Development of Liquid Cooled BLDC Motor

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***Abstract*— Brushless Direct Current (BLDC) Motor is an electromagnetic device that converts electrical energy into mechanical energy. BLDC motor is a type of motor used in electric cars and does not need brush for magnetic field replacement (commutation), but is carried out electronically commutated. In BLDC motor, temperature in the motor play important role on motor performance such as maximum power and efficiency. In this research the development of liquid cooling of BLDC motor is described. Development starts from the design, computation using software and the realization of the motor design results. The construction of a brushless DC motor is very similar to that of an ac motor, known as permanent magnet synchronous motor. The stator consisting of a core and copper windings forming a core and armature unit. There are 2 identical stators to form the BLDC.**

Keywords—Radial, BLDC, rotor, stator, windings

1. INTRODUCTION

Brushless Direct Current (BLDC) Motor is an electromagnetic device that converts electrical energy into mechanical energy. BLDC motor is a type of motor used in electric cars and does not need brush for magnetic field replacement (commutation), but is carried out electronically commutated. BLDC motors have many advantages over DC motors and ordinary induction motors and ideal choice for system applications requiring high reliability and high efficiency. In general BLDC motors are considered high performance motors capable of delivering large amounts of torque over a wide speed range.

Cooling of the main components is an important aspect in maintaining the work resistance of these components. Each component that operates will produce heat losses, including the Brushless Direct Current (BLDC) Motor. If the heat is not discharged, it will affect the performance of the BLDC Motor, even if this is allowed to continue, the temperature will increase and an overheat occurs. Overheating of an electric motor causes detrimental effects such as degradation of coil insulation, demagnetization, increased heat loss, decreased motor efficiency and reduced motor life time [1]..

The heat generated due to the current through the windings causes an increase of temperature in various parts of the electric machine [2]. The increase in temperature reduces the insulation resistance of the windings, generates thermal stress, reduces efficiency [3] and further causes machine failure [4]. Hence to develop high power and efficiency of BLDC motor, the cooling of the motor have to be considered.

This paper describes the design and realization of liquid cooled of BLDC motor. The process of the design is analytical and model method.

2. MOTOR CONSTRUCTION DESIGN

The construction of a brushless DC motor is very similar to that of an ac motor, known as permanent magnet synchronous motor. The stator winding is similar to that of a polyphase ac motor, and the rotor is composed of one or more permanent magnets. A brushless DC motor is a distinct fr ac synchronous motor in which the former combines several ways to detect the position of the rotor (or magnetic poles) to generate a signal to control electronic switches.

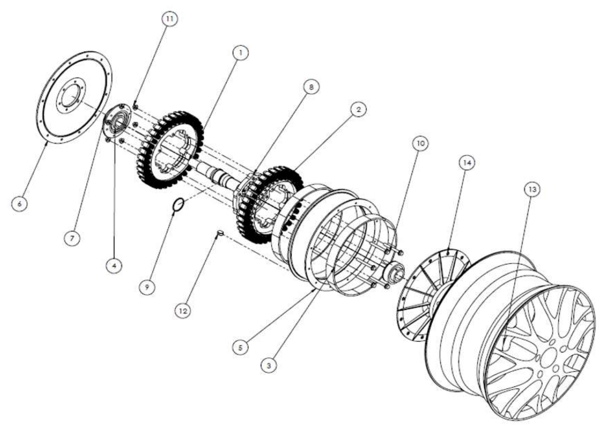

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Fig. 1. BLDC motor construction.

Figure 1 show the motor construction that consist of shaft (1), stator winding (2), rotor magnet (3), bearing (4), middle casing (5), left casing (6), bearing house (7), hub (8), clip ring (9), bolt (10), nut (11), keyway (12), wheel rim (13) and right casing (14).

The stator consisting of a core and copper windings forming a core and armature unit. There are 2 identical stators to form the BLDC that is analyzed.

3. DESIGN PROCEDURE

3.1 Motor Design Calculation

In the design process, the independent or "input" variables are dimensions, winding and properties of the magnetic material whereas the dependent variable (output variable) is the performance such as torque, current, efficiency, temperature rise, etc. In fact, there are many independent variables involved in process design and most of them are assigned their values by repetition. That is, the design procedure must be carried out to make certain assumptions, determine the test values for the independent variables and calculate the dependent values. If the performance is not satisfactory, the process continues until the desired performance is achieved. Another method for designing is, the dependent variable is fixed and thus the independent variable is derived with the help of the equation:

In this section, a general procedure for designing BLDCs, either having the dependent variable extension or arriving independent variable or vice versa is proposed. Before BLDC motor design can begin, several important decisions must be made about the features of different types of brushless motors and the availability of different magnetic materials.

To do the design, the following equations are used [5]:

Torque:

The force on the current carrying conductor of the magnetic field is given by [5]

$F = IL \times B$

where, L is the length of the conductor, B is the magnetic flux density, and the current through the conductor.

The magnitude of the force is [5]

$$F = BIL \sin \theta$$

Where θ is

BLDC motors work on the same principle as DC motors in that the armature current and the magnetic field are stored orthogonal to each other in space (θ = 90º). Thus the force on a conductor in the BLDC motor is exerted by [5]

$F_c = B_g I_c L$

The torque in the conductor is given by [5]

$T_c = B_g I_c L R_{si}$

A winding consists of 2 conductors, one above the north pole and the other above the south. Hence it's torque in one winding is [5]

$T_t = 2 B_g I_c L R_{si}$

Back Induction

In the same way, the back emf can be calculated as [5]

$$E_c = B_g L v$$
$$E_c = B_g L w_m R_{si}$$
$$E_t = 2 B_g L w_m R_{si}$$
$$E_{coil} = 2 B_g L n_s w_m R_{si}$$
$$E_{phase} = P B g L n_s w_m R_{si}$$
$$E_b = 2 P B_g L n_s w_m R_{si}$$

Where Eb is reverse induction using DC voltage

Stator Winding Design

The conductor will be determined by the maximum current density [5]

$$A_c = \frac{I_c}{J} ; \therefore D_c = \sqrt[2]{\frac{A_c}{\pi}}$$

and

$$Ac * = \frac{\pi}{4} (D_c *)^2 ;\therefore A_{cu} = n_s \times A_{cu} = n_s \times A_c *$$

where

$$\tau_c = 2_\pi (R_{si} + \frac{1}{2} d_s) \frac{1}{p}$$

$$l_t = 2L + 2\tau_c$$

Stator Design

Consider that the teeth are uniform and estimate the slot area as the trapezium. The slot area can be calculated using the following equation [5]:

$A_s = \frac{A_{cu}}{K_{fill}}$

The slot fill factor takes care of the isolation of the slot entry as well as all available estimates made while selecting the slot area as the trapezoid. Using This area has various dimensions using equations [5]

$$R_{ro} = R_{si} - g; N_s = P \times N_{ph}$$

$$\pi_s = \frac{2\pi R_{si}}{N_s} ; \textit{is slot pitch}$$

Loses Calculation

Coper loses [5]:

$$R_t = \rho_{cu} \frac{l_t}{A_{c*}} ; R_{ph} = p n_s R_t$$

Because the 2 phases produce current at the same time

$$P_{loss\_cu} = 2 I_s{}^2 R_{ph}$$

Core Loses:

Compared to copper losses, core losses are very difficult to compute because they consist of hysteresis losses and eddy currents which vary nonlinearly with frequency and magnetic density flux. Fortunately the manufacturer provides coreloss / kg steel data at various values of flux density and frequency which we can use approximate core losses. Core losses occur only in the stator [5].

$$P_{loss\_core} = coreloss/kg(f_e, B_{max}) \times W_{stator}$$

3.2 Computation

To design this BLDC motor using MAGNET software. MagNet is the most advanced package currently available for the electromagnetic modeling of devices in personal computers. It provides a "virtual laboratory" where users can create models of magnetic materials and coils, view them as plots and field graphs, and obtain numerical values for quantities such as linkage flux and strength. MagNet users only need a basic knowledge file on the concept of magnets, modeling existing devices, modifying designs, and testing new ideas.

MagNet is designed as a complete 3D modeling tool for solving static magnetic field and circulating problems. Many devices can be represented very well with 20 models, so MagNet offers 20 modeling options, with substantial savings in computing resources and solution time. With 2D modeling, MagNet can also take care of the problem by optimizing and providing automatic thermal simulation design and vibration analysis in additions.

The results of designing a BLDC motor using MAGNET software can be seen in the following figure 2:

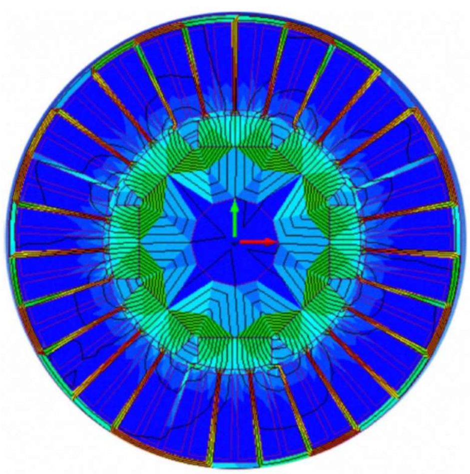

Fig. 2 . Flux magnet distribution

Based on calculation using software parameter at Table 1 below are obtained.

Table 1. Motor dimension

Parameter	Dimension
Outer diameter of stator	620 mm
Stator yoke	20 mm
Height of stator	36 mm
Rotor inner diameter	90 mm
Rotor outer diameter	420 mm
Area of Magnet	25 mm

4. Cooling System

For the effectiveness of BLDC motor cooling in order to produce high efficiency, a cooling system using liquid (liquid cooling) is determined. Furthermore, the coolant is cooled by outside air using a radiator. The scematic of cooling system is shown on Figure below.

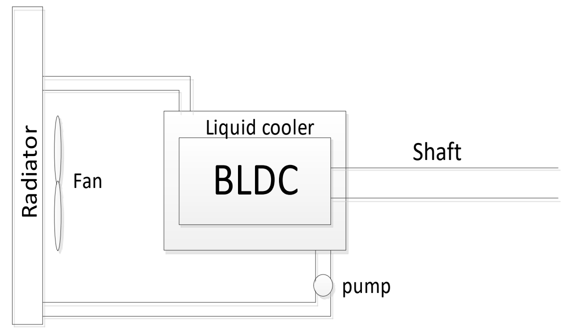

Fig. 3. Schematic of motor cooling system

The main component of cooling system is radiator. The radiator serves to cool water which becomes hot after circulating in the cooling water jacket of the motor. Generally, the radiator is attached to the front of the vehicle. The radiator consists of 2 water tubes located at the top and bottom. The two tubes are connected by a radiator grille. This grid consists of various water channels which are usually in the form of flat pipes. Water from the upper tube flows through this channel to the lower tube. To increase the amount of heat that can be dissipated, a cooler is installed on this grid.

In this case the parameters or design conditions have been determined, then do some thermal analysis first in a radiator design, with the intention of knowing the maximum possible heat transfer (Q_{max}) and the surface area of the heat transfer. In solving these problems using the LMTD method. A more practical method for solving this problem is to use the effectiveness (Ɛ) and NTU methods.

From the data obtained, starting from the design conditions at the maximum energy absorbed by the radiator up to various calculations to determine the value of the surface area for heat transfer. Where the price can be calculated if the size of NTU, C_{min} and U is known.

For the NTU value and the C_{min} / C_{max} comparison, it can be seen from the effectiveness graph for the cross flow with the two fluids not mixed. This NTU method is used when the prices of NTU, C_{min} and U have been obtained with the NTU price which is known from the effectiveness of 0.25 with a ratio of C_{min} / C_{max} = 0.25.

Based on NTU Methods the radiator dimension is described at Table 2 below.

Table 2. Radiator dimension

No	Description	Size (mm)
1.	Radiator width	475 mm
2.	Radiator height	404 mm
3.	Radiator thick	20 mm
4.	Number of tube	46
5.	Number of fin coloumb	47
6.	Number of fin/coloumb	235
7.	Tube width	15 mm
8.	Tube thick	1.5 mm
9.	Tube height	404 mm

5. MOTOR SPECIFICATION

Based on design and realization the parameter or specification of BLDC motor is described below:

Motor Type : Radial Type of BLDC motor
Rate power : 20 kW
Max speed : 6000 rpm
Electric Power voltage : 72 V
Cooling system : Liquid cooling using radiator

6. PERFORMANCE TEST

The liquid cooling BLDC motor was tested using dynamometer test bed. The dynamometer is equipped with electronic speed sensor, power sensor, temperature sensor based on Arduino. The test bed is illustrated at Figure 4.

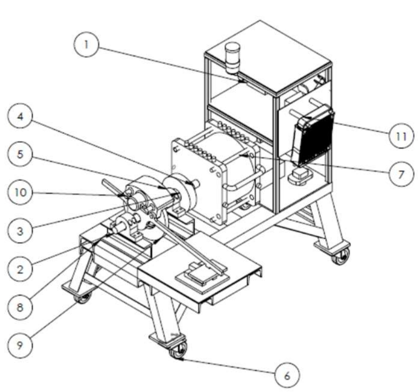

Fig 4. Motor test bed

Where:

1. Load controller
2. Speed sensor
3. 1st Coupling
4. 2nd coupling
5. Pillow block
6. Caster wheel
7. Motor
8. Bearing support
9. Temperature sensor
10. Power meter
11. Panel for instrument

The experimental test investigates the effect of air cooling temperature on BLDC motor power. Motor speed was variated by load variation by dynamometer control. Voltage and current were set of 72 V and 400 A respectively. In liquid cooling case, motor was cooled by water with various temperature from 20°C to 70°C. The result of experiment is described in following figure. In Figure 5, effect of cooling temperature on motor power is described. This figure show that higher cooler temperature cause lower power. This is in line with the theory described in the introduction, that the higher the temperature causes the magnetic strength to decrease, causing the motor power to decrease.

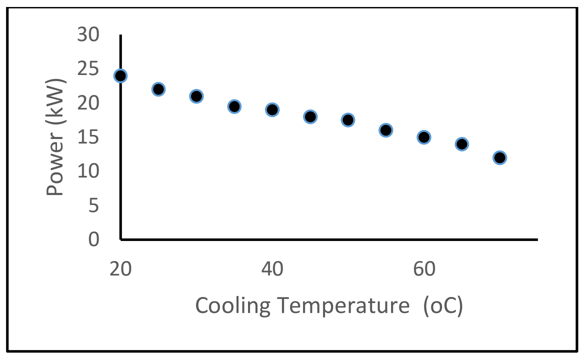

Fig 5. Effect of cooling temperature to motor power.

7. CONCLUSSION

Liquid cooled BLDC motor have been developed. The motor is Radial BLDC motor consist of 2 piece of stator windings and magnetic rotor. The motor is design analytically and numerically. The cooling system consist of radiator as main component. The radiator is designed based on NTU effectiveness method. Both motor and radiator put together to form a motor system and its cooling. Performance of the motor was test on motor test bed. Maximum motor power cooled by water is about 25 kW with rate power about 20 kW. Lowering temperature of cooling give effect on higher power output and vise versa.

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