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Research Paper

A poynting vector approach to electromechanical energy conversion on electric machine operation

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Necati Fatih DEMIRAL[1], Tayfun DOGAN[1] and Necibe Fusun OYMAN SERTELLER[2*]

[1]Marmara University, Electrical – Electronics Engineering Department-Institute of Pure and Applied Sciences, Istanbul-TURKEY.
[2]Marmara University, Electrical – Electronics Engineering Department, Istanbul-TURKEY.

*Corresponding author. E-mail: fserteller@marmara.edu.tr.

ABSTRACT

This study presents a good process of electromechanical energy conversion using the fundamental of magnetic circuits, fields, and mathematical techniques in interactive motion. With the help of the simulation program, we analyzed a conventional, brushed, two-layer direct current motor using the electromechanical conversion system by analyzing the effect of the magnetic and electric materials on it. We studied the analysis of various and most preferred ferromagnetic material on the rotor of the direct current motor using Finite Element Method. This study showed that the power flow through any area can be calculated using the Poynting vector formula appropriately and in detail. For motor effective analysis, the total electric and magnetic fields can be used to determine the total power flow through the energy conversion system. Furthermore, the Poynting vector approach is sufficient and suitable for the electrical power analysis of electrical machines when deriving mathematical models and designing electric machines. This simulation may be intended for research purposes as well as for educational studies.

Key words: Poynting vector, DC motor, magnetic field, finite element method.

INTRODUCTION

In recent years, the application of direct current (DC) motors (machines) has gained a competitive advantage vitality over alternating currents (AC) machines in industrial operations. Large and medium types of DC motors are used, mostly in machine tools, conveyor fans, pumps, hoists, cranes, paper mills, etc. because of their basic design and their efficient operation. Small DC motors are used in the control of devices and electronic systems for stabile speed and position sensing. The increasing complexity of industrial applications and the demand for greater flexibility from electrical machines creates a great demand for the application of DC motors more than in previous years. The big advantage of DC motors over other motors is the fact that their speed is easily controlled with simple mathematical equations (Fitzgerald et al., 1992; Okoru et al., 2008; Ahmed et al., 2013; Oyman Serteller, 2014).

The flow of power in rotating electrical machines is an essential topic to understand the power losses, torque and efficiency. Studying the energy or power transfer in electrical machine requires a deeper understanding of the science of energy conversion (Urban et al., 2007). This is because there has not been an adequate concentrated effort to develop numerical procedures (Ahmed et al., 2013; Donaghy-Spargo, 2017; Czarnecki, 2006; Ferreira, 1988; Sutherland, 2007) for it, the Poynting vector has not attracted sufficient interest so far. In this study, a power analysis of conventional DC motors power is completed using the Poynting vector formulas with the help of FEM analysis. We present a coherent definition with graphed quantitative results from numerical calculations, in which the energy or power flow across the air gap between the stator and the rotor, and consumed power on the rotor (Urban et al., 2007; Ahmed et al., 2013; Donaghy-Spargo, 2017). The power consumed on the rotor conductor's calculation is completed with different rotor conductor materials and with different location, presenting comparative study. This analysis also permits the development of more complete structure of the energy process and additionally, aiding the maintenance student interest in the subject.

METHODS

Since the Poynting vector is used to achieve an understanding of energy flow in rotational electric machine, the numerical simulation of the quantities of the magnetic and electric field analysis is based on the Poynting vector calculations (Urban et al., 2007; Ahmed et al., 2013; Donaghy-Spargo, 2017). To calculate the power and force tensor while the motor is rotating, the geometry, material properties, stator and rotor currents are taken into account as a design tool and for FEM analysis. Briefly, the field flux which occurred by stator and the rotor conductors' current results in torque, which tend to rotate the rotor due to Faraday law are shown in Figure 1. During the motion, the radial power flow through any area can be calculated through the Poynting vector with the formula (Ferreira, 1988; Sutherland, 2007; Esener et al., 2017):

$$\boldsymbol{S} = \boldsymbol{ExH} \quad (1)$$

where $\mathbf{S}$ denotes the instantaneous power flow per unit area across a plane (W/m^2). $\mathbf{E}(V/m)$ is the electric field vector, and $\mathbf{H}(A/m)$ is the magnetic field vector. If Equation 1 is integrated over a closed circuit with the cross section $\mathbf{A}(m^2)$, the instantaneous power flow from all electrical sources are obtained as follows:

$$P = \oint_A (\mathrm{ExH})\mathrm{dA} \quad (2)$$

The power P in Watt in the motor is encountered as power flow in the rotor magnetic field. A force tensor formula is used to perform the Poynting vector effect in magnetic field and is expressed as follows:

$$\mathbf{F} = \mathbf{BxJ} \quad (3)$$

where $\mathbf{F}(N)$ denotes force tensor value, $B = m_0 m_r H$, (Wb/m^2) the magnetic field intensity in the air gap, $m_0(4p\times 10^{-7}, H/m)$ and m_r as the magnetic permeability of the air and the rotor material, respectively. $J(A/m^2)$ is expressed as $J = \sigma E$, and σ $(1/(\Omega.m))$ is the electrical conductivity of the rotor's conductors.

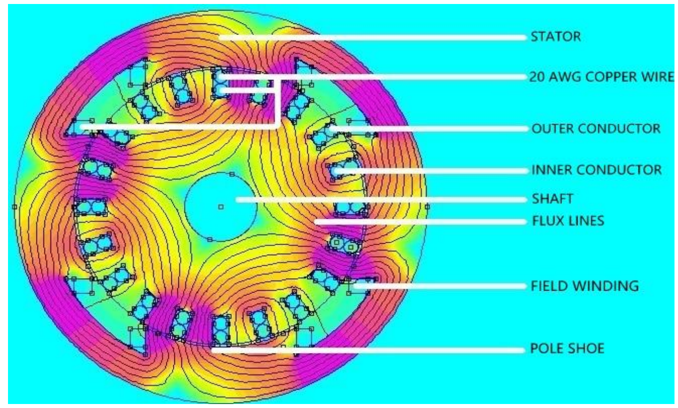

Figure 1: DC motor schematic diagram.

Table 1: Motor parameter's sizes.

DC motor specifications	Length[m]
Stator diameter outer	0.4
Rotor diameter outer	0.28
Air gap average diameter	0.005
Rotor inner conductor diameter	0.027
Rotor outer conductor diameter	0.027

NUMERICAL RESULTS

The magnetic field analysis result is shown in Figure 1. The analyzed motor sizes' values are given in Table 1.

In Figure 1, one can see the flux lines on the rotor and stator, air gap in the four poles, DC motor. The rotor conductor's current is 25A and the stator conductor' current is 1.5A.

When analyzing the main operation parameter effect on the motor, the Equation (3) is usually used; namely, the B field is produced by stator, and the current density J develops due to that field on the rotor conductors. This readily gives us the Poynting vector Equation's effect; for motor, it gives us power losses on the rotor. Figure 2 shows graphs of the air gap. It is directly proportional to the tensor force and power.

The magnetic field strength in the air gap along the rotor circumference of the selected materials is shown in Figure 2. Although M27 and M45 silicon-iron materials have similar values, the US Steel 2-S 0.024-inch soft material has made serious splashes at some points. On the other hand, the reasons for the sudden decrease in the values observed at the pole shoes are that the air gap on these points coincides with the rotor slots and the flux approaches to zero in this region.

In Figures 3 and 4, a comparison of the force of the inner and outer rotor conductors is shown. The graphs generally

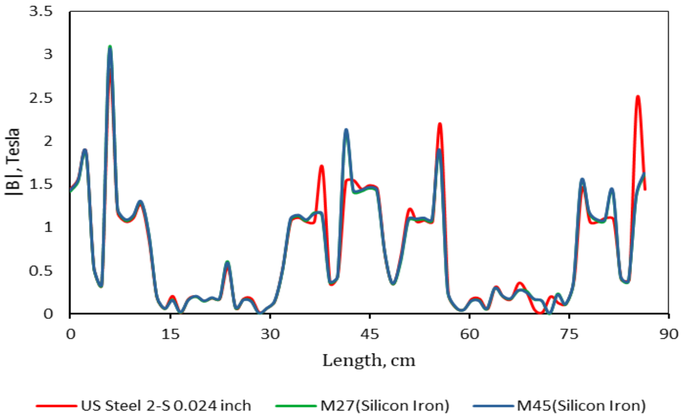

Figure 2: B curve in the air gap.

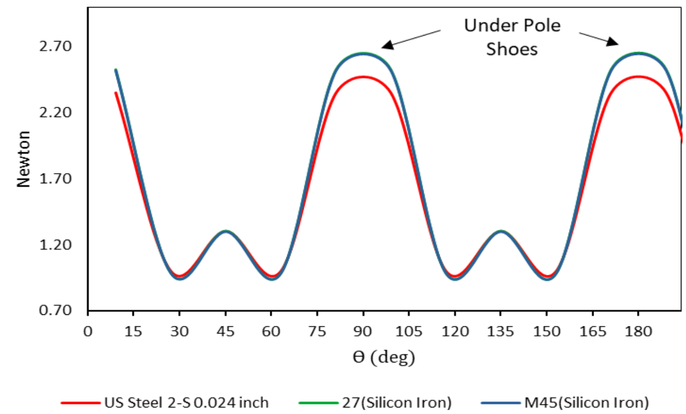

Figure 5: Resultant forces of inner conductors on different rotor materials (Angularly).

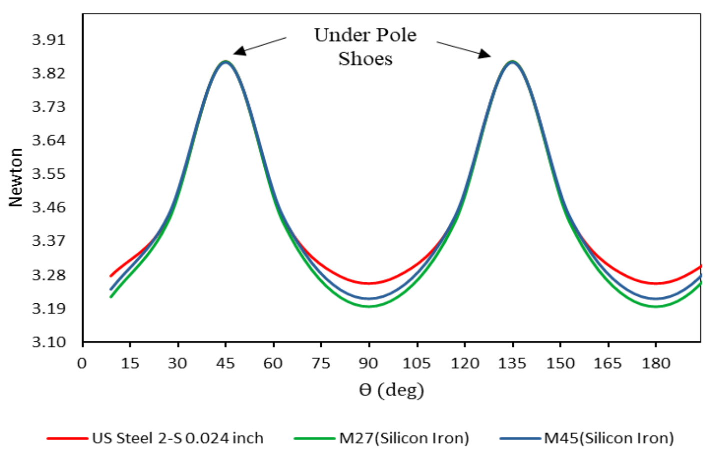

Figure 3: Resultant forces of outer conductors on different rotor materials (Angularly).

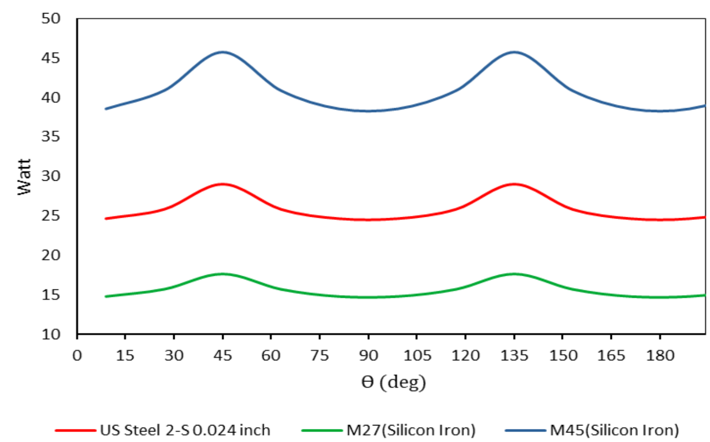

Figure 6: Power losses or Poynting Vector Losses of Outer Conductors on Different Rotor Materials (Angularly*).*

show that the force on the outer (the closest air gap) conductor is more than the inners. The effect of changes on the motor power and force are shown in the figures in detail. The fluctuations rate of the inner conductors is x3 higher than the outer conductors (min. and max. point differences), but they are not subjected here (Czarnecki, 2006; Ferreira, 1988).

When, in Figure 3, maximum force value reaches approximately 3.8 N, in Figure 4, maximum value force remains f2.7 N with more fluctuations. Maximum forces occur underneath the magnetic poles shoes.

Figure 5 shows the comparison of power losses. M27 silicon steel ferromagnetic material has least power losses for outer conductors.

Figure 6 shows the power losses of inner conductors versus angularly. The power losses of the same materials with the previous graphs decreased similarly, however, with the different rate, which is smaller than the outer conductors. M27 steel has the lowest power losses.

When the values given in the graphs is examined, it can be observed that the Poynting vector losses in the M45 silicon iron material is higher than US Steel 2-S 0.024 inch thickness soft magnetic material and M27 silicon-iron materials (Figure7). When the materials are compared, it can be observed that the loss of M45 silicon-iron material is approximately 24 W higher than M27 silicon-iron material, and about 14 W higher than US steel 2-S 0.024 inch in outer conductors. Also, it is observed that the loss of M45 silicon-iron material is approximately 18 W higher than M27 silicon-iron material and about 12 W higher than US steel 2-S 0.024 inch in inner conductors. We also observed that Poynting vector losses decreased when the magnetic permeability increased. It is noticed that; there are some discrepancies between numerical results and simulation data due to differences between the force acting points and assumptions for the simulation model (Esener et al., 2017; Parlar et al., 2017).

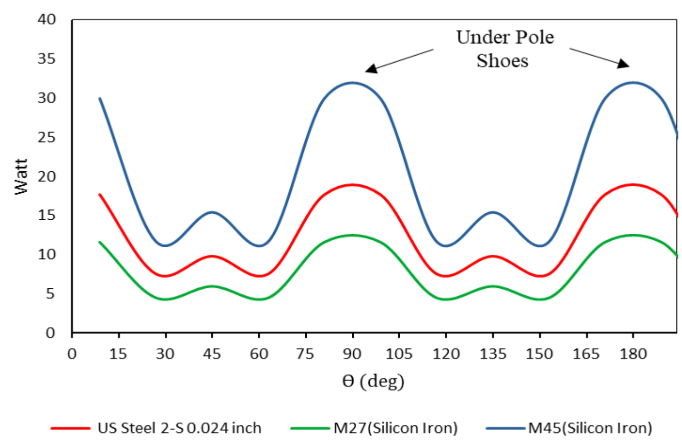

Figure 7: Poynting vector power losses of inner conductors on different rotor materials (Angularly).

Conclusion

We have presented a numerical study of the relationship between energy conversion, force and power loss to analyze the motor operation in detail. We have found that the conductor's power losses in the motor differ due to their place on the rotor. Inner conductors possess less power losses than the outer conductors. We concluded that the Poynting vector is a useful and direct way to calculate power losses for rotor conductors. Additionally, utilizing these results help to minimize the flow of energy required in designing new machine parts. We believe that, this study would be useful for engineering students who are designing and analyzing machine operation, it is useful for industry research and complex transient analysis.

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