The Study and Test for 1MW High Temperature Superconducting Motor

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***Abstract*— High Temperature Superconducting (HTS) motors have a good prospect in application of marine propulsion and wind energy for its benefits of lighter, more impact and high efficiency. A 1 MW, 500-rpm, 4 pole HTS motor was designed and tested by Wuhan Institute of Marine Electric Propulsion (WIMEP). This paper provides a summary of the key technologies, main structure and test results of the motor. This project was sponsored by China Ministry of Science and Technology funding. The aim of the project is to solve some key technologies of HTS motor and set foundation for high capacity HTS motor.**

***Index Terms*—1 MW HTS motor, marine propulsion, wind energy**

I. Introduction

HTS motors are characterized by high power density, more compact, quiet operation and high efficiency, to be an ideal candidate for marine propulsion motor and direct drive generator in the future[1~5]. Based on estimation, a 10 MW, 12rpm direct drive generator are one third weight of conventional motor of similar power and torque rating.

Fig. 1 1MW HTS motor test bed

Supported by China Ministry of Science & Technology and designed by WIMEP, the project of 1MW, 500rpm HTS motor was initiated in Dec. 2008. The main technical parameters include the following:

a) Power: 1000kW
b) Speed: 500rpm
c) Efficiency: 95%

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And also the project needs to finish the following goals:

a) HTS magnet technology
b) Topology structure of the rotor
c) Air gap armature
d) Cryogenic refrigeration system

The test of the demonstration 1MW HTS motor was finished in April 2012 at WIMEP as shown in Fig 1. The test indicated that the performance reached design requirements. The demonstration motor validated both the overall design and component design for large capacity HTS motor.

II. 1 MW HTS Motor Characteristics

The 1MW HTS motor employs synchronous structure with revolving HTS magnetic poles. The magnets in rotor adopt 1G HTS wire winding. And the stator employs Litz copper wire air-core winding. Liquid neon is selected as coolant for cryogenic system, and the liquid neon goes to the rotor from nondriven end of the rotor shaft as shown in Fig.2. The HTS magnets employ excitation with brush located at drive end.

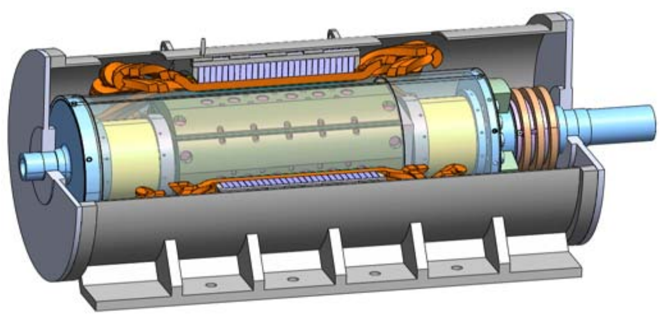

Fig. 2 The structure of 1MW HTS motor

The characteristic parameters of the motor are summarized in table1. These parameters are verified by experiments.

Table1
Parameters for 1MW HTS Motor

Parameter	Value	Units
Nominal rating	1	MW
Rated Voltage	690	V
Rated current	950	A
Power factor at rated load	0.9～1	
Rated speed	500	r/min
Frequency at rated speed	16.67	Hz
Exciting current of field winding	85	A
Air-gap flux density	0.85	T

The stator assembly includes an AC stator winding, back iron, support structure, bearing, frame and cooling fan. Fig.3 illustrates the stator winding. To reduce the AC losses, Litz wire based strand is used [6]. The winding is mounted in supporters with non-magnetic material.

The rotor includes a field winding operating at 30K, its support structure, evaporator, torque tubes, axial compensating unit, electromagnetic shield and brush exciter. An exciter power provides current to magnets by slip rings. Before assembled with the stator, the rotor vessel leak rate is needed to be detected as shown in Fig. 4. The total leak rate of the vacuum vessel is less than $2\times10^{-7}\,Pa\cdot L/s$.

Fig. 3 Litz wire stator winding

Fig. 4 Total leak rate detection

III. The Study And Test Of Key Technology

A. HTS magnets

The HTS magnet is made of Bi2223 superconductor wire. There are 4 magnets and each magnet is buildup by 4 impregnated double-pancake coils. The double-pancake coil has homogeneous temperature distribution in operating because of metal heat conduction board. The simple of the HTS magnet is shown in Fig. 5.

Fig. 5 Sample of HTS magnet

Each double-pancake coil was test at 77 K in self-field to make sure the coil in good condition. The coils for 1# magnet's I-V curves are shown in Fig. 6. The results fit well with the simulated one [7]. The magnet was measured in an instrument (Fig. 7) which simulating the working temperature and magnetic environment of the motor.

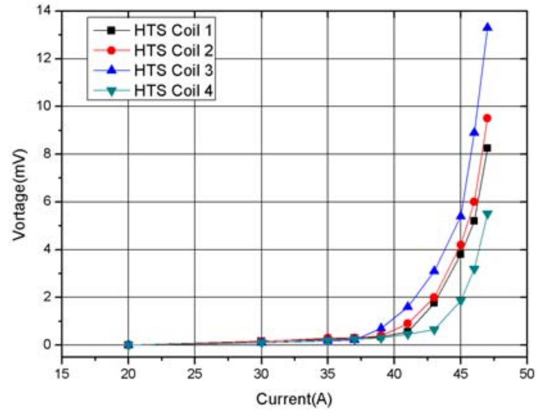

Fig. 6 Double-pancake coil's I-V curve in 1# magnetic

Fig. 7 HTS magnets testing instrument

In order to verify the calculated critical current, two double-pancakes series critical current was tested at 45 K. The test critical current was 145 A while the calculated current was 136 A. The error may be caused by I-B curve deviation and measuring error. The temperature continued to fall down. And also we tested the I-V curve at 30 K. Limited to the maximum output current of the current supply, only an exciter current of 199 A can be loaded to the two series double-pancakes with 2 mV voltage drop of each. Here, the pancake coils maximum magnetic intensity was higher than the magnet's at the exciter current of 85 A.

Each coil's I-V curve in 1# magnet is shown in Fig. 8. Because of the different magnetic environment and thermo stress, four coils behave a little different. The other three magnets behave almost the same as this one. The I-V curves tested in the motor are almost the same as tested in the magnet testing equipment.

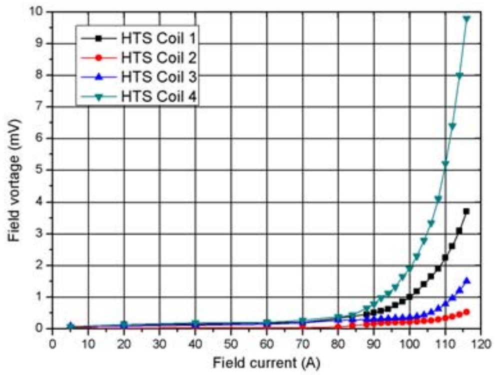

Fig.8 Coil's I-V curve in 1# magnet.

B. Torque tube

Torque tube in motor is used for support, heat isolation and torque transmission. The torque tube is made of composite material such as G10. The torque tube is suffered complex stress which including axis tensile force, torsion, bend force and temperature stress in rotor. We analyzed the stress and heat leakage using FEA [8] and designed a special device to validate the result (Fig. 9). The measured heat leak of torque tube is about 9 W. The biggest torsion we test is twice than rated torsion (limited to the device). Both the strength and heat leakage satisfy requirements.

Fig. 9 Cryogenics test platform of torque tube

C. Rotor cooling system

The cryogenic cooling system includes cryogenic coolers, Dewar, coolant transfer pipe and evaporator. The cryogenic coolers comprise one Stirling SPC-1T and two AL330 GM refrigerators. The evaporator locates in the rotor vacuum vessel and cools magnets by heat conduction. The rotor cooling system is filled with Neon. And the neon circulates in a closed loop. The neon gas is condensed to liquid neon by cold heads which locate in Dewar, and the liquid neon goes through transfer pipe to evaporator. Liquid neon evaporates there and the vapor moves through the same pipe back to the cool head and recondense there.

The cryogenic cooling system was tested as shown in Fig.10. By controlling the pressure of the neon gas, the rotor temperature can be controlled effectively.

Fig. 10 Cryogenic cooling system test.

IV. Test Results

WIMEP test the 1MW HTS motor in April, 2012. The test have carried through generator unload test, generator load test, motor unload test and motor load test, lasted 30 days.

Fig. 11 illustrates the test system schematic of 1 MW HTS motor. The converter supplies current while the generator works as a load. Fig. 12 illustrates the HTS motor cooling process which includes liquid Nitrogen precooling, coolant exchange and liquid Neon precooling. 72 h precooling time is needed from ambient temperature to 89 K. 24 h is needed for coolant exchange and liquid Neon cooling from 89 K to 30 K.

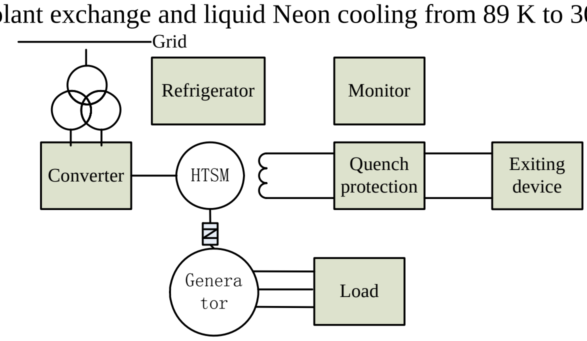

Fig. 11 Test system schematic of 1 MW HTS motor

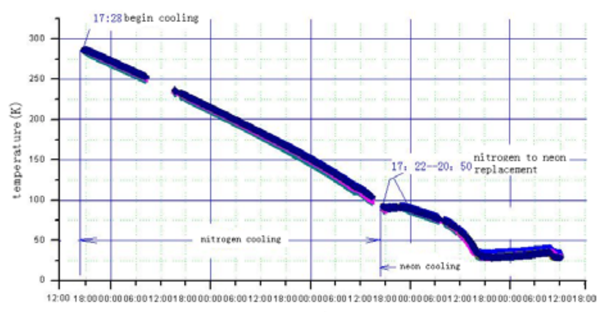

Fig. 12 Precooling process of 1 MW HTS motor.

A. The test of unloaded voltage features

Opening circuit voltage features is shown as Fig. 13 under rated speed. The exciting current is 86 A. Unloaded character is similar to linear curve because of the no-iron rotor and air gap armature. The error between calculating and measure is about 4.83%.

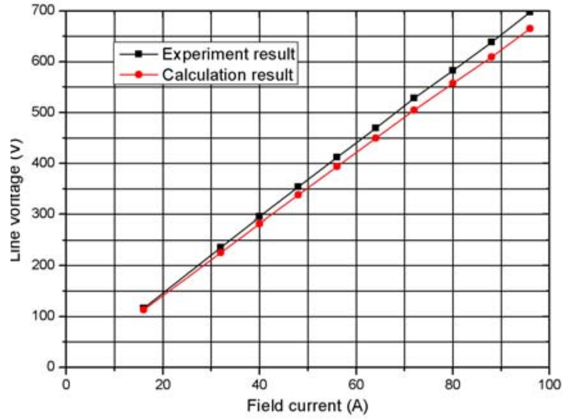

Fig. 13 Performance curve of unload.

B. The test of stator temperature rise

Working as a generator mode, stator winding was connected to a small resistance. And we adjusted magnet exciting current to 45A and stator phrase current to 1044A which is slightly higher than fully loaded current. The motor runned stable for 2 hours, and the results fitted well with the design.

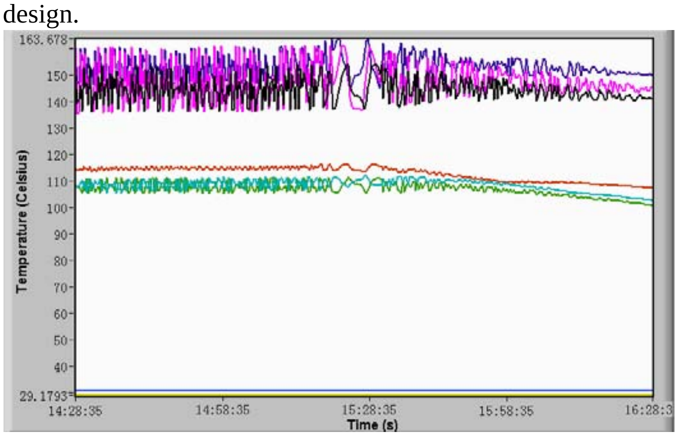

Fig. 14 The test result of stator temperature rise.

C. load test as a motor

The converter is a standard product made by WIMEP, and the load is a 1.2 MW DC generator which connected to resistance. Stator current under rated load voltage wave is shown in Fig. 15, and the current virtual value is 980A with a good sinusoid.

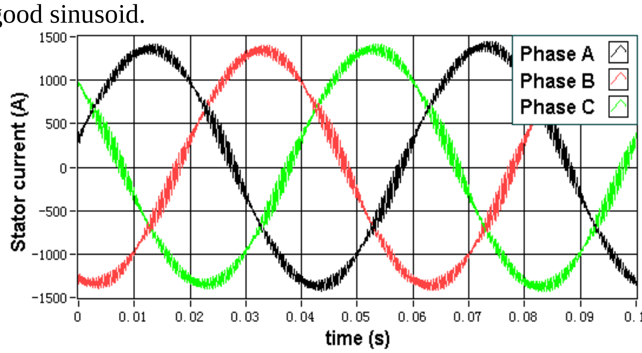

Fig.15 Stator current wave.

Motor efficiencies at different loads are shown in Fig. 16. The motor has high efficiency at a wide working range (25%-100% rated load).

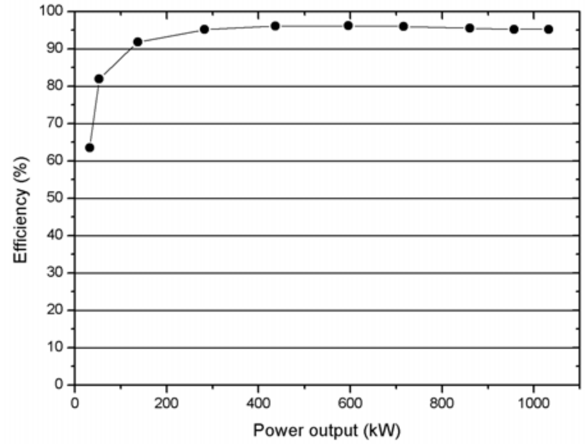

Fig. 16 Efficiency curve.

V. Conclusion

Large capacity HTS motor has good application future in marine electric propulsion and direct drive wind power generator and so on. Through the research of 1MW HTS motor, we experience the design and manufacture of HTS magnets, top structure of rotor, toothless air gap armature, cryogenics cooling system and whole motor. 1MW HTS motor has high efficiency, few stator harmonious wave and good sinusoid. HTS motor will have more advantage with higher capacity.

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