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New Shape of Rotor Flux Barriers in Synchronous Reluctance Machines Based on Zhukovski Curves

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***Abstract* – Synchronous reluctance machines become of more interest nowadays due to robust construction and lack of field winding in the rotor which significantly reduces power losses. Rotor of such machine can be of two types: axially laminated (ALA) in which steel sheets are placed along the rotational axis and transversally laminated (TLA) in which steel sheets are placed perpendicularly to the shaft. Since machines with rotors of ALA type are more difficult to manufacture, TLA type machines are more popular. Flux barriers provide anisotropy of the magnetic circuit of the rotor which is necessary to generate the torque. Shape and number of flux barriers have significant influence on motor's properties such as generated torque or torque ripple. Many attempts have been made to optimize rotor's structure from electromagnetic and structural point of view. This paper presents application of Zhukovski's function in creating of flux barriers' geometry in synchronous reluctance machine of TLA rotor type.**

Keywords—Synchronous Reluctance Machine, Zhukovski Airfoil Function, Finite Element Analysis, Flux Barriers

I. INTRODUCTION

Reluctance motors have many advantages like low cost, simple construction and do not require external excitation source which reduces rotor power losses. Development of power electronics allowed reluctance motors to be used as drives in many industry applications. This is why they are of big interest nowadays [7]. The stator of synchronous reluctance machine is identical to that of an induction motor and only the rotor has salient poles. The rotor requires no cage or field winding which makes it potentially less expensive than permanent magnet motor or an induction motor. Conventional synchronous reluctance machines have simple rotor designs but unfortunately this makes their performance poor due to an inadequate ratio between the inductances on the direct and quadrature axis. The axially laminated rotors have a good saliency ratio and performance but the manufacture process is more complicated and that makes them more expensive. In practice, transversally laminated rotor design is the best choice for industrial manufacturing [2], [3], [8]. Moreover the transverse-laminated rotor can be easily skewed, thus allowing for very low values of torque ripple [9]. Torque produced by synchronous reluctance machine depends on the $\frac{L_d}{L_q}$ ratio where L_d and L_q are machine's inductances in direct and quadrature axis respectively. One can notice that increasing L_d and decreasing L_q the ratio increases and thus the torque generated by the machine is higher. By proper distribution of flux barriers, one can find optimal value of the $\frac{L_d}{L_q}$ ratio. Different methods of optimization of rotor with internal flux barriers have been studied to increase machine's performance [7], [10], [11].

II. ROTOR TOPOLOGY

Fig.1, presents one pole of synchronous reluctance machine with four flux barriers in the rotor. Rotor symmetry d and q axes are also presented. As one can see, position and size of flux barriers affect the amount of magnetic flux in the rotor both in d and q axis. Thin flux barriers reduce the reluctance in d axis which makes the L_d inductance grow, but at the same time L_q inductance increases.

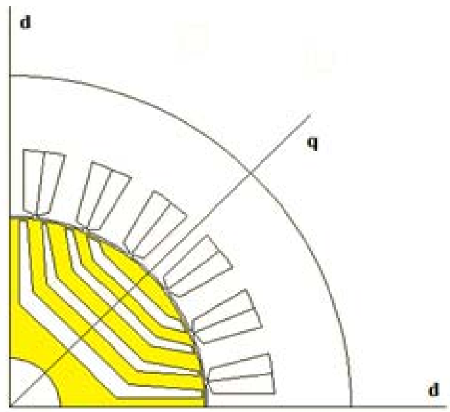

Fig. 1. One pole of synchronous reluctance machine with four flux barriers in the rotor.

Apart from the size and number of barriers, their shape is also significant since it modulates the path of magnetic flux that penetrates the rotor. In a machine with no flux barriers in the rotor, flux lines follow the path as shown in Fig. 2.

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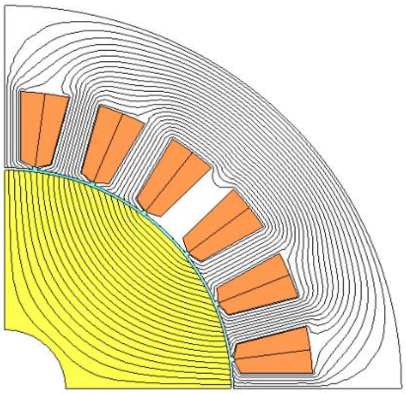

Fig. 2. Natural flux lines in machine with no flux barriers in the rotor

The shape of natural lines of magnetic flux can be recovered using Zhukovski's airfoil potential function [5].

III. ZHUKOVSKI'S FUNCTION

Zhukovski (noted also as Joukovsky) transformation is a conformal mapping and generates families of orthogonal lines. It is commonly used in aerodynamics where it reduces the flow around a wing profile to the flow around a circle [1]. Zhukovski's function is given by the formula:

$$f(z) = \frac{z + \frac{a}{z}}{2} \tag{1}$$

In this equation, z is a complex number and a is a positive number [1]. In [4] the authors applied Zhukovski's function to Coulomb problem which led them to modified function of the form:

$$g(z) = \left(z + \frac{a}{z}\right)^2 = z^2 + 2a + \frac{a^2}{z^2} \tag{2}$$

Given that $z = x + iy$ where x and y are real numbers and $i^2 = -1$, imaginary part of function $g(z)$ is of the form:

$$Im\{g(z)\} = 2xy - \frac{2xya^2}{x^2 + y^2} \tag{3}$$

Desired curve is characterized by the equation:

$$2xy - \frac{2xya^2}{x^2 + y^2} = v \tag{4}$$

Where v is a real number greater than zero. As one can notice, this equation cannot be solved analytically either for x or y, but it can be solved numerically using dedicated software. For this problem, MATLAB® software is used. Example curves plotted in MATLAB® for parameter $a = 30$ and three different values of v are presented in Fig. 3.

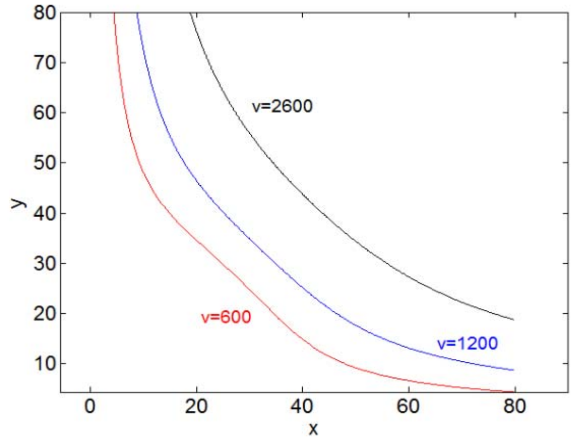

Fig. 3. Example Zhukovski curves for $a = 30$ and three different values of v

As one can see, by changing the values of parameters a and v, it is possible to modify the shape of the curves and their distance from the origin (therefore the distance between each curve), which is crucial when specifying positions of flux barriers in the rotor. Distance of the curve from the origin as a function of two parameters a and v is presented in picture below.

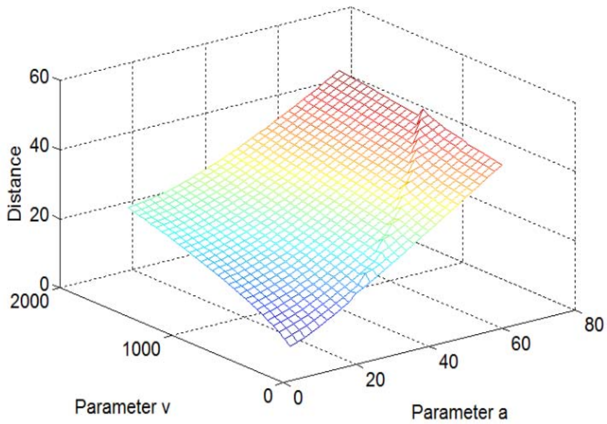

Fig. 4. Distance of the curves from the origin as a function of two parameters

IV. DESIGN PROCESS

Design process of the synchronous reluctance machine, started with setting basic geometry parameters. Next for given number of poles and flux barriers per pole in the rotor, Zhukovski's curves have been constructed using a program developed in MATLAB®. Each curve consisted of 300 points, which was enough to obtain smooth shapes of the flux barriers. These points were exported to a DXF file so that the geometry could be imported by any finite element analysis (FEA) software. The model of the machine was created in JMAG® using the DXF file with the geometry of the flux barriers. The entire process of creating the model of the machine in JMAG® was automated due to application of Visual Basic script. The process of machine's model creating is described by the diagram below.

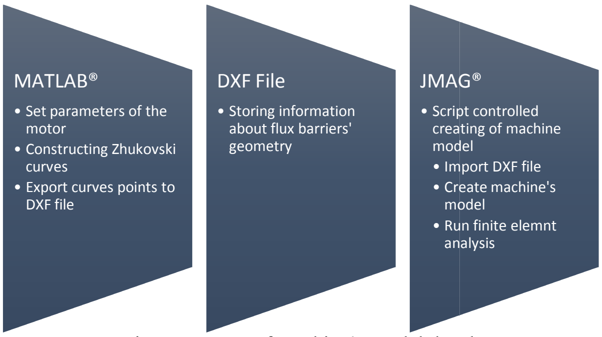

Fig. 5. Process of machine's model development

Creating of stator topology was entirely controlled by the script due to simple geometry of the stator slots.

V. RESULTS

Following the design process described in previous paragraph, a synchronous reluctance machine's model with the following geometry was created and analyzed in JMAG®.

TABLE I
GEOMETRY PARAMETERS OF SYNCHRONOUS RELUCTANCE MACHINE

Parameter	**Value**
Rotor's radius	85.5 [mm]
Air gap length	0.5 [mm]
Stator's outer radius	130 [mm]
Shaft radius	22 [mm]
Number of stator slots	24
Number of flux barriers per pole	4
Number of poles	4

Next, the designed model of the machine was analyzed in JMAG® using finite element method. Due to the symmetry of the machine, only one pole was analyzed. Its geometry, together with flux lines in no load state is shown below.

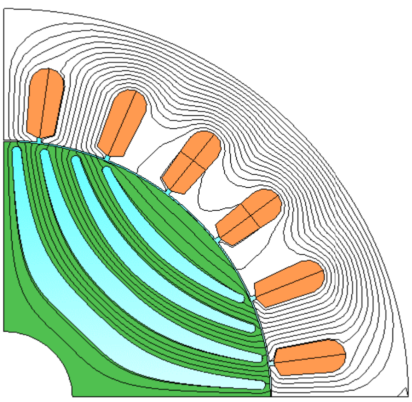

Fig. 6. One pole of the machine with flux lines: machine with Zhukovski type barriers in the rotor

The machine was supplied from three phase sinusoidal current source. It is worth mentioning that flux lines in the rotor in Fig. 6, have similar shape to that of flux barriers. For comparison, another synchronous reluctance machine's model, with round flux barriers in the rotor, has been simulated. The stator topology of the machine has remained unchanged. Topology of the second machine, together with flux lines in no load state, is presented in Fig. 7. Radial components of air gap magnetic flux density, in no load state, of both machine models are compared in Fig. 8. In both cases, the RMS value of supply current was 50 A and the rotational speed was equal to 1500 rpm. In the next step, the simulation has been run for the same values of supply current and rotational speed, but with angle between d-axis of the rotor and axis of first phase coil in the stator, equal to 30 degrees, which equals to operating of the machine in load condition. Torque waveforms of both machines are shown in Fig. 10.

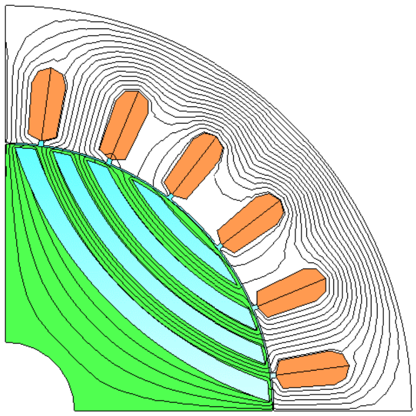

Fig. 7. One pole of the machine with flux lines: machine with round barriers in the rotor

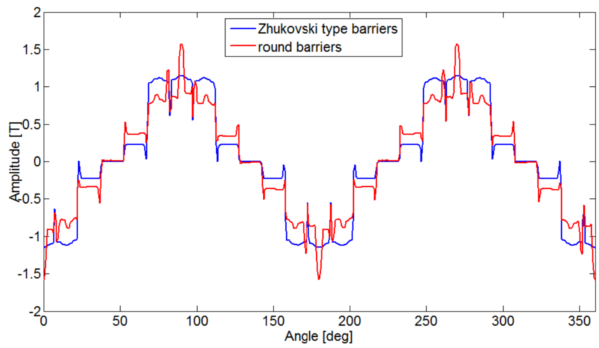

Fig. 8. Radial components of air gap magnetic flux density: machine with round flux barriers (blue) and machine with Zhukovski's curve based flux barriers (red)

Fast Fourier Transform (FFT) has been applied to air gap flux density signals, in order to compare the spatial harmonics of both machine topologies. The comparison is shown below.

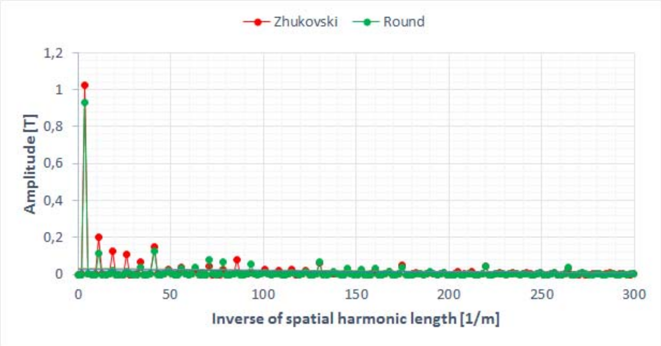

Fig. 9. FFT of air gap magnetic flux density: machine with Zhukovski flux barriers (blue) and machine with round barriers (green)

One can notice that first harmonic related to double length of rotor's polar pitch is higher for the machine with Zhukovski type flux barriers in the rotor. Machine with round flux barriers in the rotor generates more high frequency harmonics compared to the one with Zhukovski flux barriers.

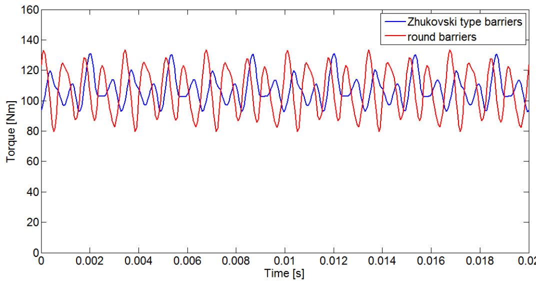

Fig. 10. Torque comparison: machine with Zhukovski's curve based flux barriers (blue) and machine with round flux barriers (red)

One can see that both machines have relatively high torque ripple. It is because no optimization of torque ripple or skewing has been applied. However, torque oscillations are higher in case of motor with round flux barriers. Values of average torque and torque ripple [6] are presented in table below.

TABLE II
AVERAGE TORQUE AND TORQUE RIPPLE VALUES OF TWO MACHINES

Zhukovski flux barriers	
Average torque	107.2 [Nm]
Torque ripple	35.6 %
Round barriers	
Average torque	106.5 [Nm]
Torque ripple	50.7 %

Machine with Zhukovski flux barriers in the rotor has developed a little higher torque than that with round barriers. The torque ripple is relatively high in both cases but for machine with round flux barriers, it exceeds 50 percent.

VI. CONCLUSION

In this paper, application of Zhukovski's function to create the geometry of rotor flux barriers has been studied. It has been proved, that flux lines in the rotor follow the path of Zhukovski's curves hence, it seems reasonable to fit the geometry of the flux barriers to their shapes. Since magnetic flux always follows the path of least reluctance, adjusting the geometry of flux barriers to natural flux path provides the maximum magnetic flux to penetrate the rotor.

Zhukovski's curves are hard to express in analytical form hence, numerical methods must be used to obtain desired flux barriers' geometry. This involves using dedicated software i.e. MATLAB®. Another issue is compatibility of the software. In this case, the geometry has to be exported to JMAG® via DXF file. The design process can be significantly simplified by using scripts. In this work, Visual Basic script has been used.

Developed model of synchronous reluctance machine has not been optimized for highest saliency ratio or minimized torque ripple, since the aim of this work is to show the possibility of using Zhukovski's curves in creating rotor's geometry. However, Zhukovski's function can be used in optimization algorithm and by adjusting the parameters of equation (4), one can obtain different shapes and positions of flux barriers and hence, different saliency ratios. Optimization of rotor's structure for saliency ratio and also optimization of entire machine's topology for reducing torque ripple will be the target of future work.

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