A Study on Design of Inverter for Multi-phase Brushless DC Ship Propulsion Motor

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Abstract — This paper describes inverter for multi-phase brushless DC ship propulsion motor. This inverter has high efficiency and relatively small size. It is separated multi-phase brushless DC motor drive and motor-inverter built-in type. Some inverter modules are damaged, the motor can be limited drive by other living inverters. In order to maintain high efficiency at low speed , same phase coils of different group are connected in series and excited by the half number of inverters than at high speed operation. Power module cooling system is circulated fresh water. Number of kW-class downsized inverter was made for study of operating algorithm. In this research deals number of MW-class inverter system design, manufacture and test.

Index Terms - inverter, efficiency, ship propulsion, motor-inverter built-in type, multi-phase

I. INTRODUCTION

In these days, the usage of electric propulsion system is gradually increased in ship propulsion system. The electric propulsion system can achieve higher efficiency and power, lower noise and vibration compared to conventional engine system.[2] Among those, multi-phase blushless DC motor would be advantageous in use. The multi-phase blushless DC motor is operated by inverter system and the overall performance of propulsion system can be affected by the control process of the inverter system. Multi-phase motor drives are not a new invention(1969) but interest in their applications has risen significantly during the last few years. The multi-phase motors reduce the inverter per-phase rating in high power drive applications, improve the efficiency of the system, and to some extent improve fault tolerance capacity.[3]
In this research, number of MW-class motor drive system design, manufacture and test.

II. DESIGN OF INVERTER FOR BRUSHLESS DC MOTOR

A. Requirements

The propulsion system of this research requires very high output power about some megawatts. Because of the property of the propulsion propeller load, not only very large output is needed on high speed but also very low output on low speed. And small dimensions and high power density is required to achieve small installation space. In this application, motor-inverter built-in type is one of important requirement and the system efficiency should be high enough even on low speed operation.

B. Basic Design

The propulsion motor of this research is the blushless DC motor excited by inverter system with a DC power source and the stator coil and the inverter system is cooled by fresh water cooling system. To guarantee the redundancy property, inverter system, the stator coil, cooling system and control system are constructed by same two sets. The inverter system consists of modular inverters and the motor can be operated even though some inverter modules are damaged. Number of inverter modules drive double phases of the separate double winding number of phase blushless DC motor. The excitation system of this research is constructed in two same groups considering redundancy property. The inverter system consists of two same groups with different power sources and the stator coil also consists of two same groups with separate inverter output.[Fig.1] In case of fault of one inverter system of power source, the motor can be operated with other inverter system up to 50[%] of the rated output. Moreover each phase coil and inverter are manufactured independently without sharing neutral point and even if some inverter modules are damaged, the motor can be excited by other living inverters. But the maximum output power is decreased in proportional to the number of normal inverters. The excitation system of this research is constructed in two same groups considering redundancy property. The inverter system consists of two same groups with different power sources and the stator coil also consists of two same groups with separate inverter output. In case of fault of one inverter system of power source, the motor can be operated with other inverter system up to 50[%] of the rated output. Moreover each phase coil and inverter are manufactured independently without sharing neutral point and even if some inverter modules are damaged, the motor can be excited by other living inverters. But the maximum output power is decreased in proportional to the number of normal inverters. One main control board and two H-Bridge control boards are mounted in each inverter module and takes control of separate two phases. Additionally, one six channel SMPS for each of control board and high efficiency mode control board are mounted. Individual inverter modules do not share A/D inputs, one inverter module has its own phases information only. As a result, currents/voltages references should be derived with these restrictions to produce constant torque.

C. Mechanical Structure

In this research, motor-inverter built-in type is very important requirements. So, inverter modules are inner motor housing.

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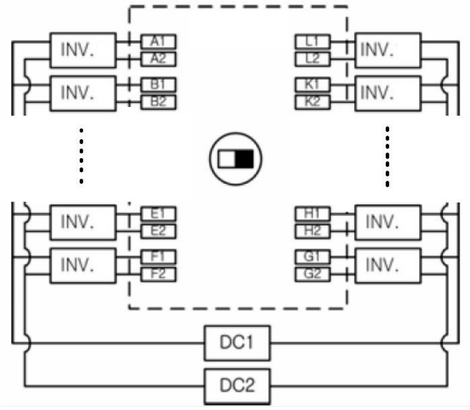

Fig.1. Inverter modules structure

It is tandem structure so that it may inverter system into motor housing. Fan shape inverter number of modules place 30 degrees intervals. In advance motor designed, after inverter design. Therefore inverter size is satisfied motor size. To arrange everything need in inverter composition to limited space DC link capacitor and electric power devices, heatsink etc. order manufacture. Because inverter module should be available replace by module at breakdown, need model that can fixate. This Cage was designed to rotate at inverter module replace. To satisfy the dimension requirements, the diameter of the Cage is limited and the axial size is limited. The fresh water cooling ling piping is attached outside the Cage. Seperated two inverters were designed by structure that enable high efficiency mode connecting same phase coils. IGBT module was used to power device of this research. Baseplate of IGBT module was contacted with water cooling system heatsink. In the case of water cooling heatsink, was designed considering heat loss of power device in limited size. It is designed as path of water cooling pipe passes by hotpoint to baseplate to do it to optimize cooling. Also it is designed affluently about 20% better than maximum heat losses and heatsink temperature getting feedback to control cooling pump.

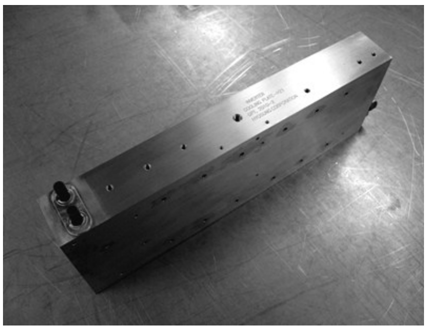

Fig.2. Water Cooling Heatsink of Power device

D. High Efficiency Operation Mode

In propulsion drives such as electric ship application, efficiency is one of the major concerns to save operating cost. To take this into account, phases in pair, for example phases A1 and A2, are connected in series at low speed region by turning on the switch for high efficiency mode shown in Fig. 4. In this mode, switching loss can be reduced with the switches of leg2 and leg3 off.

Additionally, since impedances and EMFs of two phases are series connected, the voltage reference increases at low speed and voltage syntheses error from dead time effect can be decreased as well.

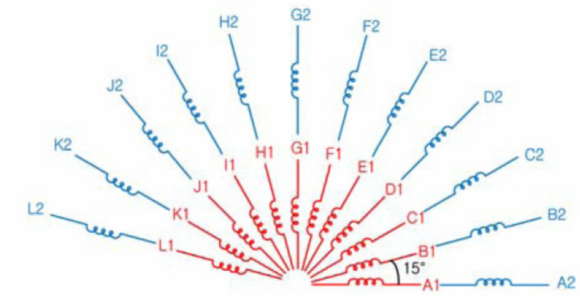

Fig.3. Electrical layout of motor

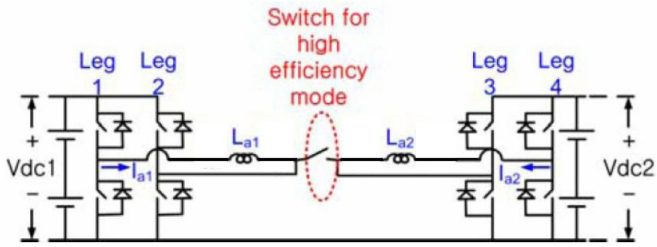

Fig.4. Topology of high efficiency mode

When the rotational speed is low, the output of the propulsion motor is very small because of the load profile of propeller. Therefore in low speed operation stage, the ratio of the inverter switching loss is increased in total system loss. And the total system efficiency in low speed operation stage can be improved by reducing this switching loss. The simulation result of the proposed high efficiency mode is shown in Fig. 5. The high efficiency mode is turned on under 40[%] of the rated speed and the efficiency of the inverter system is improved about 2[%].

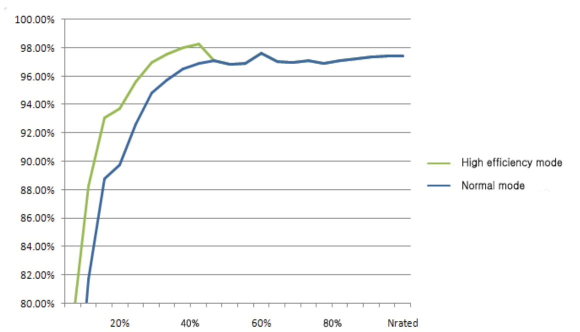

Fig. 5. Efficiency of Inverter system

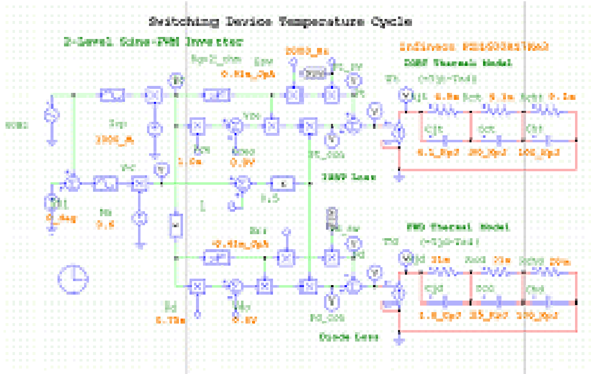

Fig.6. Simulation of power device loss

E. Development of Operating Algorithm

Manufactured scale-downed inverter and scale-downed M-G set to develop drive algorithm in Fig. 8-9. Point of drive algorithm is torque ripple reduction and high efficiency operation, and part phase breakdown.

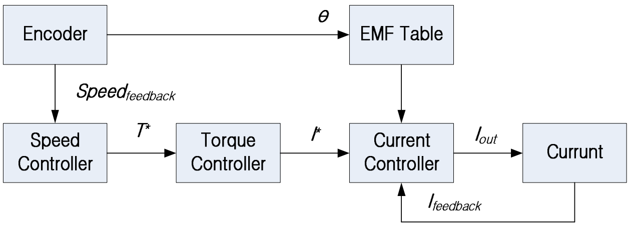

Fig. 7. Motor Control Concept

The concept of motor control is shown in Fig.7. Create torque order in speed controller, and torque order creates back EMF current order refering motor position.

Because of torque ripple reduction, back EMF measures about mechanical angle 360 degrees without measuring about electrical angle 360 degrees.

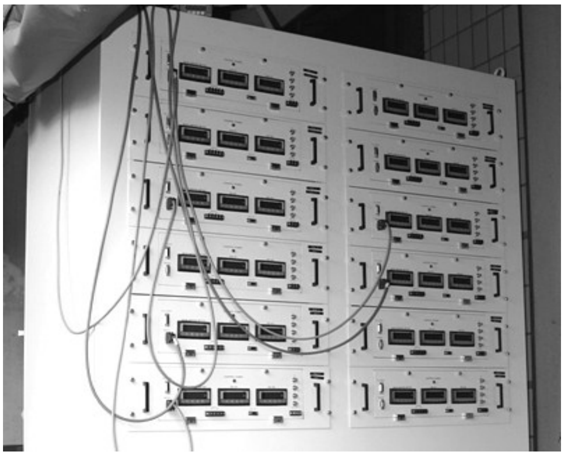

Fig. 8. Scale-downed Inverter module

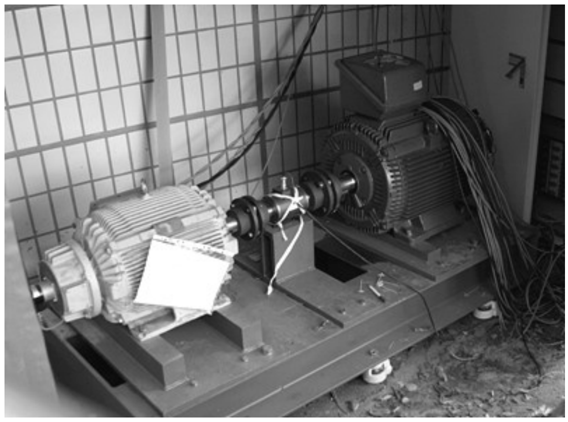

Fig. 9. Scale-downed M-G Set

III. TEST RESULT

Progressed test manufacturing module among many inverter modules. Progressed functional test of six kind of board that is mounted inverter module preferentially and module test is after board test. Electric power test progressed by four steps in Fig.11 and control method used hysteresis control. Ch1 is current order and Ch2 is output current, and Ch3 is IGBT collector-emitter voltage and Ch4 is gating voltage in Fig.12. About current order, confirmed that control is achieving well.

Number of phase and number of pole tested verification of drive algorithm by same 1/100 scale-downed motor. Inverter outputs are linked number of MW motor and 1/100 scale downed motor by multiple through switches.[Fig . 12]

Can apply uniform drive algorithm to number of MW motor by control of switch after verify drive algorithm by scale-downed motor.

Test of scale-downed motor progressed a whole phases and partial phases, CW and CCW rotation and speed control test.

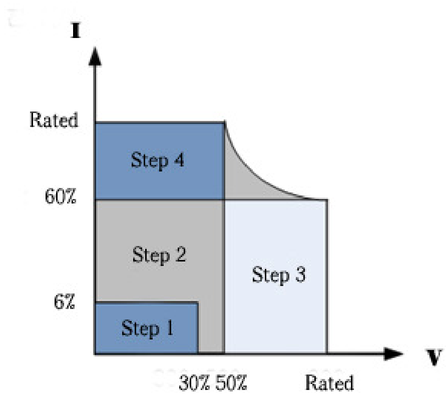

FIG. 10. STEP OF POWER TEST

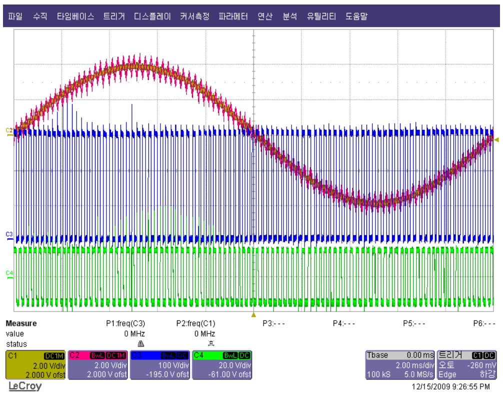

Fig. 11. Current control curve

Also, progressed high efficiency mode operation explaining in II-D.

Scale-downed motor is going to progress test continuously by verification before drive algorithm application in number of MW no-load and load test.

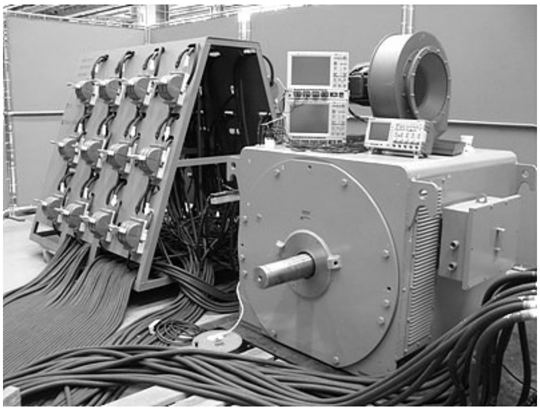

Fig. 12. Scale-downed 36-poles Motor and Switch

Measured back EMF of number of MW motor use to load generator. Back EMF curve does verification of electricity design of motor comparing with motor design data and need for data collection for inverter drive. Comparison of designed back EMF data and measured back EMF data are Fig. 13. Test data and design data were difference about 2.7%.

IV. CONCLUSIONS

This paper has discussed a separate double-winding multi-phase brushless DC motor drive. No neutral point exists and each phase is isolated electrically. Stators are doubly winded for duplicate redundancy and individual H-bridge inverters are employed so that the system is still able to operate continuously with healthy phases under fault conditions.

In addition, single inverter module can be detached from other modules for repair or replacement in case of power device breakdowns.

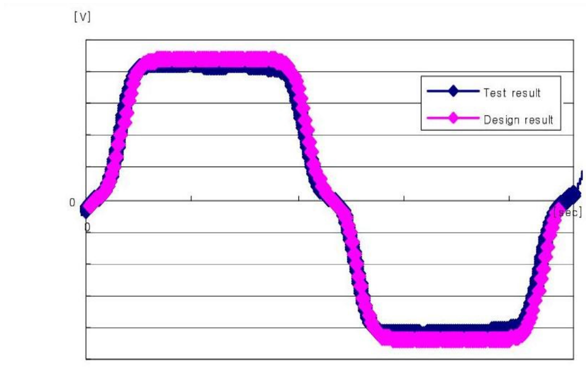

Fig. 13. Comparison of Back EMF curve

The propulsion system in this research is direct-drive type. Therefore the rated rotation speed is low(under 200[rpm]). To perform large power and high reliability, the inverter has multiple modules equal to phase number of motor. The one inverter module consists of separated two h-bridge inverter. Moreover, to improve the efficiency of the system, high efficiency mode operation is introduced at low speed region. Use 1/2 inverter and connected same phase coils by series to satisfy efficiency in low speed driving. This mode can lead to switching loss reduction from decreased number of active legs. It also improves voltage syntheses performance of inverters and therefore shows better achievement in torque production at low speed. Motor and inverter modules are designed in built-in type by tandem structure and therefore there was restriction in structure and size of inverter.

Power device used water cooling method, and heatsink was designed so that cooling may be optimized.

Test facility that can test now number of MW motor.

This facility is consisted of power supply that can run number of MW motor and load system that can inflict load to this motor.

Composed number of MW motor and 1/100 scale-downed motor to run by inverter that is identical by switch control and drive test of 1/100 scale-downed motor is complete state.

Is going to test progresses no-load drive and load drive of number of MW motor because measure output power and efficiency and noise doing by target degrees.

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