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DESIGN AND ANALYSIS OF PERMANENT MAGNET DC MACHINES WITH FEM BASED ANSYS-MAXWELL

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Abstract

Original scientific paper

In this paper, permanent magnet direct current (PMDC) motor was designed and analyzed; The obtained speed, efficiency, torque and air gap flux distributions were examined and the results were compared with literature for the motor type. In order to compare the designed machine with literature, magnets made of the same materials and having the same geometric dimensions were used, as well as the basic motor features. The rated current, voltage, speed, torque and efficiency of two surface magnet motors with different rotor structures, including the eddy current effect, torque-speed characteristics and magnetic analysis, were investigated using the ANSYS-MAXWELL program, which performs a solution based on the Finite Element Method (FEM). This study will be a useful study for the literature in terms of examining the basic structure, electromagnetic properties, speed-torque values, efficiency of motor with surface permanent magnet (PM) rotor and comparing with literature.

Keywords: *Motor, permanent magnet (PM), FEM, maxwell.*

SEY TABANLI ANSYS-MAXWELL İLE KALICI MAGNET DC MAKİNALARIN TASARIMI VE ANALİZİ

Özet

Orijinal bilimsel makale

Bu çalışmada, sabit mıknatıslı doğru akım (SMDA) motoru tasarlanmış ve analiz edilmiştir. Elde edilen hız, verim, tork ve hava aralığı akı dağılımları incelenmiş ve sonuçlar motor tipi için literatür ile karşılaştırılmıştır. Tasarlanan motoru literatürle karşılaştırmak için temel motor özelliklerinin yanı sıra aynı malzemelerden yapılmış ve aynı geometrik boyutlara sahip mıknatıslar kullanılmıştır. Farklı rotor yapılarına sahip iki yüzey mıknatıslı motorun anma akımı, gerilim, hız, tork ve verimleri, girdap akımı etkisi, tork-hız karakteristikleri ve manyetik analiz dahil olmak üzere, Sonlu Elemanlar Yöntemine (SEY) dayalı çözüm gerçekleştiren ANSYS-MAXWELL programı kullanılarak gerçekleştirilmiştir. Bu çalışma, yüzey sabit mıknatıslı (PM) rotorlu motorun temel yapısı, elektromanyetik özellikleri, hız-tork değerleri, veriminin incelenmesi ve literatürle karşılaştırılması açısından literatüre faydalı bir çalışma olacaktır.

Anahtar Kelimeler: *Motor, sabit mıknatıs (SM), SEY, maxwell.*

1 Introduction

With the developing technology, the number of high-performance products that make human life easier is increasing day by day. Along with the increasing smart technology, integrated products arising from the machinery and electronics sector are also being introduced. One of them is brushless direct current (DC) motor. It provides many advantages such as high torque density, absence of brush losses, low moments of inertia, good speed control, low maintenance costs, quiet operation and high efficiency compared to brushed DC and stepper motors, which are other stakeholders in the sector, and are used in many application areas in the sector found. In addition, although there are disadvantages such as the complexity of the control circuits and their high costs, studies to reduce the cost in this direction continue.

Some of the usage areas of brushless DC motors with different power and dimensions can be counted as industrial, household appliances, office vehicles, automotive, transportation and transportation, defense systems, health, aviation, construction-building vehicles and renewable energy systems applications [1].

In the literature, it is seen that the studies on the subject are generally in the direction of the use of motors in engineering systems, control, design stages and production process. In a study, studies were carried out on the simulation of brushless DC motor using ANSYS

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Maxwell 3D program. In this paper, the temporary and steady state behavior of four different types of motors that can be used for high-performance electric bicycles are examined and the performances of the motors are evaluated [2]. In a study on the design and prototype production of an outer rotor brushless synchronous electric motor for electric bicycles, prototype tests were carried out using the experimental setup and it was found that it largely overlaps with the simulation results [3-5]. The importance of permanent magnet motors is increasing day by day, as important developments in permanent magnets and power electronics elements reduce the size of these elements, become cheaper and more efficient. PM motors are not the most common motors used today, but they will become the most common motors over time as their cost decreases due to their compactness, high power density, high torque, high acceleration/torque ratio, easy drive and high efficiency characteristics [6-8].

There are many different types of PM motor structures according to the usage area (constant torque, constant speed, constant power). Recent studies in the open literature show that many researchers and engineers have started working on this motor design. In a study by Dajaku and Gerling [9], the parameters and electromechanical moments of PM motors of different structures used in hybrid vehicles were investigated using the ANSYS program. In another study, a new approach to optimizing surface magnet PMDC (permanent magnet direct current motor) design was investigated. Other studies have been done on analytical calculation, modeling and optimization of PM motors.

In general, these motors are tolerated at small and medium powers. It has also been used for higher powers in recent years. These motors, which have a simple structure, have independent or integrated electronic commutation, produce high torque per ampere and do not change according to the operation, these motors have attracted motors to wide areas of use, including domestic and industrial applications. pushes to produce designs. One of the configurations is a slotted and slotless BLDC motor. A spotless BLDC is a motor that comes without a stator core.

Depending on the position of permanent magnets, motors with rotors mounted inside are called axial flux motors, and radial flux motors are motors with rotors mounted on the stator. The motor assembly is simplified by the internal structure, eliminating the problem of holding the magnets against centrifugal force. It is also possible to use rectangular magnets instead of arc-shaped magnets.

In general, rotational loss (friction + wind) in motor design can be neglected because it is low compared to other losses, but it should be avoided for best results. In 2016, Prathamesh Mukund Dusane used 3D ANSYS-Maxwell for these motors with different number of grooves and poles, their drawings and results were given in detail and the results of these motors were compared with each other [10].

Motor performance can be largely predicted even before production is confirmed. This is because multiple design iterations can be done faster at lower cost and new designs are created by optimizing the original parameters. Performance analysis can also be performed under faulty conditions. Accurate calculation of motor parameters and characteristics is foreseen in terms of field calculation and result analysis [11-17].

Various design configurations exist in the literature with their advantages and disadvantages. Single-phase permanent magnet brushless DC motor with higher speed is described in [12]. This motor also has the disadvantage of high torque ripple and low torque/amperage. A two-phase motor with 100% copper usage and 67% magnet usage was investigated in [19]. In [17] it is stated that a three-phase BLDC motor is at least 15% more efficient than a two-phase BLDC motor with similar ratings.

The analysis of the machine using permanent magnetic circuit dimensions was carried out using the ANSYS-MAXWELL program. In order to make a comparison, the design of the PMDC motor has been compared with machines of different geometric structure and similar dimensions. In this study, the analysis and comparison of the magnet geometry were made together.

2 Material and Method

The benefits of using PMs in electrical machines can be summarized as follows:

- No energy is consumed for the excitation system and therefore there are no excitation losses that cause a decrease in efficiency,
- High torque and/or output power,
- Better dynamic performance,
- Simpler construction and easy maintenance,
- Cost reduction of some machine types.

There are conventional three-phase windings in the stator of the PM motor, and there are permanent magnets placed on the surface or embedded in the rotor in the rotor [2]. These motors require extensive speed control; They are widely used in devices such as computer disk drives, copiers, laser printers, scanners, office tools such as fans, industrial robots, robotic arms.

2.1 Permanent Magnets (PM)

Permanent magnets have the same effect as electromagnets in terms of magnetism; Therefore, they are widely used to provide excitation in electrical machines. These magnets are useful because they store magnetic energy and do not waste this energy during the operation of the machine. Today, the most commonly used PMs in electric motors are:

- Alnicolar: Al, Ni, Co, Fe;
- Ceramics (Ferites): Barium Feritte and Strontium;
- Rare earth magnets: Samarium-Cobalt (SmCo), Neodymium-Iron-Boron (NdFeB).

Alnico magnets are more advantageous than ceramic magnets in terms of high flux density and low temperature change. However; Although alnico magnets have lower resistance to demagnetization compared to ceramic magnets, their costs are higher. Rare earth magnets show very good magnetic properties but are generally more expensive than alnico and ceramic magnets.

2.2 Types of PM

Figure 1 shows the basic structures of three types of surface magnet PM motors. Basically, magnets can be embedded in the yoke and body of the rotor iron, as well as placed on the surface of the rotor. In addition, the magnet positions connected to the rotor can be changed as inner rotor and outer rotor. Internal surface rotor PM motor designs were made. Rotor structure and the position of the magnets placed on the rotor have important effects on the structure of the motor. In order to make the flux density in the air gap homogeneous and to obtain more uniform fluxes, the magnets to be placed on the rotor surface should be in the form of an arc. This increases the cost of manufacturing magnets. However, since rectangular magnets will be used in embedded type magnet rotors, the cost is cheaper.

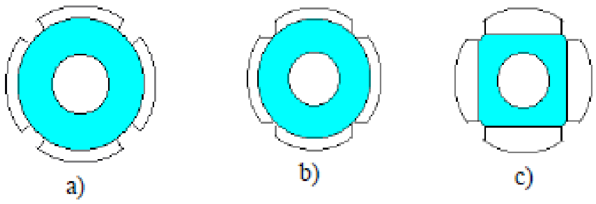

Figure 1. Different rotor structures of the surface magnet PM motor; a) surface magnets perpendicular to the rotor shaft, b) surface magnets parallel to the rotor shaft, c) bread-shaped magnets.

2.3 Mathematical Model

Magnetic energy plays a very important role in generating torque. Therefore, it is necessary to formulate the magnetic energy. In order to formulate this energy, the equation of the magnetic vector potential depending on the magnetic field strength must be known. The moment value can also be obtained from this equation. The velocity-dependent two-dimensional magnetic field equation can be expressed as follows [18]. The torque developed by the BLDC motor is expressed by equation (1).

$$\mathrm{T} = 2\mathrm{N}\mathrm{N_m}\mathrm{B_g}\mathrm{L}\mathrm{R_{ro}}\mathrm{I} = \mathrm{k_t}\mathrm{I} \quad (1)$$

Where, N is the number of turns in the groove, N_m is the number of poles, B_g is the air gap flux density, L is the active length of the motor, $R_{ro}$is the rotor outer diameter, and I is the current through the conductor. The 2N factor is that the three-phase inverter is operated in 120 0C conduction mode, that is, 2 phases carry current at any given time.

The opposite MMF expression for the BLDC motor is given in equation (2) [18].

$$\mathrm{E_b} = 2\mathrm{N}\mathrm{N_m}\mathrm{B_g}\mathrm{L}\mathrm{R_{ro}}\mathrm{W_m} = \mathrm{k_e}\mathrm{I} \quad (2)$$

Where W_m is the angular velocity of the rotor. When the torque and reverse MMF equations are compared, it is seen that the torque and back emf constants are equal in equation (3) [18].

$$k_t = k_e = 2NN_mB_gLR_{ro} \quad (3)$$

Results from the motor can be expressed in terms of main dimensions, specific electric and magnetic charges, and speed. The kVA value of the BLDC motor is given below.

$$Q = C_oR_{ro}^2LW_m \quad (4)$$

Where, C_o is a constant and is expressed as given in equation (5).

$$C_o = 11B_{av}ack_w * 10^{-3} \quad (5)$$

Where, B_{av} is the magnetic charge, ac is the electrical charge and k_w is the winding factor. Copper losses for two phases, P_{cu}

$$P_{cu} = 2I^2\frac{\rho LN^2N_c}{K_{wb}A_g} \quad (6)$$

It is expressed as Here, ρ is the density of the copper wire, N_c is the number of turns per phase, K_{wb} is the filling factor of the bare wire, and A_g is the air gap. Wind and friction losses [17]:

$$P_f = \frac{3}{100}P_{out} \quad (7)$$

The weight of the gears of the stator;

$$W_t = \rho_iA_tN_sL \quad (8)$$

is defined as. In the equation, ρ_i represents the density of iron, A_t represents the cross-sectional area of the teeth and $N_s$the number of grooves. The weight of the stator yoke is given by equation (9).

$$W_{sy} = \rho_iA_{sy}L \quad (9)$$

A_{sy} is the cross-sectional area of the stator yoke. The weight of the rotor yoke is expressed as follows [19].

$$W_{ry} = \rho_iA_{ry}L \quad (10)$$

Where A_{ry} is the cross-sectional area of the rotor yoke.
Total iron weight;

$$W_{total} = W_{ry} + W_{sy} + W_t \quad (11)$$

it has been defined as.
Total iron loss is calculated by equation (12).

$$P_{iron} = L_{kg} * W_{total} \quad (12)$$

Where L_{kg} is the loss in Watts per kg of stator material. Power input to the motor is given by:

$$P_{in} = P_{out} + P_{cu} + P_{iron} + P_f \quad (13)$$

Machine efficiency ŋ (%)

$$ŋ\ (\%) = \frac{P_{out}}{P_{in}} \quad (14)$$

Maxwell program based on FEM was used to solve the above equation. Thus, the torque value can be reached directly.

2.4 FEM Analysis of PMDC

The detailed knowledge of the flux distribution in the air gap of a PM motor plays a very important role in the accurate estimation of the torque and efficiency characteristics of the motor. For very simple geometries, the magnetic flux distribution can be calculated analytically. Magnetic flux distribution in most cases; It is obtained by numerical methods such as Finite Element Method (FEM). In this study, the magnetic analysis of the designed PMDC motors was investigated using the Maxwell 2D program. The simulation was completed using the following steps;

- Creating a geometric model,
- The assignment of the materials that make up the structure of the motor,
- Determination of boundary conditions and networking process,
- Identification of sources of electromagnetic excitation (assignment of currents to the windings),
- Determination of other quantities to be calculated (such as force, moment, and leakage flux),
- The start of the analysis process,
- Examining the results.

After the completion of these steps, the general motor structures given in Figure 2 are obtained and the path followed by the magnetic fluxes, flux densities, intensities and stored magnetic energies can be examined through the same Figs. The geometric dimensions of the slot are given in Table 1.

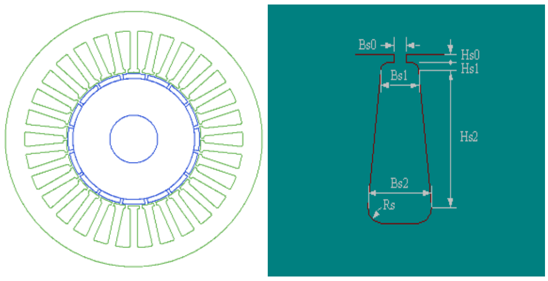

Figure 2. General view of the designed motor structure and slot type.

Table 1. The geometric dimensions of the slot.

Name	Value	Unit
Hs0	2	mm
Hs1	1	mm
Hs2	30	mm
Bs0	2	mm
Bs1	6	mm
Bs2	12	mm
Rs	0.6	mm

2.5 Parameters of Designed PM Machines

Rotor core is made of NdFeB magnets and stator core is made of M19_24G material and copper coils are placed in the stator slots. All analyzes were made according to constant power value (1500 W). For this reason, the speed changes of the motors are between 500 and 550 rpm. Dimensions of the designed motors; It depends on the type of current, the rated speed, the motor winding coefficients and the power of the motor. The general geometry of the designed motors is given in Figure 2. Rated values, stator and rotor geometries of the designed motors are given in Table 1-3. The materials used for different parts of the motors are given in Table 4.

Table 2. Parameters of the designed motor.

Parameter	Value
Rated output power (W)	1500
Rated voltage (V)	48
Number of pole	36
Windage loss (W)	20
Frictional loss (W)	10

The values of the stator and rotor geometries of the designed machine are presented in Table 3 and Table 4, respectively.

Table 3. Stator geometry parameter.

Parameter	Value
Number of slots	30
Outer diameter	210 mm
Inner diameter	110 mm
Lenght	50 mm
Stacking factor	0.95
Material	M19_24G
Conductor type	Copper

Table 4. Rotor geometry parameter.

Parameter	Value
Outer diameter	108 mm
Inner diameter	40 mm
Stacking factor	0.95
Lenght	50 mm
Material	M19_24G
Magnet thickness	4 mm
Magnet type	NdFe35

2.6 Winding Topology

Working principle of electrical machines; It is based on the magnetic field created by the current flowing through the windings of the machine and the interaction of the magnetic fields with each other. A wide variety of winding types can be used, depending on the conductor dimensions, weight, efficiency and power density of the motor. In this study, a distributed two-layer winding type was used for all motors. One of the most important factors to be considered in the winding topology of the machine is; The magneto motor force (MMF) produced in the stator windings is as sinusoidal as possible.

For this paper the number of phases in the motors is designed as three and the number of windings in each slot is 40. Figure 3 clearly shows the stator coils and the bilayer structure of the coils. The designed motors are driven by a circuit consisting of six transistors. The purpose of these transistors used in the circuit is to provide commutation. During each commutation, only the first coil of the motor stator is charged with positive voltage and the second coil with negative voltage. With the square wave obtained thanks to this circuit, the motor works without interruption [11].

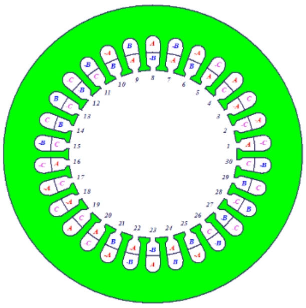

Figure 3. Stator and coil structure of motors.

3 Result and Discussion

Machine parameters and electromagnetic torque considerations are very important for the design and analysis of electrical machines.

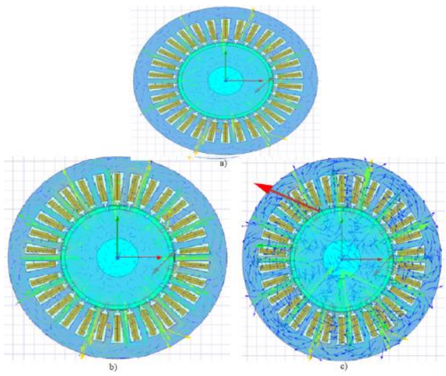

Figure 4. a) Magnetic flux lines of the designed machine, b) magnetic field strength, c) flux lines.

In the designed motor, permanent magnets of the same dimensions were placed according to the hair package structure of the rotor and magnetic analysis was performed accordingly (The flux lines of the designed motor are as in Figure 4). The simulation results are given with curves and graphs in order as in Figs. 4-8. And it has been understood that the rated operating limits are within acceptable values. The BH curves of the NdFeB magnet used in the rotor and the M19_24G materials used in the stator go into saturation at 2.46 T and 1.34 T points, respectively.

The flux distribution completes the circuit smoothly (without breaking in the air gap) over the rotor, air gap and stator. This means that the air gap area of the designed motors is at an appropriate value. In addition, it is understood from the performance curves of the motors and the tables that the air gap values left are in an acceptable range.

Tablo 5. Analysis results of the machine.

Parameter	Value
Rated speed (rpm)	920
Rated moment (N.m)	22.1
Output power (W)	1500.24
Input power (W)	1875.71
Total loss (W)	375.57
Efficiency (%)	79.2

The variation of the air gap flux density was obtained as in Figure 5. The air gap flux densities of the designed PM motor are trapezoidal and sinusoidal.

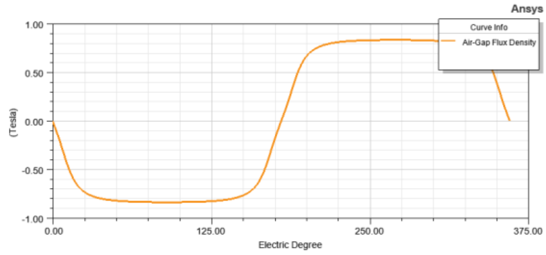

Figure 5. The air gap flux densities.

As seen in Figure 6 and Equation 2, while the motor is starting, it draws excessive current from the network since the speed is zero at the beginning.

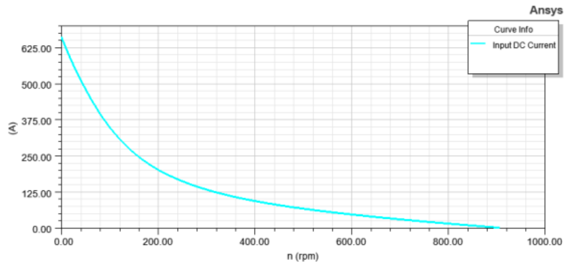

Figure 6. Current and speed curve.

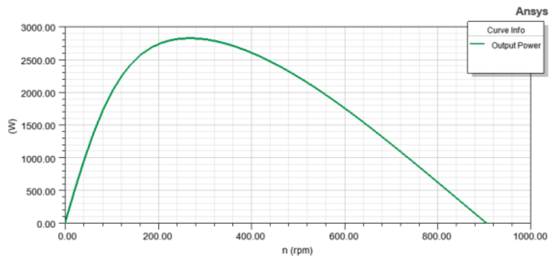

Figure 7. The rapid variation of the output power.

The rapid variation of the output power is shown in Figure 7. Where, the power-speed variation of type b motor is wider than other motor. Therefore, this type of motors are used in places that require power-speed variation in wide ranges. The efficiency-speed curves of the designed motor were obtained as in Figure 8.

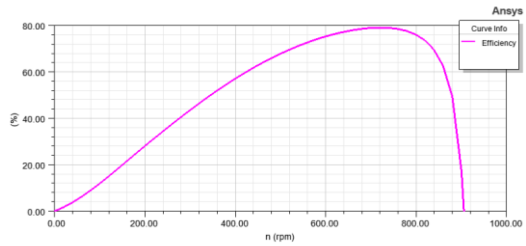

Figure 8. The efficiency-speed curves of the designed machine.

As mentioned before, torque and speed are inversely proportional to each other and the torque-speed curves of the designed motor are obtained as in Figure 9.

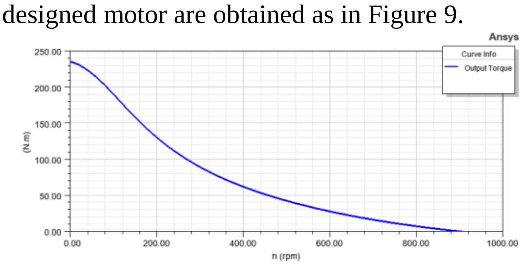

Figure 9. Torque-speed curves of the designed motor.

Output current and voltage curves are given in Figure 10 and Figure 11.

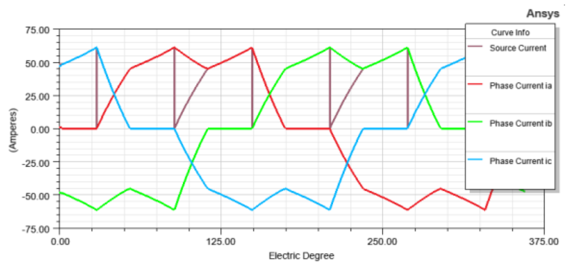

Figure 10. Current and electric degree curve

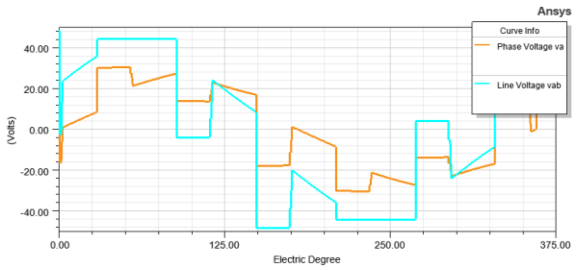

Figure 11. Voltage and electric degree curve

It is desirable that the moment-speed curve of an electrical machine is linear. It is seen that the torque-speed curves of the designed motor are approximately linear. As can be seen from the graphics obtained as a result of the study, the more the magnets spread over the rotor surface, the higher speeds they can reach with the same efficiency, by coating the rotor surface of the magnets. Similarly, higher output power can be obtained at the same speed if magnets are placed so that they cover the rotor surface.

4 Conclusion

In this paper, general and magnetic analysis of surface magnet PMDC motor was made using Maxwell program and analysis results; Topology, size, magnetic field, air gap flux, voltage, torque, velocity, losses, weight and efficiency were compared. Fundamentals of magnetic circuit and necessary basic equations used in electromagnetic field have been obtained. In this paper, Permanent magnet BLDC motor used in 1500 W and 550 rpm solar power vehicles is designed. In the study, it has been observed that the efficiency of the motor at nominal torque and nominal speed is very good. The efficiency of the motor was obtained as 79.2 %. When the analyzes are compared with the literature, it is understood that the efficiency of the machines in these structures and powers is close to each other. It is possible to design smaller and more economical machines by optimizing flux distributions and magnetic field strengths.

Declaration

Ethics committee approval is not required.

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