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Four Pole Limited Angle Toroidal Motor Magnetic Design

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Anahtar Kelimeler

Sınırlı Açılı Tork Motoru
Sınırlı Açılı Toroid Motor
Sonlu Eleman Analizi

Graphical/Tabular Abstract (Grafik Özet)

In this paper, the mathematical modeling and magnetic analysis of a four-pole limited angle toroidal wound motor are presented in detail. / Bu çalışmada dört kutuplu sınırlı açılı toroidal sargılı motorun matematiksel modellemesi ve manyetik analizi kapsamlı olarak sunulmaktadır.

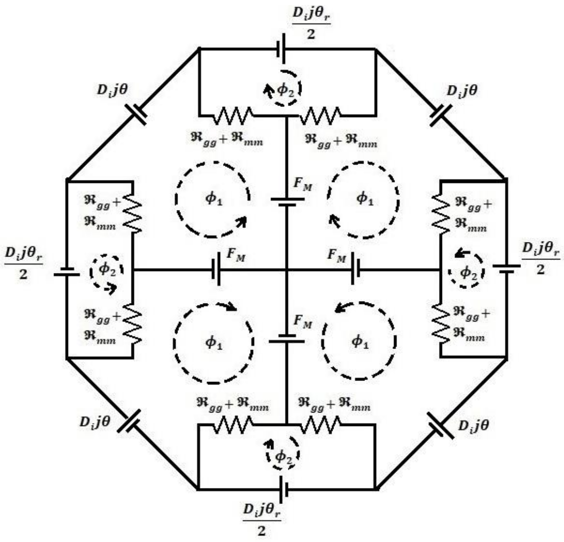

Figure A*: Arc type 4 pole limited angle toroidal motor magnetic equivalent circuit /* ***Şekil A:*** *Yay tip dört kutuplu sınırlı açılı toroid motorun manyetik eşdeğer devresi*

Highlights (Önemli noktalar)

- *4-pole LATM magnetic and transient analysis /4 kutuplu LATM manyetik ve geçici durum analizi*
- *Torque performance at different stator inner diameter variations / Farklı stator iç çap değişimlerinde tork performansı*
- *Torque performance with different winding-pole geometries / Farklı sargı-kutup geometrilerinde tork performansı*

Aim (Amaç): *This study aims to design and electromagnetic performance analysis of a limited angle torque motor. / Bu çalışma, sınırlı açılı tork motorunun tasarımını ve elektromanyetik performans analizini amaçlamaktadır.*

Originality (Özgünlük): *This study presents the design of a limited angle torque motor specific to the field of use and requirements. / Bu çalışma, kullanım alanına ve gereksinimlere özel sınırlı açılı tork motor tasarımını sunmaktadır.*

Results (Bulgular): *The designed LATM can be used in high precision applications with low magnetization risk and high torque per unit volume. / Tasarlanan LATM, yüksek hassasiyetin ön planda olduğu uygulamalarda, düşük manyetizasyon riski ve birim hacimdeki yüksek torku ile kullanılabilir.*

Conclusion (Sonuç): *As a result of the study, a LATM design with torque linearity at 95% of the peak torque in the constant torque region, with a peak torque value of 2.221Nm, has been obtained with a high torque per unit volume compared to its alternatives. / Yapılan çalışma sonucunda, sabit tork bölgesinde tepe torkun %95 inde tork doğrusallığı olan, 2.221Nm tepe tork değeri ile alternatiflerine kıyasla birim hacimde yüksek torka sahip olan bir LATM tasarımı elde edilmiştir.*

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Abstract

This article presents the theoretical analysis of limited angle torque motors (LATM), numerical modeling for 4-pole types and the effect of various dimensions on motor performance. First, the magnetic equivalent circuit model and equations of the LATM are defined and the motor torque expression for 4 poles is established. Then analytical hierarchy process (AHP), a decision-making tool, is used as a reference to determine the best LATM design parameters. The cogging torque, constant torque region and peak torque value of the motor at the lower and upper values of the obtained design parameters are analyzed in the finite element analysis environment. The transient analysis of the best design considering certain limitations is performed and the operating performance is analyzed in no-load condition. With the proposed model, the torque of the 4-pole limited angle torque motor in the constant torque region is obtained at 95% of the peak torque. This value is verified by finite element analysis.

Dört Kutuplu Sınırlı Açılı Toroid Motor Manyetik Tasarımı

Makale Bilgisi

Araştırma makalesi
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Öz

Bu makale, sınırlı açılı tork motorlarının (LATM) teorik analizini, 4 kutuplu tipler için sayısal modellemeyi ve çeşitli boyutların motor performansı üzerindeki etkisini sunmaktadır. İlk olarak, LATM'nin manyetik eşdeğer devre modeli ve denklemleri tanımlanmış ve 4 kutup için motor torku ifadesi oluşturulmuştur. Ardından, bir karar verme aracı olan analitik hiyerarşi süreci (AHP), en iyi LATM tasarım parametrelerini belirlemek için referans olarak kullanılmıştır. Elde edilen tasarım parametrelerinin alt ve üst değerlerinde motorun vuruntu torku, sabit tork bölgesi ve tepe tork değeri sonlu elemanlar analizi ortamında analiz edilmiştir. Belirli sınırlamalar göz önünde bulundurularak en iyi tasarımın geçici durum analizi gerçekleştirilmiş ve yüksüz durumda çalışma performansı analiz edilmiştir. Önerilen model ile 4 kutuplu sınırlı açılı tork motorunun sabit tork bölgesindeki torku, tepe torkunun %95'i olarak elde edilmiştir. Bu değer sonlu elemanlar analizi ile doğrulanmıştır.

1. INTRODUCTION (GİRİŞ)

Electrical machinery is used in all areas of life. Today, they are used in aviation, especially in unmanned aerial vehicles, space technology, automobiles, optical scanning, thermal imaging, servo valves, scanning mirror mechanism, laser mirrors, positioning missile guidance radar antennas, small-scale gas turbines, especially small-scale engines. These motors can be seen as key components as they significantly affect the performance and reliability of the system in their field of use. It is generally expected to be a low-cost but highly reliable component. Fast response, accurate positioning and robustness against possible parameter changes and external disturbances are preferred. LATM is one of these motors that emphasizes precision. It is preferred in situations where full and precise control over a certain range is required. For example, in aviation, the ability of fuel meters to precisely control the fuel flow is an important component in the reliable operation of the aircraft [1]. However, the lack of diversity in the limited angle torque motor and the limited number of manufacturers cause new designs using this motor to be dependent on the existing motor geometry. Therefore, given that size is an important issue in areas where limited angle torque motors are used, diversity is essential in this motor. In addition, fluctuations in rare element magnet prices have sometimes been experienced as a rare element crisis. In this context, researchers have turned to the development of electric motors with reduced rare element content. From this point of view, it is

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necessary to investigate the effect of magnet type and geometry on the material in limited angle torque motor design and to seek maximum energy in the smallest possible volume. Since there is very little research in the literature based on magnetic analysis of LATMs, new analytical solutions have been sought for the design of motors with different pole numbers and types.

In the literature, there are some studies on the design, performance comparison and improvement of LATMs. These studies focused on optimization techniques of physical dimensions and driver controls in conventional arc type rotor motors. Krishna and Kannan compared the slotted and slotless type brushless DC LATM design. They found that although slotted-wound LATMs have higher torque constants, they have greater magnetic friction and iron losses, and even torque fluctuation due to the slot [2]. Tsai et al. designed a 2-pole brushless DC LATM and investigated its performance in fuel control of a gas turbine engine and found that the precision is efficient [3]. Zarandi et al. created a magnetic equivalent circuit model for 2-pole LATM design. In order to reduce the volume and weight of the rotor, the magnet geometry was made in parts, but it was shown that the losses in the generated torque increased [4]. Wu et al. studied the design and optimization of LATM for small gap applications. The magnetic equivalent circuit model is organized in matrix format and the measurement of torque constant and linearities by MOPSO method is consistent with experimental results [5]. Hekmati et al. made a comparison between outer rotor type and inner rotor type LATMs and found performance advantages in the outer rotor type topology [6]. Li et al. analyzed a new LATM with an irregular number of slots and presented an analytical equation to support the optimum design of the LATM. It was found that the proposed design resulted in an increase in operating area and a decrease in losses [7]. Mina Roohnavazfar et al. considered the axiomatic design (AD) method to obtain the most efficient 2-pole limited angle torque motor and found that the results are reliable [8]. Widdowson et al. investigated computer-based optimizations of the LATM to maximize torque per current [9]. Saaty studied the effect of nonlinear parameters in a limited angle torque motor and found that each factor has different consequences. Analytic hierarchy process was proposed to select the best alternative design [10]. As an alternative to the time-consuming solutions of AHP, the AD (axiomatic design) approach was proposed by Suh. This solution is proposed to reduce expert requirements and save time in design solutions [11]. In the research on LATM control, Xiao et al. studied a PID controller for LATM position that includes angle, velocity and current loops, and Zhao et al. studied a PID control method that also has an acceleration loop [12-13]. Chen et al. proposed a feedback controller to manage the nonlinear variables with the variation of angle in LATM and to increase the torque produced per current. The prototype results demonstrated the operating efficiency [14].

Previous studies have only focused on magnetic analysis, simulations, optimization of LATM parameters and driver design of 2-pole LATMs with conventional arc-type rotor structure. Unfortunately, there is very little literature on the effect of rotor pole geometry and number of poles on motor performance in limited angle torque motors. Due to the high torque of the proposed frameless limited angle torque motor and the large constant torque region, it is necessary to examine many related parameters. Changes in parameters such as magnet type, geometry, stator-rotor radial and axial distances, inner diameter, air gaps, mechanical clearances, pole and stator winding arc lengths will be monitored in order to create the most suitable design for the application area. AHP, one of the decision-making tools, will be used to determine the best LATM design parameters and the outputs will be verified by finite element analysis method.

2.FOUR POLE LIMITED ANGLE TOROIDAL MOTOR MAGNETIC ANALYSIS (DÖRT KUTUPLU SINIRLI AÇILI TOROİDAL MOTOR MANYETİK ANALİZİ)

A limited angle toroidal motor is an electric machine with two or more poles and a permanent magnet rotor, fed by a toroidally wound coil on the stator. With the stator-rotor concentric structure, the radial magnetic attraction force balances each other and the state in which the rotor is inside is called the inner rotor. The interaction between the magnetic field created by the current-carrying windings and the constant magnetic flux produced by the magnets determines the direction and magnitude of the motion in the motor. Since the magnetic flux produced by the magnets is constant, the component that affects torque is the direction and magnitude of the direct current flowing through the windings and the position of the magnet. The constant torque operating field depends on the toroidal coil arc length and the pole arc angle lengths. Cogging torque is either absent or negligible. The fact that LATMs have a toroidal wound coil in a slotless structure prevents torque ripple. The small length/diameter ratio of these motors allows them to operate in very small confined spaces. In addition, the low inertia of the rotor assembly allows high angular acceleration. Brushless and non-commutation are also advantages. With these advantages, LATM is also used in military and medical applications.

The cross-section of the LATM structure with an arc-type rotor is shown in Figure 1. As can be seen from Figure 1, an arc type magnet is mounted on the rotor and designed to determine the operating area.

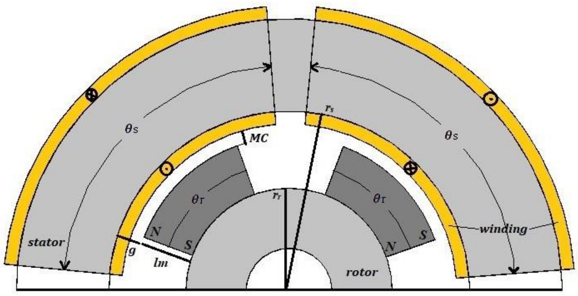

Figure 1. Arc type 4 pole limited angle toroidal motor half section (Yay tip dört kutuplu sınırlı açılı toroid motorun yarım kesiti)

In LATM design, electromagnetic, thermal, mechanical and some problems need to be investigated. Magnetic analysis is examined both analytically and through software programs. Analytical calculation requires the properties of the magnet and all the geometric values in the motor. Considering the LATM shown in Figure 1, the magnetic flux of the permanent magnet first passes through to the air gap and then into the stator material. The magnetic flux, which is splited into two here, completes its circulation on the stator and completes its circuit with the air gap on the other pole, the magnet surface on the other pole and rotor. This circuit circulation, which is linear when there is no current in the windings, completes its circuit by concentrating in one direction according to the direction of the current when the current flows through the windings. When there is current in the windings, a force is generated in the air gap due to magnetic interaction and as a result of this force, rotational movement occurs in the rotor. The value and area of influence of this torque is determined by some calculations. In magnetic circuit analysis, it is first necessary to determine the magnetic reluctances in the flux path. The magnetic flux produced by the magnet will be scattering in two different directions due to the arc type of the magnet. The circuit analysis of this situation is shown in Figure 2.

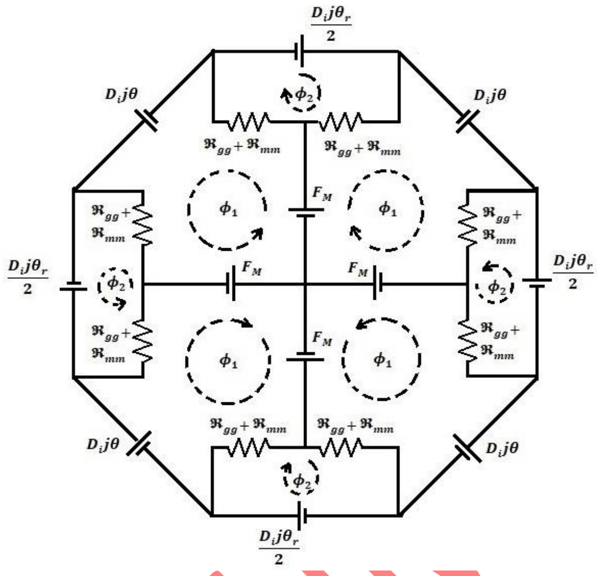

Figure 2. Arc type 4 pole limited angle toroidal motor magnetic equivalent circuit (Yay tip dört kutuplu sınırlı açılı toroid motorun manyetik eşdeğer devresi)

As can be seen from Figure 2, the magnetic flux produced in F_M (magneto motor force produced by magnet) completes its circuit in such a way that there are two approximately equal magnetic flux distributions from the arc-shaped magnet and the air gap to the neighboring magnets. This is expressed in the equivalent circuit as $\Re_{gg}$ (magnetic reluctance of the half-arc in the air gap) and $\Re_{mm}$ (magnetic reluctance of the half-arc magnet). As it is known, the magnetic reluctance of a material is directly proportional to the length of the magnetic flux path and inversely proportional to the permeability and cross-sectional area of the material, as expressed in the following equation [15]. Since half of the arc type magnet is considered in the magnetic equivalent circuit, the cross sections are taken as half.

$$\Re_{mm} = \frac{l_m}{\mu_0 x \mu_m x (A_m/2)} \tag{1}$$

$$\Re_{gg} = \frac{l_g}{\mu_0 x (A_g/2)} \tag{2}$$

where A_m and A_g are the cross-sectional areas of the magnet and the air gap, respectively, and μ_0 and μ_m are the relative magnetic permeability values of the gap and the magnet. In the Eq. 1 and 2, l_m is the radial length of the magnetic flux on the magnet and l_g is the air gap distance. The directions of the magnetic flux formed by the interaction of the magnetic flux created by the current passing through the windings and the magnet are shown in Figure 2. The magneto motor force that creates the magnetic flux in the magnetic equivalent circuit is of two types. One is the magneto motor force F_M

produced by the magnets, and the other is the magneto motor force F_W produced by the current carrying windings. These two magneto-motor forces determine the direction and magnitude of the circulating magnetic flux. When the position of the rotor is in the center of the opposite winding, the magneto motor force generated by the windings is calculated as follows;

$$F_w = \frac{N_s I_s}{\theta_s}\theta_r \tag{3}$$

where N_S and I_S are the number of turns in the winding and the current passing through the winding, respectively. In the Eq.3, θ_r is pole arc length and θ_s is the coil arc length. As seen in Eq. 3, the magneto-motor force of the winding opposite the pole is equal to the pole arc length ratio of the total ampere-turn value of the winding. While the magneto motor force of the winding effects across the pole in the ratio of the pole arc length, it effects outside the pole region in the ratio of the rotor position angle. The effect of the magnetomotive force of the winding across and out of the pole in the equivalent circuit is shown in Figure 2 with a linear current density expression. Linear current density is the current density per unit length of the winding and is calculated as follows [4,9];

$$J = \frac{N_s I_s}{(D_i/2)\theta_s} \tag{4}$$

where D_i is stator inner diameter. The circulating magnetic flux in the magnetic equivalent circuit is the ratio of the total magneto motor force to the equivalent reluctance. Considering the magnetomotor force of the magnet and the magnetomotor force of the windings connected to the rotor position, the circulating magnetic fluxes are:

$$\phi_1 = \frac{2xF_M}{2(\Re_{gg}+\Re_{mm})} + \frac{D_i j\theta}{2(\Re_{gg}+\Re_{mm})} \tag{5}$$

$$\phi_2 = \frac{\frac{D_i j\theta_r}{2}}{2(\Re_{gg}+\Re_{mm})} \tag{6}$$

where, θ is rotor position. The difference between stator winding and pole arc lengths is the region where the torque is constant and is called constant torque region. The constant torque region depends on the stator winding arc length and pole arc length as follows:

$$\theta_0 = \frac{\theta_s - \theta_r}{2} \tag{7}$$

The LAT motor runs at constant torque within the range of $\pm\theta_0$. In the literature, torque in the constant torque region is required to be more than 80% of the peak torque [2,3].

For the torque produced in the motor when the magnetic reluctance of the stator and rotor is neglected; the torque can be calculated by calculating the derivative of the total coenergy produced by the windings and the magnet with respect to the rotor position. The total coenergy, energy and the torque can be expressed by the following equations [4]:

$$W_T' = \sum \int \lambda\, di = \sum \frac{F\phi}{2} \tag{8}$$

$$W_T' = \frac{4\left(\frac{N_s I_s}{\theta_s}\right)^2}{(\Re_{gg}+\Re_{mm})}\theta^2 + \frac{8F_M\left(\frac{N_s I_s}{\theta_s}\right)}{(\Re_{gg}+\Re_{mm})}\theta + \frac{4F_M{}^2 + \left(\frac{N_s I_s}{\theta_s}\theta_r\right)^2}{(\Re_{gg}+\Re_{mm})} \tag{9}$$

$$T = \frac{\partial W_T'}{\partial \theta} = \frac{2N_s I_s}{\theta_s}\,\frac{\left(\frac{4N_s I_s}{\theta_s}\theta + 4F_M\right)}{\Re_{gg}+\Re_{mm}} \tag{10}$$

$\theta = 0$; torque;

$$T_p = \frac{8F_M N_s I_s}{(\Re_{gg}+\Re_{mm})\theta_s} \tag{11}$$

According to the equation obtained in the analytical calculation, the electromagnetic torque is directly proportional to the magneto motor force of the magnet, number of turns and current magnitude and inversely proportional to the magnetic reluctance and stator winding arc length.

3.DESIGN IMPROVEMENT METHODS AND FINITE ELEMENT ANALYSIS (TASARIM İYİLEŞTİRME YÖNTEMLERİ VE SONLU ELEMAN ANALİZİ)

The mathematical model of the 4-pole LATM provides the magnetic analysis and torque calculation. Eq. 5 and Eq. 6 are used to determine whether the material is in magnetic saturation by considering the circulating magnetic flux and the cross-sectional ratio of the material. The mathematical model allows the output to be predicted according to the type and geometry of the material to be selected. The principle of operation is quite simple and design improvement is required to achieve maximum torque output without cogging torque in the smallest possible volume. In this context, design improvement should be done by determining usage area constraints and minimum requirements. When determining the variables, the parameters where the material does not saturate are determined using a mathematical equation. However, due to the non-linear structure of the material used in the motor, the magnetic flux density distribution can only be determined through computer aided programs. In general, the accuracy of the solution is increased with the finite element method (FEM). As it is known, the solution in FEM is based on the principle of dividing the material into a finite number of small regions. In the solution region, the effect of the elements connected to each other in a chain is analyzed. The degree of accuracy is proportional to the number of meshes of the appropriate size. Therefore, the most accurate result is achieved through time-consuming simulations. It is aimed to achieve maximum torque within certain cogging torque limits with the smallest possible volume and less material.

There are multiple variables in limited angle torque motor design. While each parameter change has its own consequences, sometimes changing certain parameters together produces different results. The best design should be selected by considering industrial requirements and restrictions in design criteria. For this purpose, there is a need to use a decision-making tool. AHP, one of the useful tools that can be used in the multi-criteria decision-making process, is discussed in this article. Using AHP has the advantage of choosing a higher quality alternative in both objective and subjective problem areas that can control the consistency of comparisons [4]. In AHP, which is widely used as a powerful and flexible decision-making tool, some effective criteria are taken into account and evaluated according to expert judgments and acceptable design solutions. The weight, volume, magnetic torque, copper loss and mechanical clearance of the LATM are considered as criteria. In the LATM design procedure, it is desirable to minimize weight, volume, maximize torque as high as possible, and maximize mechanical clearance considering the manufacturing process. Therefore, it is necessary to first define the decision problem in detail and create a decision hierarchy. The hierarchy framework for LATM design is shown in Figure 3.

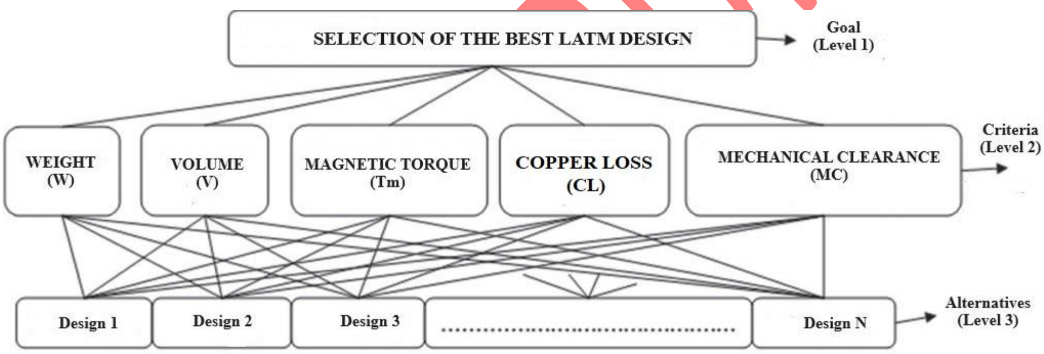

Figure 3. Hierarchy framework of the LATM design (LATM tasarımının hiyerarşik çerçevesi)

The first level is the overall objective of the decision making and the selection of the best LATM is specified here. The second stage is the criteria defining LATM efficiency, where the designs are determined based on the knowledge of the industrial application of the LATM. In the last stage, decision alternatives are identified. Prior to the analysis, pairwise comparison matrices should be created and priority vectors should be determined using the arithmetic mean, geometric mean or least squares method. Considering the industrial limitations and requirements, five different designs are selected with the help of analytical calculations. The following table is taken as a performance priority criterion and the priority vector is determined by arithmetic method.

Table 1. Criteria matrix (Kriter matrisi)

	Weight (W)	Volume (V)	Torque (Tm)	Copper Losses (CL)	Mechanical Clearance (MC)
Weight (W)	1	1/3	1/9	1/7	1/5
Volume (V)	3	1	1/7	1/5	1/3
Torque (Tm)	9	7	1	3	5
Copper Losses (CL)	7	5	1/3	1	3
Mechanical Clearance (MC)	5	3	1/5	1/3	1

$$\text{Priority vector} = \begin{bmatrix} 0.0348 \\ 0.0678 \\ 0.5028 \\ 0.2602 \\ 0.1344 \end{bmatrix} \quad (12)$$

The samples taken from Design 1 to Design 5 are compared with each other separately in terms of each criterion in the table above. The priority vector is determined from the matrices obtained from the comparisons and these vectors together form the main matrix. When the resulting main matrix is multiplied by the priority vector of the criteria matrix given in Eq. 12, the design with the highest value is the best design determined by AHP. The determined alternative values are verified in finite element analysis and the effect of changing some parameters in the design on the motor is examined. In the search for alternative designs considering industrial requirements, the parameters given in the table below are determined. Table 2 shows the parameters obtained as a result of some improvements made for the 3.5 inch outer diameter motor subject to the study.

Table 2. Main design parameters (Ana tasarım parametreleri)

Parameter	**Value**	**Parameter**	**Value**
Pole Number, (p)	4	Magnet length, (lm)	5 mm
Stator outer diameter, (Do)	3.5 inch (88.9mm)	Air gap, (lg)	3 mm
Stator inner diameter, (Di)	70 mm	Mechanical clearance, (MC)	0.5 mm
Rotor outer diameter, (Ro)	64 mm	Stator-rotor material	Steel 1010
Rotor inner diameter, (Ri)	26 mm	Torque constant	1.11 Nm /A
Motor axial length, (La)	32 mm	Excursion angle	± 45

The effects of some variables on design improvements are examined. These are values such as stator and rotor inner diameter changes, air gaps, mechanical clearances between pole windings, magnet thickness, length, arc degree and type, axial and radial distances in the motor, winding arc length, etc. These variables affect variables such as torque and cogging torque. Although examining these parameters individually gives an idea of the effect on motor performance, the main result is that all components change together. This prolongs the simulation process for multiple variables at the same time. Based on the reference parameters obtained with AHP, geometric changes of all components, material selection analysis for magnet and core are performed using the finite element method with the Ansys-Maxwell software program.

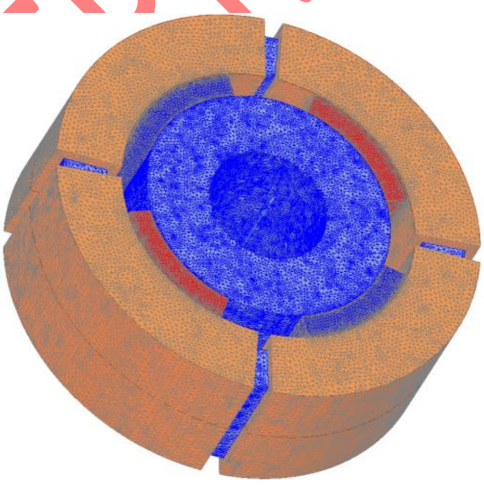

Figure 4. Mesh plot of the the LATM design (LATM tasarımının ağ çizimi)

In Ansys Maxwell, the design geometry is first created with the values taken from Table 2. The magnetostatic solver is selected for the solid model shown in Figure 4, and mesh elements are created for this analysis. For a better and more precise solution the analysis is examined with 1200000 mesh elements. After determining the current directions of the windings and the poles of the magnets, magnetic analysis is started. For a 4-pole motor, a variable is assigned to the rotor position in the ±45 degree operating region, and the values of the rotor at different positions are examined. As a result, the torque constant in Table 2 is obtained.

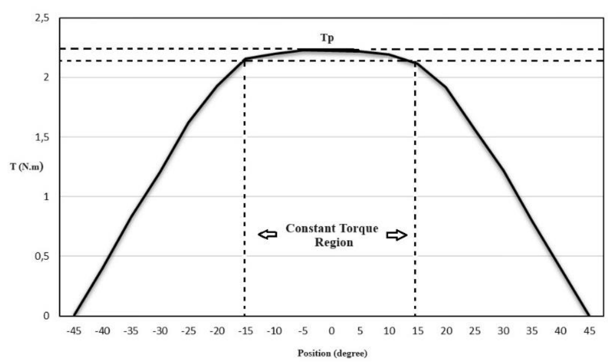

Figure 5. Torque-angle characteristic of the LATM design (LATM tasarımının tork-açı karakteristiği)

When the values in Table 2 are taken, the variation of the magnetic torque obtained from the finite element analysis according to the rotor position is shown in Figure 5. When the rotor position is moved from -45 degrees to +45 degrees, the force in the air gap affects the torque. When it moves from -15 degrees to +15 degrees, a constant torque region is formed. It is desirable that the peak torque in the constant torque region is close to the torque values at the inlet and outlet of the constant torque region of the rotor, that is, the torque curve is linear in this region.

In addition, inductance values, magnetic flux and flux densities, peak torque, constant torque region and cogging torque are determined. In order to obtain the effect of the parameters determining the LATM on the motor in the magnetostatic solver, first of all the effect of the inner diameter of the motor with an outer diameter of 3.5 inches, together with the stator and rotor pole arc lengths, is analyzed.

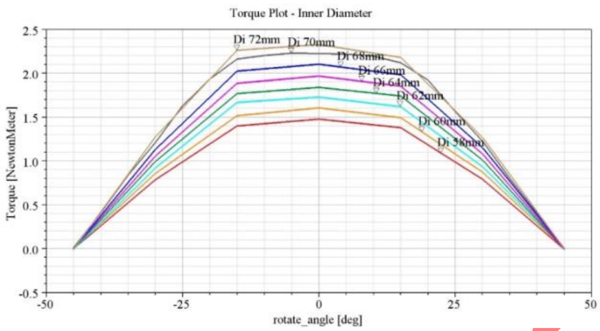

Figure 6. Effect of stator inner diameter change (Stator iç çap değişiminin etkisi)

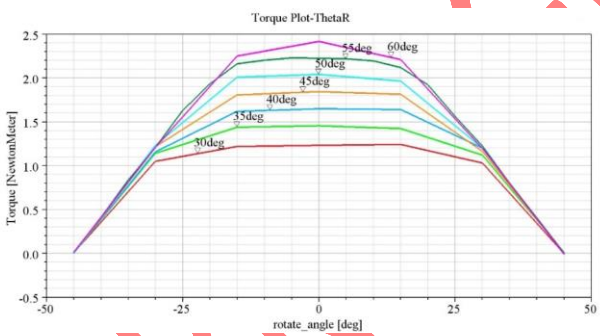

Figure 7. Effect of pole arc length change (Kutup yay uzunluğu değişiminin etkisi)

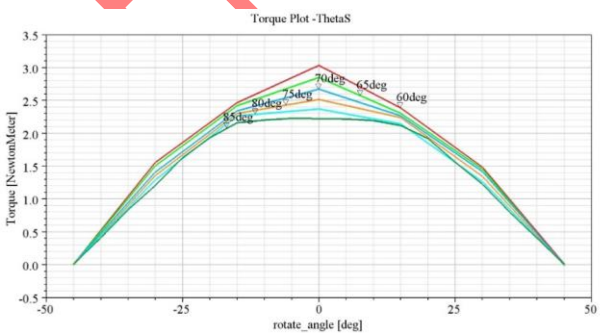

Figure 8. Effect of coil arc length change (Sargı yay uzunluğu değişiminin etkisi)

In Figure 6, it is seen that the increase in the inner diameter causes an increase in the torque. However, in the constant torque region, the torque curve linearity changes. At this stage, the value where the inner diameter is 70 mm is the value that meets the most linear and the highest torque together. Likewise, Figure 7 and Figure 8 show the effects of pole arc lengths on torque when the stator winding is 85 degrees, and the effects of the coil arc length wound on the stator on torque when the pole arc is 55 degrees. It has been determined that the arc lengths increase the torque as they get closer to each other, but decrease the constant torque region. Considering the magnet cost and the magnetic saturation limits of the material, the effect of the magnet thickness on the torque is analyzed in Figure 9 and the maximum torque value is desired with the smallest possible magnet. Air gap and mechanical clearance are also analyzed in the design development stages and it is observed that the torque increased in the smallest possible air gap. In addition, 0.5 mm changes in the mechanical clearance are tested and it is determined that the increase and decrease in the clearance affect the torque as can be seen in Figure 10. Considering the ease of design and winding thickness, an air gap of 3 mm is chosen for the design.

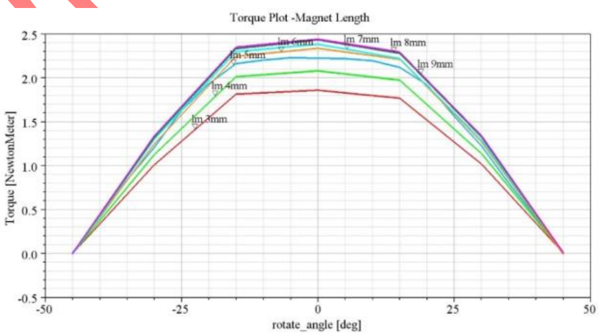

Figure 9. Effect of magnet thickness. (Mıknatıs kalınlığı etkisi)

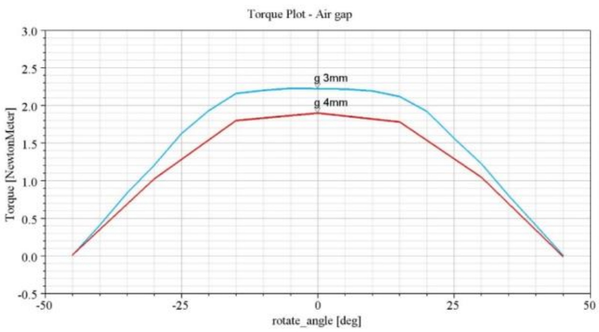

Figure 10. Effect of air gap and mechanical clearance (Hava aralığı ve mekanik açıklık etkisi)

Although the change of the rotor inner diameter has no direct effect on the torque, it should be taken into account in the saturation of the material and the weight of the moving part. Since it is observed that the magnetic saturation in the rotor is exceeded at the values above of 26 mm, the design is created with an inner diameter of 26 mm.

4.SIMULATION RESULTS (SİMULASYON SONUÇLARI)

The magnetic analysis is completed by considering the constraints and requirements. Magnetic flux values, magnetic flux densities and peak torque values obtained in Ansys-Maxwell matched with mathematical expressions to a certain extent. Taking the values in Table 2 into Eq. 11, a peak torque of 2.414 Nm is obtained. This value is the value where leakage is ignored and the actual value is the result obtained in the simulation where leakage in the nonlinear material is taken into account. The curve is given in Figure 11. The error due to the 8.69% leakage flux shown in Table 3 also confirms the mathematical expression. Considering the torque linearity in the constant torque region, the lowest torque in the constant torque region is 95% of the peak torque. This is the most linear curve in the design development stages.

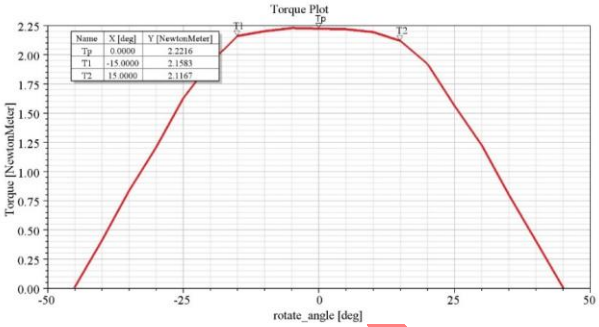

Figure 11. LATM magnetic torque plot (LATM manyetik tork eğrisi)

Table 3. Comparison of analytical model and FEA (Analitik model ve sonlu eleman analiz karşılaştırması)

	Analytical Model	**FEA**	**Error (%)**
Peak Torque (Nm)	2.41	2.22	-8.69
Average Airgap Flux Density (T)	0.681	0.688	0.891

Table 4. Comparison of LATM3500 and others (LATM3500 ve diğerlerinin karşılaştırması)

Product Name	**Number of Poles**	**Torque Sensivity (Nm/A)**	**Peak Torque (Nm)**	**Outside Diameter (mm)**	**Motor Axial Height (mm)**
LATM3500	4	1.11	2.221	88.9	32
Ref-2	4	0.20	0.35	84	16
Ref-4	2	1.11	2.48	89.46	48
ICPE TQR-28	4	0.148	0.296	70	16
MOOG TD4094	6	0.339	1.016	103.98	23

When the torque value obtained from the simulation results is compared with the alternatives, it is seen that the peak torque value per unit volume is higher. The comparison table in terms of the outer diameter and axial heights of the motor compared to its counterparts is as follows. The design is named as LATM3500 and the Table 4 shows the designs taken from the reference sources numbered 2 and 4 in the literature researches and the products of some manufacturers with similar geometry.

The magnetic flux density in the air gap, which provides the force and thus the torque, is given in Figure 12. It has been shown that the design is optimized without saturation of the material, which has been found to have similar and symmetrically balanced fluxes at all poles.

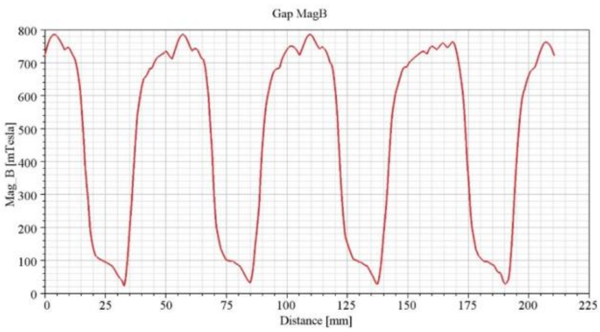

Figure 12. Magnetic flux density change in air gap (Hava aralığındaki manyetik akı yoğunluğu değişimi)

The vectoral direction and magnitude of the magnetic flux is shown in Figure 13, where it completes its circuit without reaching magnetic saturation. In addition, vectoral magnetic flux directions confirm the magnetic equivalent circuit.

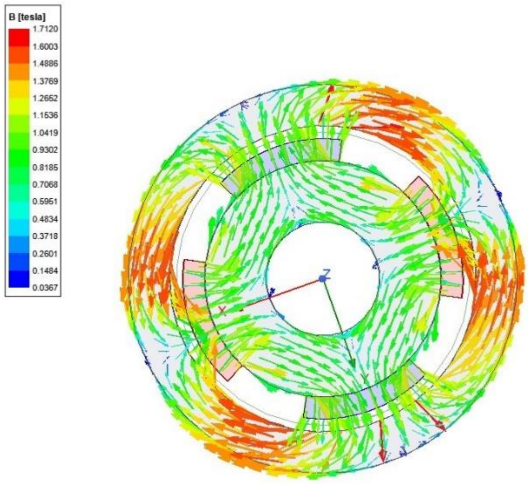

Figure 13. Magnetic flux density vector distribution (Manyetik akı yoğunluğu vektörel dağılımı)

A transient analysis is performed for the position response of the design. It is important to calculate the moment of inertia correctly in order to calculate the exact torque from time-varying position information. Since calculations are difficult due to the complexity of the structure, Ansys-Maxwell transient solver is used. After determining the moment of inertia and damping coefficient in the mechanical transient analysis, the change curve of the rotor position with respect to time is created. The position response of the design is examined in the transient analysis when current passed through the windings at no load. When a voltage of 70 V is applied to the stator terminals, the rotor moves thanks to the magnetic flux generated. As can be seen in Figure 14, the rotor moves from 0 degrees to 45 degrees in 150ms.

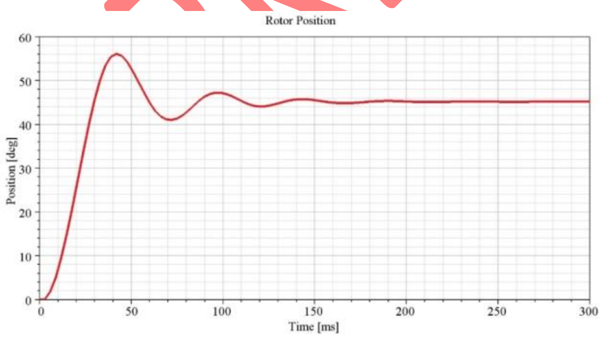

Figure 14. FEA result for position response of LATM (LATM'nin pozisyon tepkisi için sonlu eleman analiz çıktıları)

5.CONCLUSIONS (SONUÇLAR)

In this study, the mathematical model and magnetic analysis of a 4-pole limited angle toroidal motor, which is not available in the literature, are completed. The effects of changing the magnet and stator-rotor geometry on the performance of the motor are investigated. In the constant torque operating region, both linear and high torque, minimum cost, minimum volume and weight values are determined with the help of AHP. A linear torque curve that does not fall below 95% of the peak torque in the ±15 degree operating region was obtained. It is seen that the torque constant per unit volume is more advantageous than the alternatives produced in the industry and the designs obtained in article researches. In addition, by examining motors with different geometry and number of poles, it was ensured to reduce the dependence on traditional type motors in the inventory of a few manufacturers and to shed light on the design of the LAT motor specific to the area of use.

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DECLARATION OF ETHICAL STANDARDS (ETİK STANDARTLARIN BEYANI)

The author of this article declares that the materials and methods they use in their work do not require ethical committee approval and/or legal-specific permission.
Bu makalenin yazarı çalışmalarında kullandıkları materyal ve yöntemlerin etik kurul izni ve/veya yasal-özel bir izin gerektirmediğini beyan ederler.

AUTHORS' CONTRIBUTIONS (YAZARLARIN KATKILARI)

Akın AYDIN: He conducted the research, analyzed the results and performed the writing process.
Araştırmayı yapmış, sonuçlarını analiz etmiş ve makalenin yazım işlemini gerçekleştirmiştir.

Ali SAYGIN: He contributed subject and article evaluation.
Konu ve makale değerlendirmesinde katkıda bulunmuştur.

CONFLICT OF INTEREST (ÇIKAR ÇATIŞMASI)

There is no conflict of interest in this study.
Bu çalışmada herhangi bir çıkar çatışması yoktur.

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