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Unbalanced distributed and balanced concentrated winding comparison in servo motor applications

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ABSTRACT

A comparison between unbalanced distributed winding and balanced concentrated winding is presented in this paper. The application is a torque motor where low speed and high torque are main requirements. Concentrated winding slot/pole combination is selected so that winding factor is maximum and as well as it is equal to the winding factor of the unbalanced winding motor. Stator and rotor Magneto-Motive Force (MMF) functions are obtained for both motor types to model torque ripple components in the frequency spectrum. Finite element analysis (FEA) and experimental results are presented to compare back EMF waveforms, magnetic loading, torque constant and thermal performance of two motors.

Two designs have identical stator outer diameter (OD) and active axial length. The detailed comparison shows that two motors have similar torque constant. The behavior of two motors under heavy load differs and concentrated winding design performs better. Thermal performance of the designs is also compared and it is observed that concentrated winding design has also less winding temperature rise.

1. Introduction

Torque motors are direct drive low-speed servo machines, and they are preferred when high torque density is a major requirement. Other requirements dictated by such direct drive servo applications are usually low torque ripple, low cogging torque, low inertia, and predictable torque constant under normal and heavy load conditions. Designing a torque motor with low weight and small volume in the face of these requirements is a major challenge.

Surface-mount permanent magnet motor with concentrated winding offers a solution to reduce motor volume due to shorter end turns. Lower copper losses due to shorter end winding, wider constant power range, better fault tolerance are other advantages cited in the literature [1,2]. On the other hand, the design of such a machine should be handled more carefully since some side effects such as higher torque ripple and higher radial force magnitude may occur [3]. Root causes of these side effects are winding structure and rotor/stator magnetic circuit structures.

This paper presents a comparison of a concentrated winding motor with an unbalanced winding one. The concentrated winding motor is a custom design motor for the application whereas unbalanced winding motor is an off the shelf product and it is currently being used in the application.The application details are mentioned in Section 2. Some geometric data and winding details of two motors are given in Section 3. Section 4 is the performance comparison of two motors. Finally, thermal performances of the motors are compared in Section 5.

2. Application

Stabilized turret platforms are commonly used in defense systems such as remote weapon stations, missile systems, main battle tanks, etc. Those systems are designed to provide high accuracy and reliability operation. The closed loop servo control of the system is mainly achieved via electric motors, motor controllers, and feedback elements. Utilizing the brushless servo motors is considered as a contemporary approach for the actuation subsystem due to their highly accurate, reliable and maintenance-free characteristics. The mechanical connection would be provided by mechanical transmission elements such as pinion and ring gear, gearbox, lead screw, belt & pulley, etc. But, those transmission elements induce some

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Fig 1. An example of a stabilized turret platform: remote weapon station system — MUHAFIZ® (Photo Courtesy of ASELSAN Inc.).

problems based on the backlash, reduced efficiency, low rigidity and mechanical complexity. Direct drive brushless servo motors eliminate those problems with the help of the direct torque and speed transfer to the mechanical system. So, direct drive servo motors come into prominence when high dynamic performance and high position accuracy is required. In addition to that, direct drive brushless servo motors provide high torque/volume ratio, and they are integrated into the mechanical platform without mounting elements. As a result making use of direct drive brushless servo motors imply low weight and low volume turret system. One example of turret system is shown in Fig. 1. In this paper, design considerations of a direct drive servo motor which is used in electro-optical director application.

3. Basic design choices of two motors

3.1. Concentrated winding motor with 36 slots/32 poles combination

Concentrated double layer winding is the design choice for the motor. Shorter end turns and lower overall volume are two major driving motivations for the selection. 36 slots and 32 pole combination is selected to maximize winding factor [1]. Pole number is selected as high as possible to increase torque density. Since the application requires low-speed operation of the motor, high pole number does not constitute a harmful effect on the core loss and efficiency.

3.2. Distributed winding motor with 39 slots and 12 poles

This motor is currently being used in the application. It was designed with double layer distributed winding. 39 slots and 12 poles for three phase motor yields unbalanced winding.

36/32 motor is designed specifically for the application whereas 39/12 motor is an off the shelf product and adapted for the application. The design of 36/32 motor is driven by a geometric envelope of 39/12 motor which is confined by stator outer diameter (OD), inner rotor diameter (ID) and axial length. Other internal geometric parameters are free variables, and they are optimized during the design to meet torque output while obeying certain limits of slot current density and magnetic flux density. Because of the intermittent operation of the application, 8 A/mm^2 of current density is observed. Magnetic flux density limit is set to 1.7 T on average by considering saturation limit of selected magnetic material.

Table 1 shows the summary of some key points of two motors. As mentioned outer envelopes of two motors are identical whereas

Table 1
Some geometric and electrical data of 39/12 and 36/32 motors.

	39/12	36/32
Average phase resistance (mΩ)	539.5	357.9
Line-to-line inductance (mH)	5.4	1.734
Winding factor	0.947	0.945
Stator outer diameter (mm)	180	180
Rotor outer diameter (mm)	113	135.5
Stack length (mm)	30	30
Stacking factor (k_{stk})	0.97	0.97
Skewing factor (k_{skew})	1	0.88

36/32 motor has almost 20% larger rotor diameter than 39/12 motor has. This case implicates more than 40% higher torque capability for the same electric and thermal loading this is well known from the $T = KD^2L$ sizing equation. However, 40% torque increase would not be possible because larger rotor diameter reduces stator winding slot area for the fixed stator OD. Hence the slot current density of 36/32 motor would be higher than slot current density of 39/12 motor because of the smaller winding area. On the other hand, due to the longer end winding, distributed wound 39/12 motor has higher phase resistance value than concentrated wound 36/32 motor as given in Table 1. Stator winding area versus current density versus phase resistance relation is investigated during thermal analysis for two motors. Analysis indicates that concentrated-winding 36/32 motor has some advantages for thermal loading of the machine.

4. Comparing two winding structures

Before starting performance comparison of two motors, it is worth to give their characteristic features as cited in the literature. The concentrated winding is well known for sub-harmonics in its MMF distribution [4]. Although not commonly used, unbalanced distributed winding also suffers from the low order magnetomotive force (MMF) harmonic [5,6]. The unbalanced winding is a result of improper slot/pole combination whose major advantage is lower cogging torque. Sub-harmonics of MMF do not have any contribution to useful torque production. They may be responsible for many performance deteriorating features such as torque ripple, higher radial force, and additional core loss. As far as MMF harmonics are concerned, balanced concentrated and unbalanced distributed windings resemble each other.

Before starting a comparison of two motors, it would be helpful to determine the sub-synchronous and super-synchronous components in MMF. In the MMF harmonic content, a number of pole pair is the main space harmonic order. Harmonic orders smaller than main space harmonic order are called sub-synchronous components. Similarly, harmonic orders greater than main space harmonic order are called super-synchronous components.

4.1. Stator MMF comparison

Stator MMF distribution of the machine with 39/12 slot/pole combination is given in Fig. 2. The results are given for 14.5 Arms phase current, and 16 turns per coil winding design. Fig. 3, on the other hand, shows the MMF distribution of the machine with 36/32 slot/pole combination. This machine has the same effective (RMS) phase current. But its number of turn per coil is fixed at 18 during the design. Fig. 4 shows the MMF harmonic contents of 39/12 and 36/32 machines. It should be noted that Fig. 2 is only valid for symmetrical phase current. In this application, the current regulation algorithm of the motor driver assures the current symmetry. Hence, balanced current is considered in the analysis.

As seen from harmonic contents of two motors, sub and super harmonics occur in two motors. Fundamental components of 39/12