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Design and Experimental Study of a Novel Two-stage Brushless Hybrid Excitation Synchronous Machine

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Abstract. A novel two-stage brushless generation system which is based on Tangential / Radial Hybrid Excitation Synchronous Machine (T/R-HESM) is proposed in this paper. The configuration and operation principle are introduced. Meanwhile, a novel two-stage brushless scheme is designed. Comparing with traditional brushless scheme, the problems such as complex system and long axial length can be overcome by novel scheme. In this paper, this novel scheme which can realize complete self-excitation, is introduced in detail and compared with current scheme. In the aspect of excitation system, the exciter is designed. Finally, a prototype is made to verify the correctness and reliability of this novel two-stage brushless scheme by experiment. From above-mentioned study, the application of hybrid excitation synchronous machine is expanded in the areas of aerospace, wind generation and so on.

Key words

generation system, hybrid excitation, two-stage, brushless, self-excitation

1. Introduction

Hybrid excitation synchronous machine (HESM) was firstly proposed by USSR scholar in 1980th. Primary excitations by permanent magnets as well as a secondary field coil excitation source are utilized in HESM. By combining the advantages of permanent magnet (PM) machines with the possibility of controlling magnetic flux by excitation coils, this kind of electrical machine has a widely used prospect. So, HESM has become the new research hotspot [1-3].

Meanwhile, avoiding slip rings and brushes is the key technical problem to improve reliability and ensure long-term operation without maintenance. Many schemes are proposed. For example, in the area of aviation, three-stage brushless exciter synchronous machines are adopted as main generation system of aircrafts. As Fig.1 shows, this scheme consists of auxiliary exciter, exciter and main-generator [4-6]. Permanent magnetic generator is chosen to be auxiliary exciter, which provides electrical power to a rectifier/chopper set. The chopper is connected to the stationary excitation windings of exciter, whose three-phase output exciter is rectified and applied to exciting windings of main generator. Sometimes, the permanent magnetic generator is replaced by power supply. In the area of civil grid generation, the rectifier can be connected to grid. So, the auxiliary exciter or power supply is abandoned. In the area of off-grid generation, the excitation current of generation system is provided by the output voltage of main generator. However, residual voltage is too low to start the generation system. So, auxiliary power supply cannot be avoided.

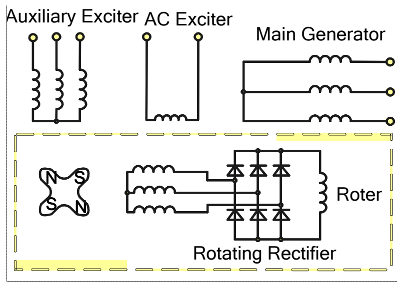


Fig. 1. The traditional scheme three-stage brushless synchronous generator

In order to expand the application field of HESM, T/R-HESM is proposed in this paper. The new configuration and operational principles are described. Its 2D model is built by finite element method (FEM) to get the static characteristics. Then, a novel two-stage brushless scheme which is based on T/R-HESM is proposed in this paper. In this scheme, the structure of this scheme is described and the method of excitation is given. In this scheme, auxiliary exciter or power supply can be eliminated. The generation system can be started without the help of gird, which realize complete self-excitation. Finally, the results of experiment demonstrate the correctness of design.

2. Configuration and Operational Principle of T/R-HESM

T/R-HESM is composed with stator core, rotor core, armature coils, field coils and permanent magnets (PM) as shown in Fig.2.

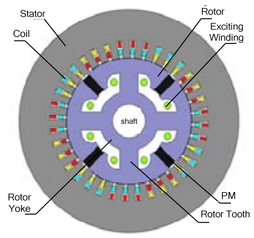


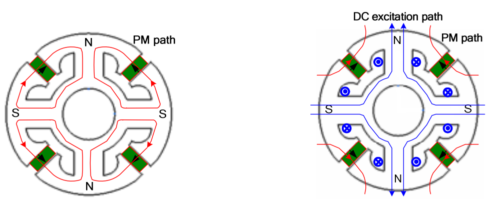
Fig. 2. Structure of T/R-HESM.

A 1.5kW/380V T/R-HESM with two pairs of poles and 36 slots is designed for the following study.

The flux of T/R-HESM is mainly composed of flux produced by PM and flux produced by DC excitation current in parallel independently.

When the field coils are without excitation current, the magnetic path of the PM is as shown in Fig.3 (a). Because of greater magnetic reluctance of air-gap, the flux forms a magnetic short circuit in the rotor iron core, while it does not pass through the air gap.

When excitation current flows through the field coils, there are two magnetic paths as shown in Fig.3 (b). The direction of this magnetic flux produced by field windings is radial. The other is the magnetic path of PM whose direction is radial.



(a) Without excitation current. (b) With excitation current.

Fig. 3.Magnetic flux path of T/R-HESM under different conditions.

In order to analyze the magnetic flux distribution and obtain static characteristic of T/R-HESM, finite element method (FEM) is adopted to study the performance of the machine. When there is no excitation current, a magnetic short loop is formed in rotor core by PM when there is no excitation current. So, the rotor core is relatively saturated. However, a little magnetic flux forms a loop from rotor shoe to stator, which passes through air gap as Fig.4 shows. So the generator can still provide output voltage without excitation current. The No-load characteristic is as Fig.5 shows. I_F refers to the excitation current of T/R-HESM, U_o is the output voltage of T/R-HESM. It can be obtained that the output voltage of T/R-HESM is about 50V when there is no excitation current.

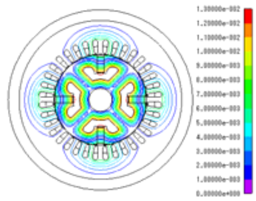


Fig.4.Magnetic field distribution of the T/R-HESM without excitation current.

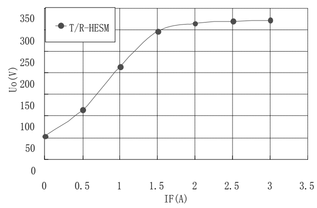


Fig.5.No-load characteristic.

3. The Realization of Brushless Excitation Two-stage Operation

A. The realization of two-stage brushless scheme

As Fig.6 shows, the novel two-stage electric excitation scheme is composed of T/R-HESM, exciter and rotating rectifier. T/R-HESM is the main generator in this generation system. Exciter is revolving-armature type machine. Uncontrollable three-phase bridge rectification circuit is chosen as rotating rectifier. The three-phase input terminals of rotating rectifier are connected to the output terminals of armature of exciter. The output current of exciter is rectified by rotating rectifier. The output terminal of rotating rectifier is connected to exciting windings of T/R-HESM. External power source can be eliminated because T/R-HESM is chosen as main-generator. Owing to the permanent magnet of T/R-HESM, there is still output voltage when there is no excitation current of T/R-HESM. Because a little magnetic flux of permanent magnetic passes through the air gap to produce output voltage, which can provide excitation energy for exciter. The output current of exciter will rise to rated value under the control of regulator. The output voltage will rise to rated value step by step. The excitation voltage of exciter is controlled by regulator. The output current is rectified by rotating rectifier which is applied to exciting windings of T/R-HESM. Meanwhile, the regulator and protector also can be supported by output voltage of T/R-HESM. Without auxiliary exciter or external power source, this generation system can satisfy the request of aero machine and realize complete self-excitation.

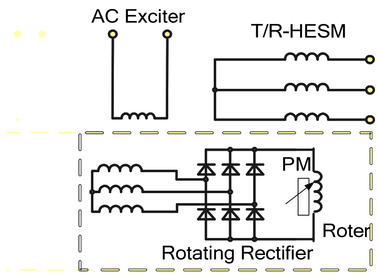


Fig. 6. The novel scheme of two-stage brushless synchronous generator.

B. Exciter Design

The key to the design of brushless excitation is the rational design of exciter. Excitation current is provided by exciter with the help of rotating rectifier. The load and working temperature of main generator are changed by a big margin in operation. So, the regulation output voltage of exciter U_F should be regulated on a large scale. The approximate liner transformation between the excitation current of exciter I_f and the output current after rectification I_F is requested as well. I_F is also the excitation current of T/R-HESM. So, saturation of magnetic circuit has to be avoided in the design of exciter to guarantee the characteristic of current amplifier.

Exciter is designed as revolving-armature type machine with four pairs of poles and 30 plots. The rated excitation current of T/R-HESM is 2.25A. Considering 1.5-2 times margin, excitation current of exciter is requested to provide current by 2A. The characteristics of current amplifier of exciter after regulation are shown in Fig.7. The design of exciter can satisfy the request of design by analyses.

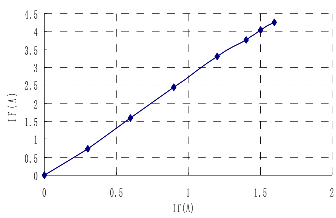


Fig. 7.The characteristics of current amplifier of exciter.

4. Experimental Study

In order to validate the correctness of electromagnetic design and simulation analyses, a prototype of 1.5kW, 380V is designed to do experiment. The parameters of the prototype are the same with the above-mentioned design, including T/R-HESM and exciter.

A. Experiment of exciter

Firstly, the experiment of exciter is carried off to verify the current amplifier at the rated speed. The changes of output voltage of exciter after rectification U_F can be obtained by changing I_f. The peak-to-peak value of U_F is divided by impedance of exciter excitation windings, then I_F can be gained. So the characteristic of current amplifier can be obtained as Fig.8 shows.

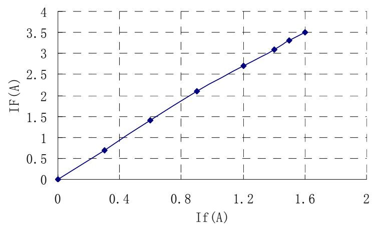
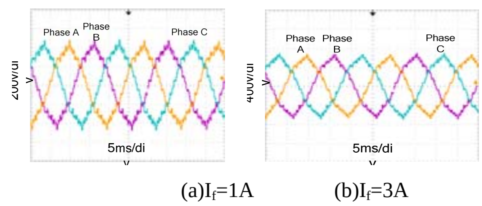


Fig.8.The characteristics of exciter.

B. No-Load experiment

No-load experiment is carried out. The two-stage generation system is composed by main generator and exciter. The generator is operated at the rated speed 1500rpm by prime mover. The DC excitation current I_f is applied to the excitation windings of exciter. The no-load line-to-line voltage and no-load characteristic can be obtained by regulating I_f as Fig.9 and Fig.10 show respectively. It can be concluded that the maximum no-load line-to-line voltage can reached to 425V, which satisfies the design target.



(a)I_f=1A (b)I_f=3A

Fig. 9.Output Voltage under different exciting current of exciter.

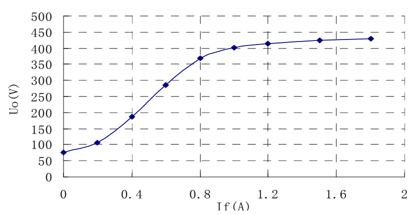
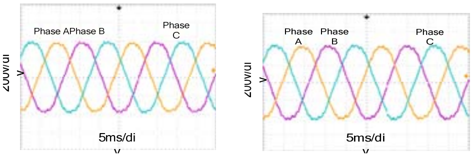


Fig. 10. No-load characteristics of generation system.

C. Load experiment

Three phase output line-to-line voltage under different resistive load at the rated speed when excitation current is 0.85A is as Fig.11 shows, which is much better than that of no-load output voltage. I_L is the output current of T/R-HESM.



(a) I_f=1.0A , I_L=1.95A (b) I_f=1.2A , I_L=2.2A

Fig.11. Load voltage waveform.

Keeping the rated speed, the output voltage can be gained by changing excitation current at 0.8A, 1A and 1.2A. The external characteristic can be obtained as Fig.12 shows. The external characteristics are hard.

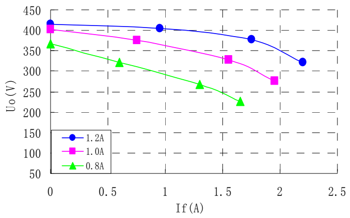


Fig.12. External characteristics under different exciting current.

5. Conclusion

In this paper, a novel hybrid excitation brushless synchronous machine with rotation rectifier is designed. The structure and operation principle of main generator T/R-HESM are analyzed. Because the structure of T/R-HESM has two magnetic sources, the output power can be regulated conveniently while keeping higher power density. When there is no excitation current, the output voltage can still be gained which can be used to start the generation system adequately.

This new brushless scheme can be applied in the area of wind power generation, aviation and so on which has good reliability and increased application.

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