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A new structure for hybrid stepper motors with improvements in torque density

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Abstract

Stepper motors are one of the highly used actuators in robotics and automation industries. Among various types of them, hybrid stepper motor is the most famous one because of its highest torque density. In this paper a new structure for hybrid stepper motors with a significant improvement in motor torque density is introduced. This improvement is based on flux path optimization and reducing reluctance in the stator. In this design, the magnetic flux path is reduced only to a small section along with the stator height. Furthermore, the rotor and stator teeth are longer in height which is due to the optimization of the space in the motor and also, the rotor diameter has become bigger. These changes have increased motor torque density dramatically. To investigate the influences of these improvements, a conventional hybrid stepper motor with the same volume is chosen and modeled. Both of these 2 motors are simulated using Ansys Maxwell software. Comparing their results proves that the torque density in the new motor structure is increased by more than 200%.

Key words

Holding torque, Hybrid stepper motor, torque analysis, Torque density

I. INTRODUCTION

Stepper motor is a common actuator in most of mechatronic systems such as industrial robots, humanoid robots and even CNC machines. These motors can be considered as a synchronous motor which rotates in discrete steps. On important characteristics of this motor is that in contrary to other types of motors, these motors are made to have produce high cogging torques which is ideal for position controlling. Stepper motors are categorized in 3 different types. Variable reluctance stepper motor has a stator with several poles and a light toothed rotor. Permanent magnet stepper motor which is the second type of stepper motors has a stator structure similar to variable reluctance stepper motors but its rotor is a non-salient pole rotor composed of permanent magnet material. The last type of stepper motors is the hybrid stepper motor. This type is a combination of 2 previous types. It has a stator similar to other types but its rotor consists of a permanent magnet and a toothed cylinder covering the permanent magnet. Due to the combination of teeth and permanent magnet in this rotor, this motor has usually high torques but low speed.

Within previous decades, too many papers have been published about stepper motors. However, most of them are about different methods for controlling its speed or its position and a very small part of these researches are about stepper motors` structure and very few efforts have been made to improving its torque density.

Jenkins et al. [1] have investigated a method for optimization of rotor magnets and stator coils flux balance to obtain desired holding torque. By preparing the equivalent magnetic circuit of the motor, they could calculate its parameters for different rotor positions. Jung et al. [2] also have worked on holding torque optimization in permanent magnet stepper motors. They analyzed the stepper motor with several selected parameters such as teeth form and the number of wire-turns in each stator pole using 3D FEM along with the design of experiment (DOE) method. Kosaka et al. [3] also investigated a nonlinear magnet analysis in a hybrid stepper motor. Their aim was to increase 3D FEM analysis speed.

Matsui et al. [4] have worked on analyzing continuous torque in hybrid stepper motors. They prepared the motor`s magnetic circuit and divided the air gap between rotor and stator into 5 separate spaces and calculated permeability for each section and calculated the motor`s continuous torque with the use of these calculations. Rao et al. [5] also analyzed hybrid stepper motor`s torque using its equivalent magnetic circuit along with 2D FEM. They have used the same method as Matsui et al. Stuebig et al. [6] have introduced a method to calculate the stepper motor parameters by combining FEM and analysis method which is faster compared with those methods alone. They used the motor`s equivalent magnetic circuit and 2D FEM to calculate magnetic permeability for each element. After the calculation of the required parameters, the motor`s torque was calculated. Kang et al. [7] introduced a parametric magnetic model for a 5-phase hybrid stepper motor and with the help of 2D FEM, the motor`s torque calculated. Lim et al. [8] with the help of neural network could estimate unknown parameters in a 5-phase stepper motor for applying to equivalent magnetic circuit and FEM.

A lot of researches also have been done on different methods to control stepper motors behavior and response. Furthermore, several different structures for stepper motors are introduced by researchers. New methods to control rotor position without using mechanical or electrical and just by mathematical calculations along with digital signal processing have been proposed by Bendjedia et al. [9], Lin et al. [10] and Butcher et al. [11]. Le-Huy et al. [12] have proposed a comprehensive model to be used in MATLAB-SIMULINK for calculating motor`s parameters. Lu et al. [13] have designed a new stepper motor with permanent magnets applied to its stator structure. Kavitha et al. [14] also have designed a novel disk type stepper motor.

Based on the above-mentioned information, this type of motor needs more attention. Hence, in this paper, a new structure for hybrid stepper motors is introduced which provides higher torque density compared with conventional stepper motors. In section II, conventional hybrid stepper motors are described. Then, in section III a real conventional motor is introduced and modeled. In section IV, the new motor is introduced and described and in section V, 2 motors are compared and their results are investigated.

II. CONVENTIONAL HYBRID STEPPER MOTORS FUNDAMENTALS AND MODELING

Hybrid stepper motors consist of a 3-part rotor and a stator. The rotor includes a permanent magnet between 2 half rotors that makes one half rotor N magnetic pole and the other half, S magnetic pole (Figure 1). For 1.8° stepper motors, both half rotors have 50 teeth and these half rotors are positioned in nonalignment state with each other.

The stator in these stepper motors usually has 8 poles with 5 teeth on every pole. These 8 poles usually are divided into 2 phases with 90° mechanical phase difference for each pole of a phase. Each stator pole has a coil that excites and magnetizes it at the right time. Since stator poles are as long as 2 sections of the rotor plus the gap between them, this excitation produces both attraction and repulsion at the same time. Up rotor and down rotor have different magnetic poles and are in nonalignment state hence, each excited stator pole attracts teeth of the half rotor with opposite magnetic pole and repulses teeth of the other one. Figure 1 shows the arrangement of the motor components.

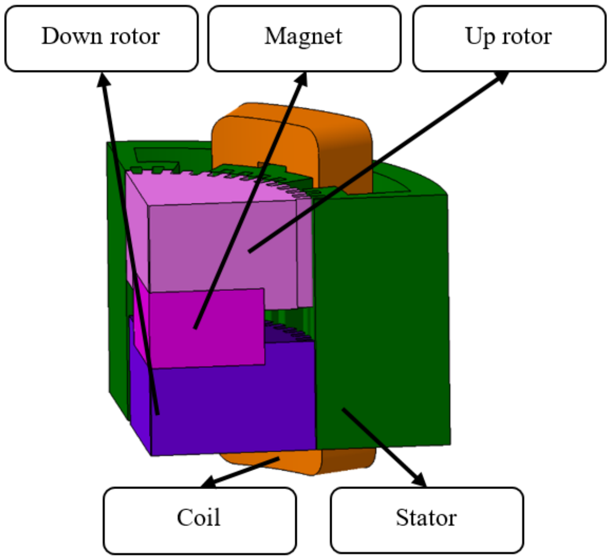

Figure 1: A quarter of conventional hybrid stepper motors

To understand hybrid stepper motor fundamentals and the way it works better, a sample conventional hybrid stepper motor was modeled and simulated. Therefore, a Japanese stepper motor named Sanyo Denki with model number 3210-770-103 which is a 2-phase hybrid stepper motor was chosen (Figure 2). Its specifications and dimensions are listed in Table 1.

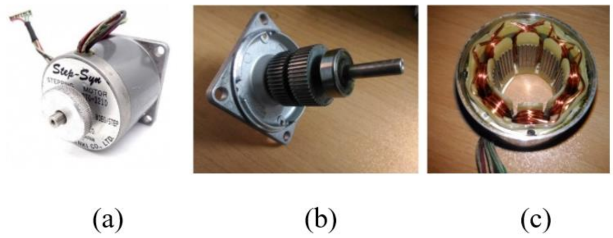

Figure 2: Sanyo 3210-770-103, (a) Whole motor, (b) Rotor, (c) Stator

Table 1:Sanyo motor specifications

Motors outer diameter	56.5 mm
Motor body height	52 mm
Stator outer diameter	54.1 mm
Stator inner diameter	30 mm
Number of teeth in each stator pole	5
Stator teeth depth	1.25 mm
Stator height	23 mm
Air gap	0.1 mm
Rotor outer diameter	29.8 mm
Each rotor`s height	10 mm

Distance between 2 rotors	3 mm
Number of teeth in each rotor	50
Rotor teeth depth	1.5mm
Magnet`s diameter	20.8 mm
Magnet`s height	13 mm
Number of wire-turns per coil	32
Wire diameter	0.6 mm
Stator and rotors material	Steel 1008
Magnet`s material	NdFe35
Stator and rotors teeth fillet radius	0.125 mm
Maximum nominal current	3 A
Angle per step	1.8°

This motor consists of 8 coils on its stator and 2 rotors which are connected by a magnet and have a 3mm air gap that has made them apart. The up rotor and down rotor teeth are in nonalignment condition which is necessary for the magnetic flux to pass correctly and the motor to rotate.

To model this motor, some specifications such as magnet type were unknown; therefore, the trial-and-error method was used to identify these unknown parameters. To do this, one of the motor phases was excited with several coil currents and the motor holding torque was measured. The test procedure consists of making a load torque large enough so that the motor torque is failed to hold that load. This critical load is recorded as holding torque threshold for that specific current excitation. Table 2 shows the results for tested points.

Table 2: Stepper motor experimental results

Current [A]	Weights mass [gr]	Torque [N.mm]
1.05	218	130.8
1.53	297	178.2
1.96	373	223.8
2.35	433	259.8
2.73	477	286.2

Then, a model for this motor was prepared in Ansys Maxwell software and model was excited with these currents using different permanent magnet materials to find the proper one. Finally, the model results were compared with the real motor results. Practical evidences proved the similarity of the model motor to the real motor with a good approximation. Figure 3 shows the holding torque vs. current comparison between the model and the real motor.

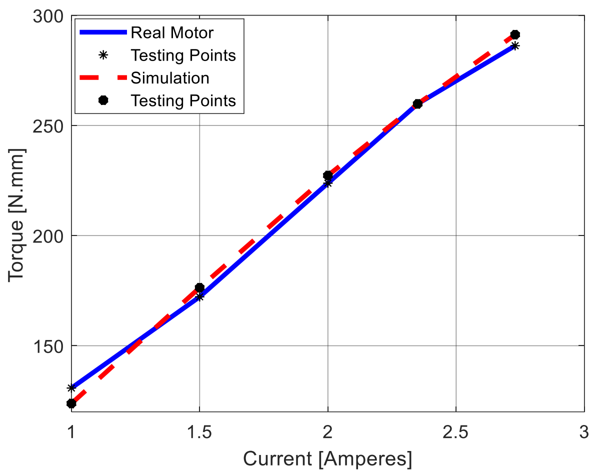

Figure 3: Real motor and simulated model output torque

III. DESIGNING THE NEW STRUCTURE

Design of the new motor with higher torque density is based on the analysis of the conventional motors. In conventional hybrid stepper motors the magnetic flux path has to pass a longer path to complete its circuit. Longer path means higher reluctance and less focused flux which will lead to less interaction between rotor and stator and so weaker torque. Also, since the motor needs to compensate for reduced flux, it needs more wire-turn numbers in stator poles. This problem causes saturation to happen in the coil holding places of the poles which is due to the thinner area section these places have. Figure 4 illustrates the flux path schematic in a section of conventional hybrid stepper motors.

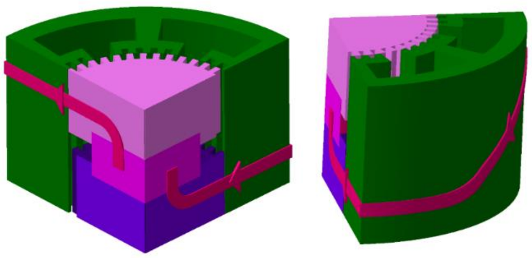

Figure 4: Flux path schematic in a quarter of the motor

As can be seen in Figure 4, in conventional stepper motors, the magnetic flux should pass a quarter of the stator to reach the appropriate pole to pass to the rotor. If the new design reduces the flux path, the motor needs fewer wire-turns for the same level of magnetic flux in the air gap. Therefore, the saturation problem in critical areas of the stator will decline significantly. Besides that, since the demand for more wire-turns is reduced, not only the cross-section of the coil holding part of the poles can be bigger but also the stator poles can be smaller which means the motor can have a rotor with a larger diameter. Hence, the motor can produce higher torques for the same excitations. Moreover, due to the increase in coil holding parts cross-section, it can accept higher levels of excitation without going to the saturation phase.

The new structure has reduced the above-mentioned problems. It has a rotor similar to the rotor in conventional stepper motors but in stator each pole is divided to an upper pole and a lower pole with coils turned in opposite directions (Figure 5). So, the stator has 2 phases with 16 poles in it and each phase has 8 poles. As is clear in Figure 5, this structure makes a strong magnetic field in each section of the stator and this is because of coils wire-turn directions. Since the upper rotor has N magnetic pole and lower rotor has S magnetic pole, the interaction between each pole and the rotor is independent. Hence, each pole can produce attraction or repulsion independently. Therefore, there is no need for half rotors to be in nonalignment state; in fact, they must be in aligned state. Also, in the new design, the flux passes the stator axially from up stator pole to down one or vice versa (Figure 6) which means it does not need to pass a quarter of the motor which happens in conventional hybrid stepper motors. Consequently, the flux faces less reluctance and less division. Therefore, the motor will have the same flux in the air gap with less excitation. In Figure 7 the new design and the whole motor is illustrated.

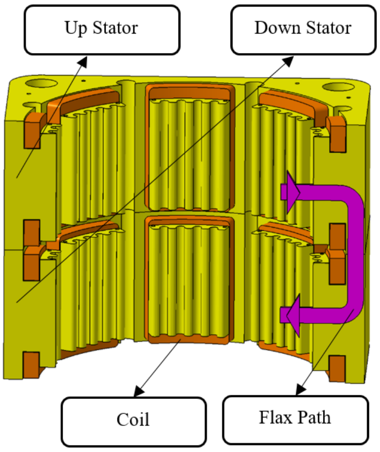

Figure 5: Schematic of half of the stator and the flux path through the virtual magnets made in each pole couple

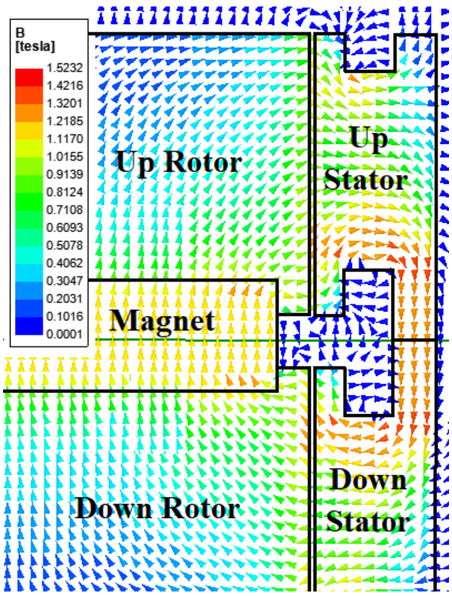

Figure 6: Magnetic flux path in the new model

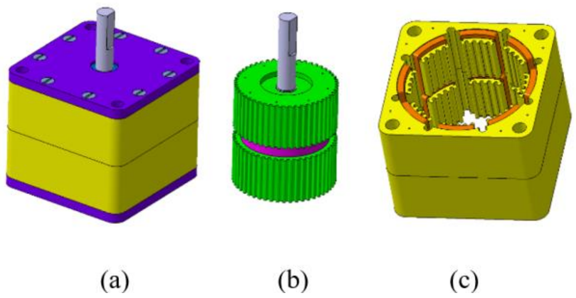

Figure 7: New designed motor, (a) total, (b) rotor, (c) stator

As mentioned before, wire-turn numbers in the new design have been reduced therefore, the stator poles have become smaller letting the rotor to have larger diameter. consequently, the rotor in the new motor is almost 1.35 times the rotor in the Sanyo stepper motor. New motor structure specifications are listed in Table 3.

Table 3: New motor specifications

Motors outer width	56.4 mm
Motor body height	50 mm
Stator outer width	56.4 mm
Stator inner diameter	50.4 mm
Number of teeth in each stator pole	5
Stator teeth depth	0.75 mm
Stator height	2*17.5 mm
Air gap	0.1 mm
Rotor outer diameter	40 mm
Rotor height	2*17.5 mm
Distance between 2 rotors	3 mm
Number of teeth in each rotor	50
Rotor teeth depth	1.25 mm
Magnet`s diameter	35 mm
Magnet`s height	5 mm
Number of wire-turns per coil	26
Wire diameter	0.6 mm
Stator and rotors material	Steel 1008
Magnet`s material	NdFe35
Stator and rotors teeth fillet radius	0.125 mm
Maximum nominal current	4 A
Angle per step	1.8°

After designing the new motor model, to investigate its performance, it was tested with 1.5A coil excitation. Output torque peak to peak difference in this motor was significantly higher than the conventional motor. Figure 8 shows the torque curve for both motors with 1.5A coil excitation.

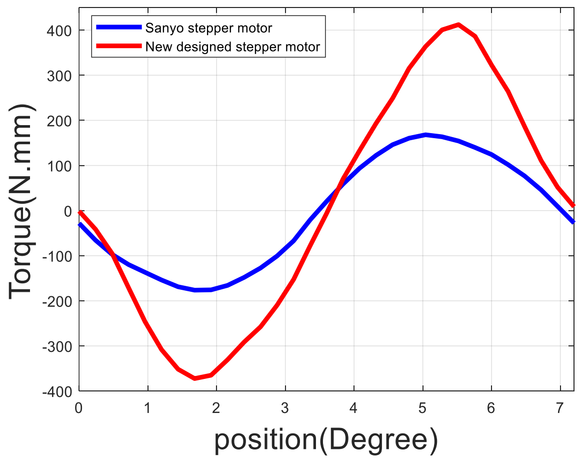

Figure 8: Comparison between Sanyo stepper motor and new designed stepper motor at 1.5A coils excitation

IV. MOTORS COMPARISON

The comparison between 2 motors for 1.5A coils excitation illustrated the significant improvement in torque density for the new motor. To ensure that this trend continues for various coils excitation, the 2 motors were tested for several sample points to check the amount of torque produced by them. Figure 9 represents these 2 stepper motors` output torques for different coils excitations. The new motor uses only 16% more wire than the Sanyo stepper motor with the same volume, but as it is clear from the Figure 9, its output torque for different excitations is significantly higher than the conventional stepper motors. Besides, the Sanyo stepper motor around 3A starts to be influenced by saturation effects whereas this problem for the new motor starts from excitations more than 4A.

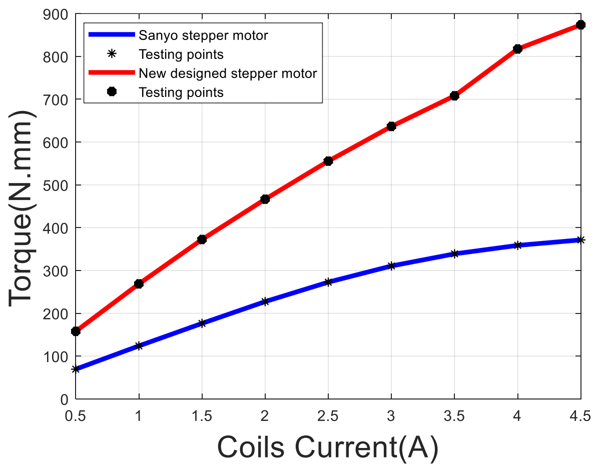

Figure 9: Two motors` output torque and saturation effects on their performance

V. CONCLUSION

In this paper, a new hybrid stepper motor with higher torque density compared with conventional ones was introduced. In the presented motor each stator pole divided to 2 section and each section has a coil and roles as a new pole. This change makes the flux path shorter and leads to a more focused flux flows through the stator and more powerful interaction between rotor and stator. So, the presented design has a higher torque compared to conventional stepper motors with the same size. However, the manufacturing process in the new motor is a little more complicated due to winding each upper and lower pole of stator separately but it seems that the advantages of higher torque density can overcome it.

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