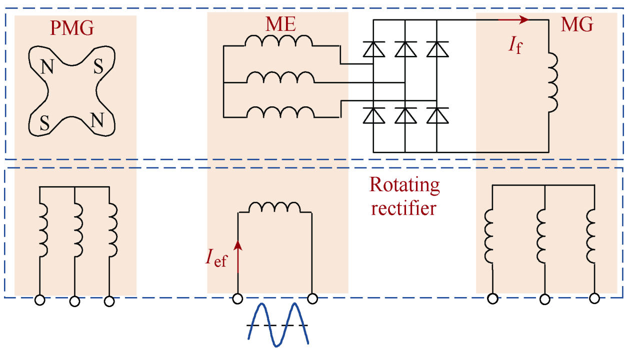


Fig.3 Schematic diagram of the single-phase AC excitation method

In [25], a two-phase AC excitation method is proposed to solve the problem of the excitation of SG, as shown in Fig.4. Two-phase symmetrical windings, which have phase difference of 90 electrical degrees, is employed as the field winding of ME. In starting mode, the two-phase windings connected to a two-phase inverter generate a rotating magnetic field, which is superior to the single-phase oscillating magnetic field and contributes to the starting performance.

In [26-28], a typical three-phase excitation strategy is put forward to achieve main engine starting successfully. As shown in Fig.5, symmetrical three-phase excitation windings are the combination of the AC excitation in starting mode and DC excitation in generating mode. In starting mode, the symmetrical three-phase excitation windings can provide a rotating magnetic field. In generating mode, the symmetrical three-phase excitation windings provide the DC field current of ME.

In addition, PMG is utilized to assist the APU or main engine's start-up[29].

Some ideas, which combine the original ME stator winding with another set of excitation winding, are discussed[30-32]. Both a multiple phase AC excitation winding and a distributed DC field winding are mounted on ME stator. In starting mode, the AC excitation winding receives excitation power from an external power source. In generating mode, the DC field winding is used for regulating the voltage of MG, while the AC excitation winding doesn't work.

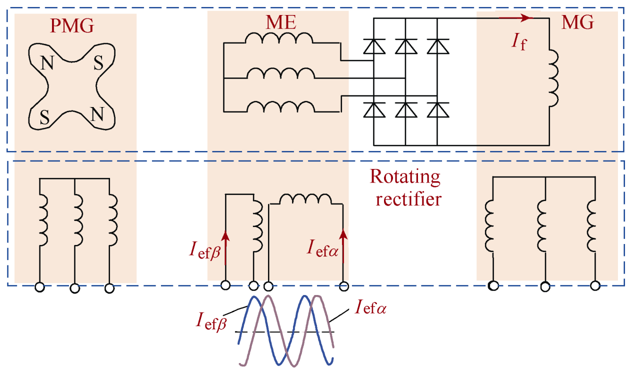


Fig.4 Schematic diagram of the two-phase AC excitation method

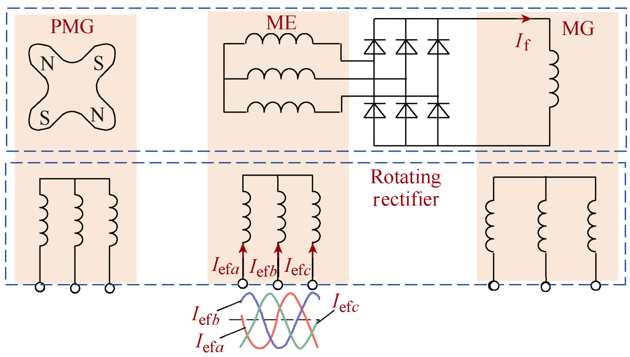


Fig.5 Schematic diagram of three-phase AC excitation method

Furthermore, in [33], the ME stator winding, which is divided into a number of sections with a plurality of power switches electrically coupled, is proposed. The ME stator winding is in series with one another in generating mode, and in parallel with one another in starting mode. The reconfiguration of ME stator windings is realized by the function of power switches.

3.2 Cage-type induction machine

The cage-type IM is another potential machine for VFAC generation systems due to inherent brushless construction, low maintenance demands, good overload protection capability, etc. However, the excitation regulation is difficult and the performance with the variations of load and speed is poor in IM generation systems.

Recently, the control strategies and the optimal schemes of cage-type IM are mainly studied[34-35]. In order to provide variable reactive power and facilitate the control of output voltage, many control schemes have been proposed in cage-type IM generation systems with the advanced static power converters. Connecting a DC-AC voltage-source inverter in parallel or series with the loads to provide variable excitation is one of the most effective schemes[36]. However, harmonics are injected into the load current and induced the output voltage ripples in the scheme.

A dual stator-winding induction generator(DWIG) with a static excitation converter (SEC) is proposed in [37]. The output voltage can be regulated effectively and the harmonics arising from power electronics switches can be reduced or eliminated in the DWIG. Fig.6 shows the diagram of the DWIG VFAC generating system, which is proposed in [38]. It has two sets of stator windings. One is the power winding, which is used to generate electrical energy, and the other is the control winding, which is connected to the SEC to regulate the excitation current.

Cage-type IM can operate as a general induction motor to start the engine. The starting strategy of IM-based SG systems is simple and easy to implement.

3.3 Hybrid excitation synchronous machine

HESM is of growing interest due to the prominent controllability of air-gap flux. Since the air-gap flux is produced by the permanent magnets and DC field windings, it can be weakened or strengthened by regulating the magnitude and direction of field current[39-41]. For the superiority regarding high power density and simple brushless structure, HESM

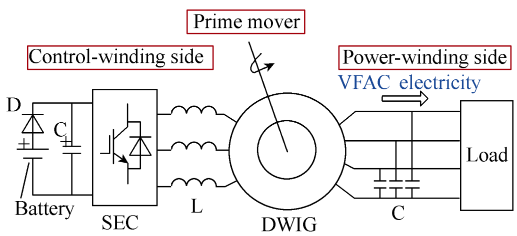


Fig.6 Diagram of the DWIG VFAC generator system

possesses considerable applicability for VFAC generation systems by integrating the advantages of permanent magnet synchronous machine (PMSM) and WRSM.

An HESM-based HVDC system for aircraft applications has been studied and proposed in [42]. The generation system is an HVDC system, including an HESM and a diode rectifier. The HESM has autonomous operation capabilities due to the permanent magnets. The constant output voltage can be achieved reliably by avoiding a rotating rectifier in the HESM.

4 Implementation of HESM-based VFAC SG system

To meet the requirements of VFAC systems, a new HESM-based VFAC SG system is proposed and developed in this paper.

4.1 HESM with magnetic shunting rotor

Axial magnetic flux through stator core and housing is utilized to regulate the main air gap flux in most HESMs, which distorts the stator magnetic field and back EMF. The distorted back EMF is undesirable in AC generation systems. To overcome the problem above, an HESM with magnetic shunting rotor is proposed and optimized in [43-45]. Fig.7 shows the structure of the HESM with magnetic shunting rotor. It is developed on the basis of conventional interior PMSM. A simple brushless excitation structure is realized by the fixed magnetic bridge. In order to improve power density, the excitation structure is optimized by built-in static magnetic bridge[46].

Fig.8 shows the flux paths of the HESM with magnetic shunting rotor. The PM axial flux can be readily regulated by field current. Correspondingly, the radial magnetic flux is changed with field current. From the flux paths in Fig.8, it can be seen that the air gap flux is weakened by the axial flux path and the axial flux path is saturated when the field current is zero. So the air gap flux can be weakened hardly with

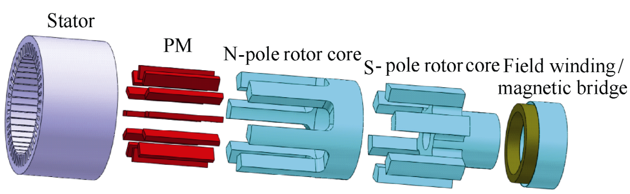


Fig.7 Configuration of the HESM with magnetic shunting rotor

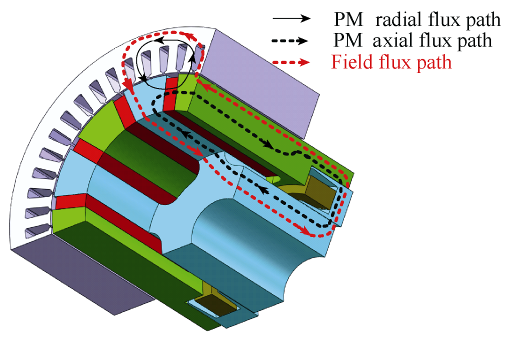


Fig.8 Flux paths in the HESM with magnetic shunting rotor

negative field current. Therefore, the optimized flux regulation capability is obtained by applying zero to maximum positive field current. The back EMF of the HESM is sinusoidal for no magnetic field distortion in the stator, which is essential to VFAC SG systems. Constant output voltage in the whole operating region can be realized by regulating field current.

In order to provide the axial flux path of the HESM, the solid rotor is utilized, which causes the serious rotor eddy current loss. The stator slot width and air gap are analyzed to reduce the solid rotor eddy current loss. The heating power generated by the field windings and some of that produced by the rotor outside surface transfers to the magnetic bridge and is taken away by the external water-cooled jacket.

4.2 HESM-based VFAC SG system

As previously mentioned, the simple brushless structure, comparatively high power density and sinusoidal back EMF make the HESM with magnetic shunting rotor become a promising candidate for VFAC generation systems. Compared to WRSM-based VFAC SG system, the starting control strategy of the HESM-based VFAC SG system is simple and easy to implement.

Fig.9 shows the diagram of the HESM-based VFAC SG system. The SG system consists of an HESM, a main power converter, an excitation power converter, an AC contactor, a SG controller, etc. In starting mode, the DC power source can supply electrical energy to the main power converter and the excitation power converter simultaneously. The DC power source can be provided by ATRU which is connected to the ground power unit or the APU generation system. The AC contactor acts in transition mode. The operation of the HESM-based VFAC SG system can be divided into starting, transition and generating modes. Control strategies are discussed separately in different operating modes.

In starting mode, K_S and K_E are closed, K_G is open, and the AC contactor is connected to the main power converter. The DC power source supplies the starting power and excitation power. The SG controller drives the main power converter and the excitation power converter by detecting the armature current, field current and position signal. A proper starting control strategy is critical to the engine start.

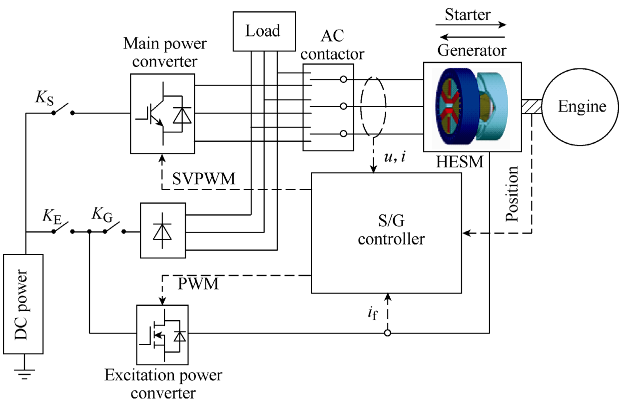


Fig.9 Diagram of the HESM-based VFAC SG system

In transition mode, K_S and K_E are opened when the speed reaches the self-sustaining speed and then the HESM can operate in generating mode. In generating mode, K_E is closed again when the speed reaches a certain speed below the minimum generating speed and then the field current is regulated corresponding to the output voltage. The AC contactor is connected to the load, KG is closed and KE is opened when the set frequency is detected.

Compared to WRSM-based VFAC SG system, the features of the HESM-based VFAC SG system are as follows:

- The brushless structure is realized by the fixed magnetic bridge and the reliability of the system is improved.
- Due to the introduction of field windings, the excitation control strategy of output voltage regulation is similar to WRSM.
- The control strategy of armature current in starting mode is similar to that of PMSM due to the permanent magnetic field. With a proper coordinated operation between field and armature currents, the starting performance can be optimized.
- Aiming to realize voltage regulation and de-excitation in wide speed range, the flux regulation capability needs to be optimized.
- A tradeoff between flux regulation capability and power density should be considered further.

4.3 Implementation and experimental verification

To confirm the feasibility of the HESM-based VFAC SG system, a 12kVA system has been developed as shown in Fig.10 and the control algorithm is implemented on the system. Experiments are carried out.

Fig.11 shows the phase voltage and current of the HESM, which indicates the harmonic component of

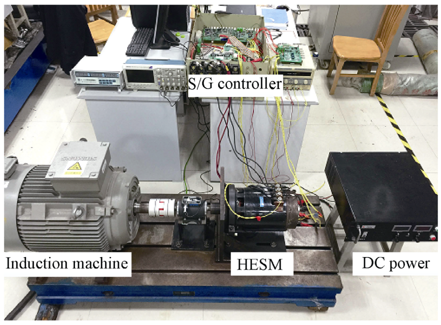


Fig.10 Experimental platform of the HESM-based VFAC SG system

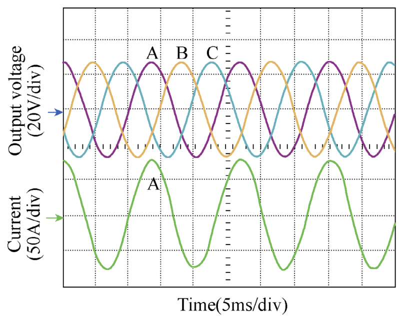


Fig.11 Waveforms of the phase voltage and current

the phase voltage is low and suitable for VFAC SG systems. As shown in Fig.12, the short-circuit current of the HESM can be regulated by field current, which is significant to VFAC SG systems.

Fig.13 indicates the starting mode of the HESM-based VFAC SG system. The starting mode is separated into two stages. A constant torque control strategy is applied at the first stage and then a constant power control strategy is employed. Fig.14 shows the transition mode of the HESM-based VFAC SG system. The generating mode of the HESM-based VFAC SG system is shown in Fig.15. The dynamic performance of regulating output voltage under abrupt electric load change and engine speed change is investigated as shown in Fig.15. The HESM-based VFAC SG system can complete all the three modes.

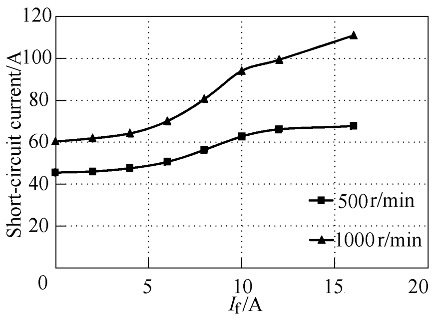


Fig.12 Short-circuit current vs. field current of the HESM

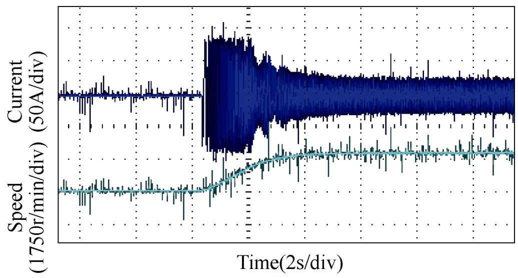


Fig.13 Experimental starting process of the prototype HESM-based VFAC SG system

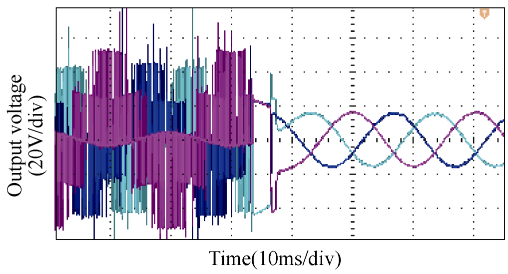
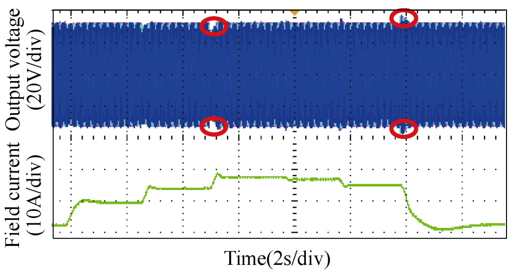
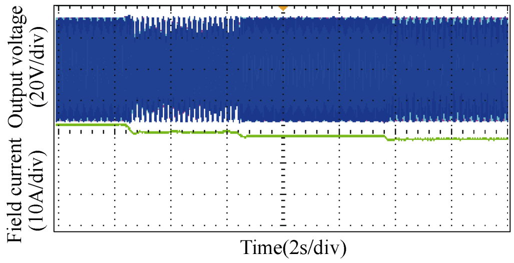


Fig.14 Experimental transition process of the HESM-based VFAC SG system



(a) Abrupt electric load change



(b) Abrupt engine speed change

Fig.15 Experimental generating process of the HESM-based VFAC SG system

5 Conclusion

In this paper, an overview of VFAC generators for safety-critical aircraft applications is presented. There are some critical technical issues to be solved in adopting conventional WRSM in VFAC generation system, such as, high frequency reactance and overvoltage. Meanwhile, some new VFAC candidate generators are discussed. A new HESM-based VFAC SG system is proposed and demonstrated in this paper.

Compared to CFAC generation systems, VFAC generation systems are preferred for MEA since the CSD is eliminated and the SG system is likely to be realized. Currently, WRSM is widely used and dominant in either CFAC or VFAC generation systems. However, the motoring operation of WRSM depends on careful redesign of machine and correlative starting excitation and control strategies. The main excitation methods of WRSM motoring include single-phase ac excitation, two-phase ac excitation and three-phase ac excitation. Some new candidates, including HESM and IM, are also promising candidates in VFAC systems.

The research results prove the feasibility of the HESM with magnetic shunting rotor for VFAC SG system application. In the HESM-based VFAC SG system, the simple brushless structure of the HESM is realized and the motoring operation is relatively easy to implement. With a proper coordinated control between field and armature currents, the starting and generating control strategy can be optimized. For these features, the proposed HESM-based VFAC SG system is a competitive candidate for MEA. Meanwhile, the flux regulation range and power density of HESM system need to be improved further.

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