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Experimental Evaluation of Static torque Characteristics of a Double-Stator Switched Reluctance Machine

***Abstract**. Double-stator switched reluctance machines have higher torque density and lower vibration and acoustic noise level in comparison with conventional switched reluctance machines. Static characteristics of a 8/6 Double-stator switched reluctance machine have already calculated using finite element method. However, no measurement has been presented for the static torque of the machine. This paper presents experimental evaluation of static torque characteristics of a 8/6 double-stator switched reluctance machine. For this purpose, an experimental setup is developed for static torque measurement of the machine for different current levels and rotor positions. Finite element calculation the static torque of the machine is also presented for the sake of comparison. It is observed that, experimental results are reasonably close to the simulation results.*

***Streszczenie.** W artykule opisano badania eksperymentalne nad maszyną reluktancyjną przełączalną 8/6 DSSRM (ang. Double-Stator Switched Reluctance Machine), mające na celu oszacowanie charakterystyki statycznej momentu maszyny. Do realizacji badań zbudowano stanowisko, pozwalające na pomiary momentu przy różnych wartościach prądu oraz pozycji wirnika. W analizie wyników wykorzystano metodę elementów skończonych. Wyniki eksperymentalne są zbliżone do symulacyjnych. (**Eksperymentalne wyznaczenie charakterystyki statycznej momentu maszyny reluktancyjnej przełączalnej o podwójnym stojanie**).*

Keywords: Double-stator, switcher reluctance machine, measurement, finite element method, static torque.
Słowa kluczowe: podwójny stojan, maszyna reluktancyjna przełączalna, pomiar, metoda elementów skończonych, moment statyczny.

Introduction

High torque density is an essential requirement for electrical machines used in many applications such as aerospace and automotive systems [1]. Switched reluctance machines are doubly-salient singly-excited reluctance machines, which has salient poles on both rotor and stator sides with no excitation windings, magnets, or cage winding on the rotor [2]. SRM drive systems have gained considerable popularity for automotive, defense and aerospace applications which require ruggedness, high speed capability, and fault tolerance [3-5]. However, they suffer from some drawbacks such as a high level of vibration and acoustic noise, large torque ripple, and low torque per unit volume with respect to permanent magnet machines [5-7].

Many efforts have been performed on the design and control of SRM to improve their. However, most of these approaches are trying to handle pole arcs of stator and rotor to reduce the torque ripple [8-12]. Nevertheless, handling the pole arcs has severe problems, such as decreasing average torque and increasing weight of the motor.

A novel double-stator switched reluctance machine (DSSRM) is introduced [13]. In contrast with conventional SRM in which majority of the generated electromagnetic forces is in radial direction with no contribution to the motion, DSSRM offers a much more efficient configuration in terms of generation of motional forces. DSSRM provides a substantial improvement in energy conversion efficiency by establishment of a novel shortened flux path [12]. Therefore, DSSRM has much higher torque density compared to conventional SRM which makes them suitable candidate for EV and HEV applications.

Determination of the static torque characteristics is an important issue in the optimal design and control of the DSSRM. It can be achieved by different methods such as analytical methods, numerical methods and experiments. Finite element method (FEM) has been applied to a DSSRM for determining its static characteristics [13]. However, no measurement and experimental evaluation is presented for static torque characteristics of the machine. This paper presents an experimental method for measuring static torque characteristics of a 8/6 DSSRM. Static electromagnetic torque of the machine is measured for different rotor positions and current levels. The FEM is also used for comparison with measurement results. Experimental results verify the results obtained by FEM.

Double Stator-Switched Reluctance Machine

Double-stator switched reluctance machine (DSSRM), is a novel variable reluctance synchronous machine that is designed to perform at high torque levels [12]. This machine benefits from two stators which are made of laminated ferromagnetic material (M-19) and are equipped with concentrated windings. They are located on the interior and exterior of a cylindrical rotor. The rotor is formed by segments of laminated M-19 which are hold together using a non-ferromagnetic cage. The cross section of a 4-phase 8/6 DSSRM is illustrated in Fig. 1. The specifications of the prototype DSSRM are listed in Table I.

Finite Element Analysis

Time stepping FEM is used for analysis of the machine for comparison with measurement results. Using magnetic vector potential and based on Maxwell equations the motor equation of the motor in 2D plane is expressed as:

$$\nabla \times \frac{1}{\mu} \nabla \times A_z + J_0 = 0 \quad (1)$$

where: μ, A_z and J_0 are the permeability, the magnetic vector potential in z-direction and the imposed current density respectively.
The current density is calculated as:

$$J_0 = \frac{NI}{A_c} \quad (2)$$

Where: *N*, *I* and A_c are the number of turns of coil, the phase current and the effective area of coil respectively. The current in each coil is also determined as:
where V_{DC}, E and *R* stand for the applied voltage, the inducted back-EMF of coil, and the coil resistance respectively.

$$I = \frac{V_{DC} - E}{R} \quad (3)$$

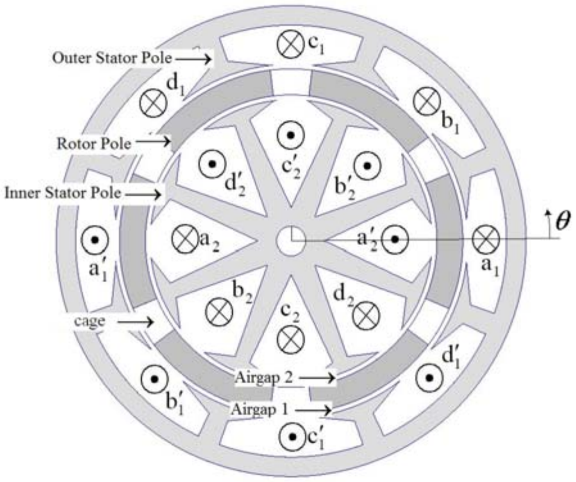


Fig. 1. Cross section of a 8/6 four-pole DSSRM

TABLE I: Parameters of the DSSRM

Number of stator poles	8
Number of rotor poles(Segments)	6
Number of phases	4
Outer radius of outer stator	72.0mm
Outer radius of inner stator	43.9mm
Rotor segment thickness	9.0 mm
Airgap 1 and Airgap 2	1.0mm
Stack length	115.0mm
Arc of the rotor segments	47 degree
Number of turns per phase	50
Rated current	30A
Rated voltage	100V
Resistance per phase	0.78 Ω
Stator winding material	copper
Lamination material	M19
Mass of copper	3.1kg
Mass of iron	5.0kg

By solving (1) to (3) in each time step the magnetic field is determined in every part of motor. Flux density distribution in the machine is for both unaligned and aligned positions for (i=20 A) is depicted in Fig. 2. Based on obtained magnetic fields and Maxwell stress tensor method normal and tangential components of the force density as well as total torque applied to the rotor are calculated as [13]:

(4) $$f_n = \left(B_n^2 - B_t^2\right) / 2\mu_0$$

(5) $$f_t = \left(B_n B_t\right) / \mu_0$$

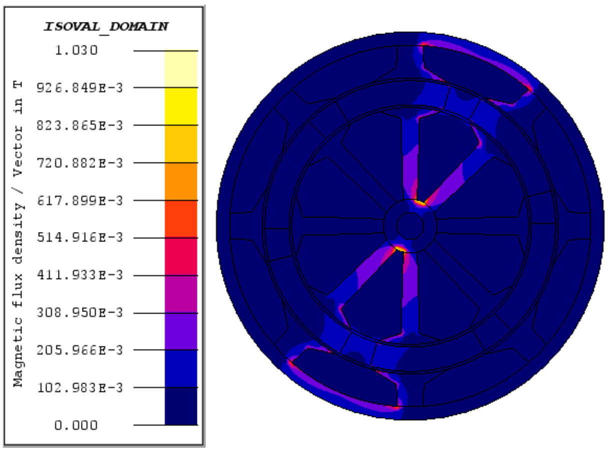
(6) $$T = \int_0^{2\pi} L f_t R^2 \theta d\theta$$

where *L*, *R*, B_n and B_t are the stack length, the air-gap radius, the normal component of flux density and the tangential component of flux density respectively.

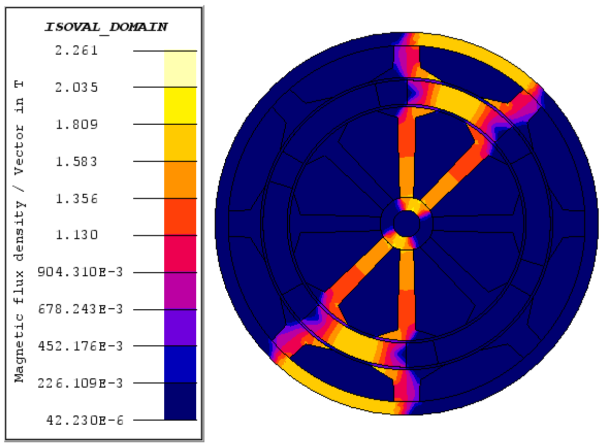
Experimental Study

In this section the static magnetic torque of a DSSRM with specifications listed in Table I is measured. Static torque measurement is done in this study using an experimental setup as shown in Fig. 3. To perform the test, rotor is locked in each specific rotor position using the index head. The experimental measurements are started when the rotor is fully aligned and ended when the rotor is completely unaligned. A torque meter is installed between rotor shaft and index head. A dc current is injected to the phase winding. The output voltage of the torque meter and the phase current are measured and the static torque for different rotor positions ($\theta = 0$ to 30 degree) and currents (i=2.5, and 10 A) are obtained. The results are shown form Fig. 4 and Fig. 5. It can be seen that the peak torque occurs at half aligned position. The higher the excitation currents, the higher the peak torques.

It is observed a good agreement between experimental measurements and finite element (FE) calculations.



(a)



(b)

Fig. 2. Flux density distribution of the DSSRM A) unaligned b) aligned

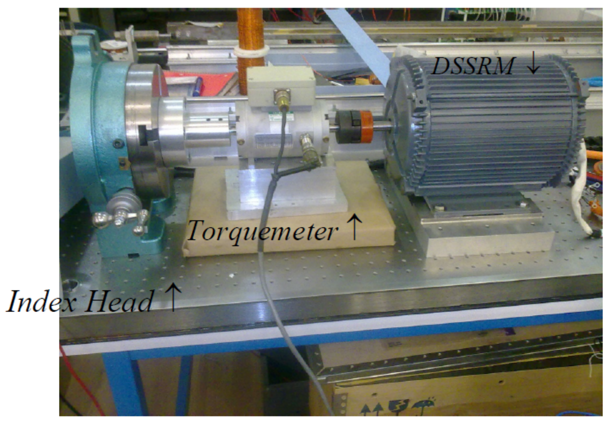


Fig. 3. The test set-up for the static torque measurement.

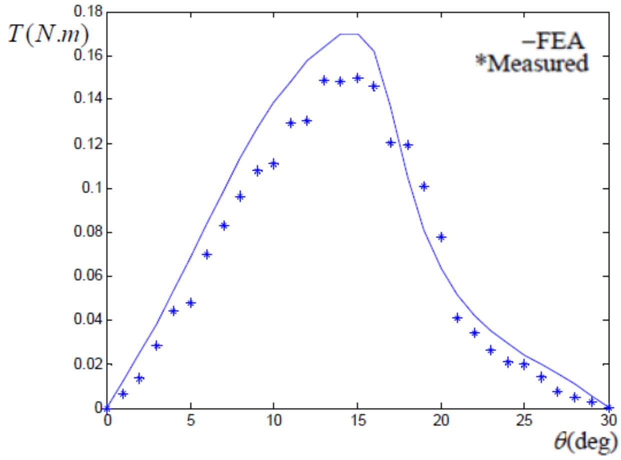


Fig. 4. Static torque rotor position for i=2.5 A

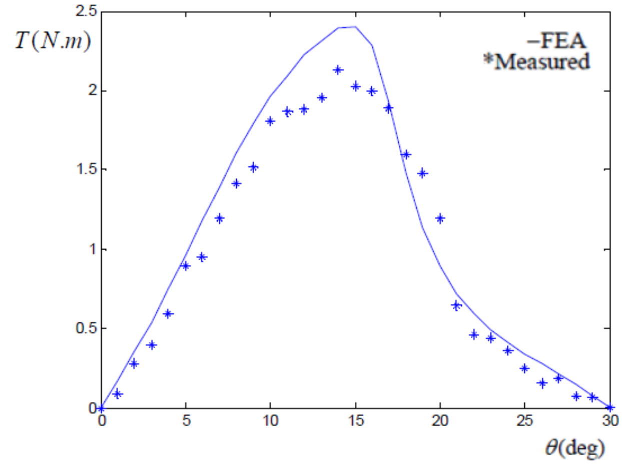


Fig. 5. Static torque rotor position for i=10 A

However, a difference between FE and measured results is observed which is mainly due to three dimensional effects which are ignored in FE analysis and modeling of the nonlinear characteristics of laminations. However, this difference is limited to around 12 percent for the worst case occurring in the peak of torque curve.

Conclusion

Static torque characteristics of a 8/6 double-stator switched reluctance machine is measured. For this purpose an experimental setup including the machine, the index head and a digital rotary torque meter is used to measure the static torque performance of the machine as a function of rotor position for different current levels. A finite element model of the machine is used to compare the numerical results with measurements. It is shown that the difference between finite element calculations and experimental results is less than 12 percent for static torque measurements.

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