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Efficiency analysis of BLDC motor for variable magnetic field

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ABSTRACT

With the developing technology, direct current motors have been widely used in industrial applications. The limited use of brushed models in some areas has made Brushless Direct Current Motors stand out. In this paper, the design and analysis of an efficient, high power density, brushless direct current motor (BLDC) for use in electric vehicles is carried out. In this direction, studies have been carried out to reduce the reverse induced voltage, which is the biggest problem of electric motors in the electric vehicle sector. Analyzes were carried out with ANSYS subprograms, which realized a Finite Element Method (FEM) based solution to change the nominal values of the BLDC motor by changing the distance between the rotor and the stator. According to the results of the analysis, it was concluded that the method used in the study can also be used in high speed applications of brushless direct current motors.

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1 Introduction

Direct Current (DC) motors are widely used in industrial applications. The limited use of brushed models in some areas has brought Brushless Direct Current Motors (BLDC) to the fore. The constant need for maintenance of brushed type motors creates a disadvantage in variable conditions and in areas that are used continuously. For this reason, brushless DC motors have a wide range of uses. Brushless DC motors stand out with their high performance values. Brushless DC motors with outer rotor type are used in applications that require high torque and inertia. These types of motors are used in many areas such as vehicle wiper motors, automatic windows, robotics, generators, electric vehicles, unmanned aerial vehicles, and the white goods sector. Although there are various disadvantages such as motor protection and resistance to vibrations in applications with outer rotor, they do not require any transmission organ because they provide direct drive, they are preferred in applications that require higher efficiency than other types of motors (especially in electric vehicles). Apart from this, the motor drivers used for brushless direct current motors have a more complex structure compared to other motors. Due to the high torque values of brushless DC motors with outer rotor, they can be used especially in electric vehicles.

In this sector, which is in the process of development worldwide, various competitions are held in various countries in order to raise awareness about electric vehicles. The increase in interest in these competitions, which are mostly university-participated, paved the way for the organization of these races in every country. Improvements are being made in electric motors. In such motor applications, the load against the system creates an opposite force depending on the distance between the rotor and the stator. Optimization studies on this radial gap have increased the efficiency [1]. Reducing torque ripple in permanent magnet motors significantly affects efficiency [3-5]. In motors, the voltage induced by the rotation of the rotor in idling state adversely affects the efficiency. This induced voltage is an important factor in motor design. Figure 1 shows the rate-dependent variation of this induced voltage [6-9]

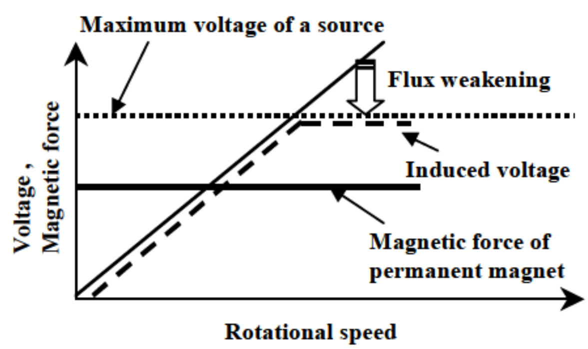

Figure 1. *Voltage regulation at variable-speed using flux-weakening control for a conventional permanent magnet motor [6].*

Today, there are various replaceable magnetic field applications in permanent magnet motors. In these applications, in order to reduce the reverse induced voltage, magnetic coercive force is created with different types of magnets on the permanent magnets of the motor. Figure 2 shows the configuration of the machine created in this way.

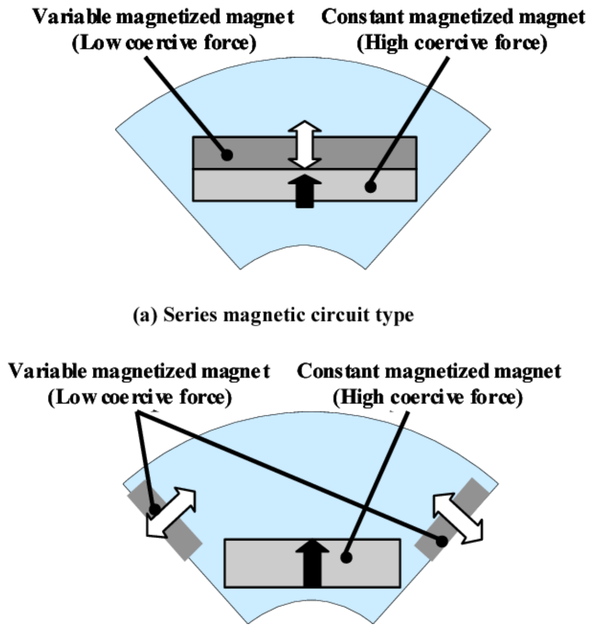

Figure 2. *Configuration of the magnetically forced motor*

In the mentioned application, four magnets with low coercive force, that is, four magnets with high coercive force, whose magnetization amount varies according to the magnetic field force it is exposed to, were used at the corner points. It is desired to create a forcing magnetic field force on permanent magnets with magnets with low coercive force. Applied for machines with internal rotor. This practice has some negative effects. The stator flux density was adversely affected in regions with low coercive magnets. This reduces high motor torque and causes flux loss. As a result, these triggered values increase the speed of the machine, but affect the efficiency negatively.

In this study, different from the application mentioned above, in BLDC motors, a variable magnetic field application has been made depending on the distance between the stator and the rotor. As a result, it is aimed to reduce the reverse induction and to make the maximum velocity threshold changeable.

2 Methods and materials

2.1. General Structure and Model of BLDC Motor

As a general structure, position sensors are used in brushless direct current motor to be driven according to the state variables. The basic features of the machine are shown in Table 1.

Table 1. *The basic features of the machine*

Parameter	Value
Rated Voltage	134 V
Rated Output Power	15 W
Rated Speed	187.5 rpm
Number of Pole	16
Rotor Position	Outer
Rotor Length	26 mm
Number of Slots	12
Operating Temperature	75 °C

The modeling of the machine used was carried out in the RMxprt design module of the ANSYS Maxwell program. Complete electrical and mechanical modeling of the motor has been applied. Modeling as close to reality as possible was carried out, and the graphics and values used in the next section were made according to this modeling. The mentioned machine model is shown in Figure 3.

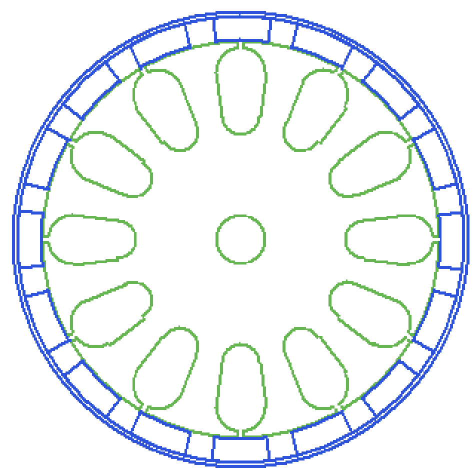

Figure 3. *Modeled brushless DC motor*.

In the mentioned motor, a magnet type called superficially inclined diameter magnetized magnet is used. The need for hard magnetic materials has brought developments in this field.

2.2. Exchangeable magnetic field definition

Brushless DC motor with Switchable Magnetic Field, which will be applied in prototype models designed for electric vehicle races, will provide a purpose to increase the speed threshold of the applied vehicle. In the study, it is aimed to reduce the back electromotive force that will occur in the armature part depending on the vehicle rotor rotation speed in cases where the efficiency of the vehicle is not a priority. The change of magnetic flux applied by hard magnetic materials at the peak value of the efficiency-speed curve to be determined will be realized by means of movable connectors. Thus, it is aimed to reduce the back electromotive force (back-EMF) on the stator [10-11].

2.3. Magnetic effect calculation

The back electromotive force created by the magnets is equal to the voltage induced in the stator tooth due to rotor motion and can be calculated as follows [5].

$$e_T = \frac{\partial \Phi}{\partial t} = \omega_m \frac{\partial \Phi}{\partial \xi} \tag{1}$$

Where, Φ is the flux due to the magnet when there is no current flowing in the stator, e_T is the induced voltage, ω_m is the angular velocity, N is the number of turns, t is the time index, and ξ is the rotor position. The equation of the flux to be obtained depending on the flux density is as follows.

$$\Phi = NRL \int_{\theta_2}^{\theta_1} B(\theta)d\theta \tag{2}$$

Where, B is the flux density generated by the magnets on the active tooth. R is the axial stator radius, L is the depth in the axial direction, N_s is the number of slots, θ_1 and θ_2 are expressed as the transition positions of a pole on a slot. Using Equation 1 and Equation 2, the following expression can be reached;

$$e_T = N\omega_m RL \frac{\partial}{\partial \xi} \int_{\theta_2}^{\theta_1} B(\theta)d\theta \tag{3}$$

V=$\omega_m R$ indicates the linear speed of the motor. B_1 and B_2 are opposite magnetic flux densities of magnets. If ξ and θ values are equal or there is a constant difference, the induced voltage is shown as in Equation 4;

$$e_T = NV(B_2 - B_1)L \tag{4}$$

2.4. Permanent magnet distance effect

By creating a special design, Neodymium N50M class magnets are used in order to provide the high torque requirement at the start of the motor and the properties of these magnets are as given in Table 2.

Table 2. *Properties of these magnets*

Material Type	Residual Flux Density (Br)	Coercive Force (Hc)	Intrinsic Coercive Force (Hci)	Max.Energy Product (BH)max
N48	13.8-14.2 KGs	>11.0 KOe	>12 KOe	45-48 MGOe

The magnetic density provided by hard magnetic materials changes according to the distance. A superficially curved diameter magnetized magnet type is used in the brushless direct current motor that is aimed to be applied. The calculation of the change with respect to this magnet is given in the following equation [2].

$$B_{(z)} = \frac{\mu_0 M}{\pi}\left[arct\frac{ab}{(z-c)\sqrt{a^2+b^2+(z-c)^2}} - arct\frac{ab}{(z+c)\sqrt{a^2+b^2+(z-c)^2}}\right] \tag{5}$$

Magnetic field calculations for any point in space are as shown in the equations below [2].

$$B_x(x,y,z) = \frac{\mu_0 M}{\pi}\ln\frac{F_2(-x,y,-z)F_2(x,y,z)}{F_2(x,y,-z)F_2(-x,y,z)} \tag{6}$$

$$B_y(x,y,z) = \frac{\mu_0 M}{\pi}\ln\frac{F_2(-y,x,-z)F_2(x,y,z)}{F_2(y,x,-z)F_2(-y,x,z)} \tag{7}$$

$$B_y(x,y,z) = \frac{\mu_0 M}{\pi}[F_1(-x,y,z) + F_1(-x,y,-z) + F_1(-x,-y,z) + F_1(-x,-y,-z) + F_1(x,y,z) + F_1(x,y,-z) + F_1(x,-y,z) + F_1(x,-y,-z)] \tag{8}$$

$$F_1(x,y,z) = arct\frac{(x+a)(y+b)}{(z+c)\sqrt{(x+a)^2+(y+b)^2+(z+c)^2}} \tag{9}$$

$$F_2(x,y,z) = \frac{\sqrt{(x+a)^2+(y-b)^2+(z+c)^2}+b-y}{\sqrt{(x+a)^2+(y+b)^2+(z+c)^2}-b-y} \tag{10}$$

In Figure 4, the space of the magnet, whose calculations are given above, is shown. μ0 represents the permeability of the air, the coordinate axes of the X,Y,Z three-dimensional space, r the center of the magnet, r' the magnetic flux density that will fall on it, the point to be calculated, x, y, z the distance from the magnet center of the point to be calculated in its own coordinates. 2a, 2b, 2c show the dimensions of the magnet [2].

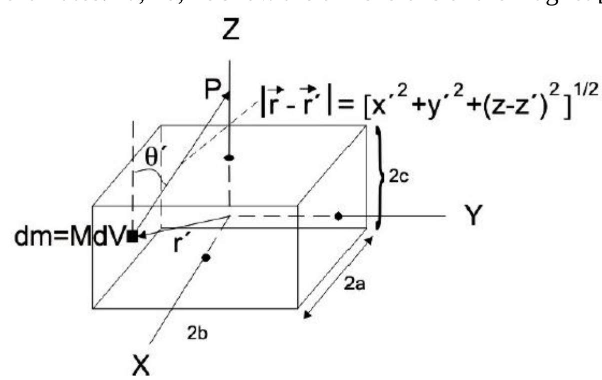

Figure 4. *Block magnet area calculation scheme.*

3. Results and discussion

The infrastructure of the mobile system to be applied to the BLDCM is currently being worked on and the majority of it is mechanical systems. In this study, the results to be obtained in the case of the physical application of the aforementioned system are simulated. The basic structural movements that will enable the formation of the system have been determined gradually. In these stages, it is planned to separate the rotor from the stator part by a mechanical design. The remaining dimensions of the rotor in the stator according to the steps to be provided by the designed system.

There is a section called the air gap between the stator and the rotor. While designing the motor, the magnetic flux density affected by this field should be considered. This gap affects the induced voltage and the current generated on the coils. The air gap of the system to be applied in the machine changes axially at each stage. In the previous section, the calculation of the magnetic flux created by the distance on the coils is shown. In the initial state of the modeled brushless direct current motor, this air gap was determined as 2 mm and the air gap of the modeled motor is shown in Figure 5.

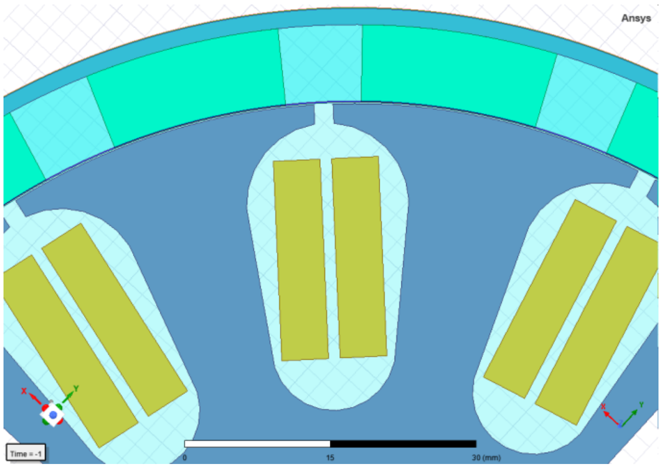

Figure 5. *The air gap of the machine modeled with ANSYS Maxwell 2D Design.*

4. Simulation results

Assuming that the movable rotor system of the modeled brushless direct current motor is applied, necessary analyzes are made in the analysis section of the ANSYS Maxwell program. According to the first case, the peak and maximum velocity value of the yield curve were determined and shown in Figure 6.

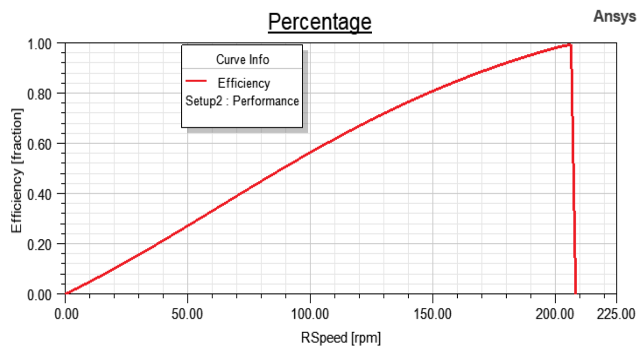

Figure 6. *Yield-Speed graph in the first case (Rotor length =26 mm).*

Accordingly, it is expected that the speed will increase with the next step change after the transition points are the points where the motor efficiency is maximum. It is thought that the rotor position should change step. With this approach, it was determined that the transition points to be made between the stages should be as shown in Figures 7-9.

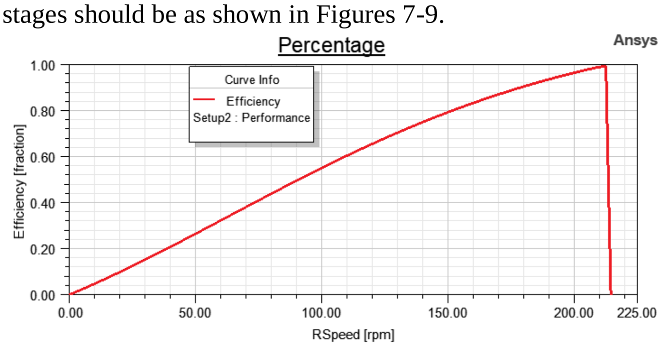

Figure 7. *Efficiency-Speed curves for rotor length=30 mm position in the modeled system.*

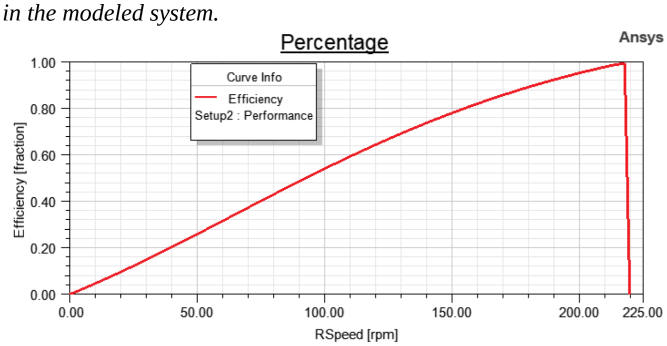

Figure 8. *Efficiency-Speed curves for rotor length=34 mm position in the modeled system.*

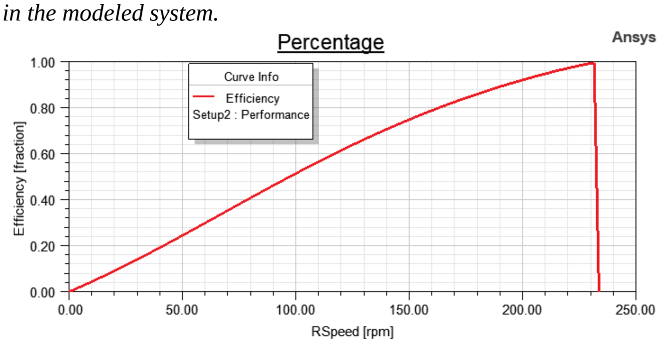

Figure 9. *Efficiency-Speed curves for rotor length=38 mm position in the modeled system.*

The values obtained when the rotor length is increased gradually while keeping the stator length constant are presented in Table 4.

Table 4. *Efficiency-speed values obtained depending on the rotor length*

Rotor Length (mm)	Speed (rpm)	Efficiency (%)
26	206.8	98.3
30	218.1	98.1
34	223.2	97.6
38	235.1	98.4

5. Conclusion

Motor designers should first determine the area where the brushless DC motor will be used and the main expectation before starting the design work. While designing the machine, the limitations of the area to be used, ease of production and cost expectations should also be considered. Performance expectations such as speed, output power and efficiency may also vary depending on the area to be used. In addition, since situations such as variable speed request may occur during operation, it may be important to examine the machine performance in the entire operating range according to the number of revolutions of the machine. At this point, the design of how the designer will use his machine is important. In this study, the application of the changeable magnetic field, which is created as a result of physical motion, is examined. An machine with different characteristics has emerged at each stage. This has shown that a variable speed motor can be achieved by applying a variable magnetic field system. As a result, the switchable magnetic field system, which is considered to be applied, has revealed that it can be used in race organizations where the speed factor is important or in passenger and commercial electric vehicles.

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