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# Design and Optimization of a PMSM for Obtaining High-Power Density and High-Speed

**Gullu BOZTAS[1*], Merve YILDIRIM[2], Omur AYDOGMUS[3]**
[1]Electrical and Electronic Engineering, Technology Faculty, Firat University, Elazig, Turkey
[2]Electrical-Electronic Engineering, Engineering Faculty, Firat University, Elazig, Turkey
[3]Mechatronics Engineering, Technology Faculty, Firat University, Elazig, Turkey
[*1]gboztas@firat.edu.tr, [2]merveyildirim@firat.edu.tr, [3]oaydogmus@firat.edu.tr

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**Abstract:** It is very important to obtain high power in a small volume for many applications. Especially, power/weight (W/kg) ratio needs to be well balanced in electric and aircraft vehicles, military and robotic applications. High power density can usually be obtained with a magnet-assisted motor. However, it is very difficult in terms of design for the motor to have both high power and low weight. Therefore, motor design should be supported by a good optimization. In this study, Multi-Objective Genetic Algorithm (GA) is used to obtain high power and low weight. Thus, targets are achieved by both optimizations at the same time. Rotor inner diameter, stack length, magnet insert, magnet thickness, and magnet angle are optimized in this paper. The motor is designed as 24 slots and 16 poles. 1100 generations are obtained by optimization and it has been decided that 1092$^{th}$ generation is the most suitable motor. Hence, motor having approximately 8 kW output power and 1.3 kg rotor mass is designed. The motor efficiency is obtained about 97% when friction and ventilation losses are neglected. As a result, it is observed that designed PMSM with high-power density and high speed can be used in the robotic and military applications.

**Key words:** Optimization, High Power Density, Genetic Algorithm, Motor Design, Permanent Magnet Synchronous Motor.

## Yüksek Güç Yoğunluğu ve Yüksek Hız elde etmek için PMSM'nin Tasarımı ve Optimizasyonu

**Öz:** Birçok uygulama için küçük bir hacimde yüksek güç elde etmek oldukça önemlidir. Özellikle, elektrikli ve hava araçlarında, askeri ve robotik uygulamalarda güç/ağırlık (W/kg) oranının iyi dengelenmesi gerekmektedir. Yüksek güç yoğunluğu genellikle mıknatıs destekli bir motor ile elde edilebilir. Ancak motorun hem yüksek güce sahip, hem de düşük bir ağırlığa sahip olması tasarım açısından oldukça zordur. Bu yüzden iyi bir optimizasyon destekli tasarıma ihtiyaç duyulmaktadır. Bu çalışmada, yüksek güç ve düşük bir ağırlık elde etmek için Çok Amaçlı Genetik Algoritma kullanılmıştır. Böylece her iki optimizasyon hedefine aynı anda ulaşılması sağlanmıştır. Rotor iç çapı, paket boyu uzunluğu, mıknatıs derinliği, mıknatıs kalınlığı ve mıknatıs açısı bu makalede optimize edilmiştir. Motor 24 oluklu ve 16 kutuplu olarak tasarlanmıştır. Optimizasyon ile 1100 adet jenerasyon sonunda 1092. jenerasyonun en uygun motor olduğuna karar verilmiştir. Böylece yaklaşık 1,3 kg rotor ağırlığına ve yaklaşık 8 kW çıkış gücüne sahip bir motor tasarlanmıştır. Sürtünme ve vantilasyon kayıpları ihmal edildiğinde motor verimi %97 civarında bir verim elde edilmiştir**.**

**Anahtar kelimeler:** Optimizasyon, Yüksek Güç Yoğunluğu, Genetik Algoritma, Motor Tasarımı, Kalıcı Mıknatıslı Senkron Motor.

## 1. Introduction

In recently, Permanent Magnet Synchronous Motors (PMSMs) have been popular in many areas such as aerospace, automotive industry especially electric vehicles, and robots due to its high efficiency, fast torque response, and high power density [1–3]. Optimization methods in this motor design are also significant research areas. Especially, the design optimization of the PMSM has great importance in terms of the cost and energy saving [4]. Therefore, there are a lot of studies about this topic in the literature. First of all is optimal design of axial-flux PMSM by using GA in [5]. Air gap, permanent magnet flux density, current density and number of stator winding turns are examined by GA optimization method. Maxwell 3D analysis based on Finite Element Method (FEM) is realized to compare the design and optimization results. It is observed from the simulation results that a rms current value and copper loss causing the motor temperature at the rated torque are significantly decreased by reducing the input voltage. By using GA optimization, a five-phase slotless PMSM with an external rotor is designed for high torque density in [6]. A higher torque density for PMSM can be provided by having a trapezoidal back EMF. For this reason, back EMF waveform is optimized by a multi-objective GA optimization based on the analytical

[*] Corresponding author: gboztas@firat.edu.tr. ORCID Number of authors: [1] 0002-1720-1285, [2] 0003-1284-7324, [3]0001-8142-1146

model. FEM analysis is realized to verify the analytical results. Then, a prototype of the designed PMSM is manufactured and FEM analysis and analytical results are validated by the experimental results.

In [7], optimal design of PMSM is presented by utilizing GA to obtain high efficiency and low permanent magnet weight at the rated load and speed. Multi-objective functions in GA are taken as the sum of the PMSM efficiency and the inverse value of the permanent magnet total weight. After that, two PMSM models are handled and FEM analyses of the PMSMs are performed by comparing each other. Convenient motor model is selected to validate the PMSM design with GA. Authors in [8] propose an optimal GA design of PMSM with low speed and high torque used in unmanned ground vehicle. Maximum efficiency is selected as object function in GA. Stator and rotor lamination structures and stator windings are designed. The size of permanent magnet and the length of air gap are calculated. Then, the PMSM is analyzed by FEM solution. PMSM design without optimization is compared with that of the GA optimization method.[9] explains an optimal design of in-wheel PMSM by using GA to obtain high efficiency and low weight. The current density, the length ratio, the inductions in the air gap and stator teeth, stator yoke, and rotor core are taken as design parameters in the optimization. As a result, in-wheel PMSM is optimized by GA method. An optimal design of a surface-mounted PMSM is studied by using improved GA with subdomain model for multi-objective in [10]. The aim of this study is to improve the performance of surface-mounted PMSM in terms of the magnetic field distribution, efficiency, and cost and. Firstly, a subdomain model is created for the analysis of the flux density harmonics. After that, the multi-independent-population GA with time-saving subdomain model is designed for the Pareto optimal set solutions. Finally, FEM analysis of the optimized PMSM is realized and the optimized design results are compared with the first design results.

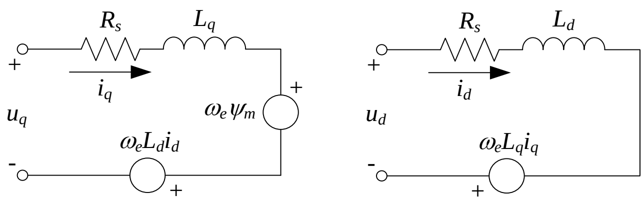
The rotor structure of PMSM is optimized by GA in [11]. Two kinds of stator windings and two types of current driving methods are examined for designing the rotor structures. It is seen that the PMSM having the best rotor structure has the largest average torque. A novel nine-phase PMSM with consequent pole rotor is designed for high-power traction applications in [12]. Multi-phase PMSMs are used in special areas desired higher torque/power density. The constant power–speed range of this motor is quite wide rather than the conventional PMSMs. FEM analysis of the motor is realized and the performance of nine-phase PMSM with consequent pole rotor is compared with a nine-phase surface mounted PMSM. It is observed that the proposed motor has simpler rotor structure and lower magnet cost and temperature than the surface mounted PMSM. In [13], the design of the high power-density PMSM and driving system is studied. The control parameters are given in the design and the system stability is researched. Then, FEM analysis of the PMSM is realized and the analysis results are compared with the experimental results in terms of the back-emf and the efficiency. It is obtained from the results that the high power density driving system is proper for the areas with high-performance required high speed. High power density PMSM with high electromagnetic load and lightweight structure is studied in [14]. However, there is a drawback about the iron core material to obtain high magnetic load and lightweight structure is only utilized in the rotor design. Four topologies are used to examine the lightweight structure applied in the stator for reducing the total weight. Besides, the high performance soft magnetic alloy core is preferred for high power density PMSM. The proposed method is validated by comparing the electromagnetic performances of four motors.

Design and optimization of high power density PMSM with surface mounted magnet is explained for pod propulsion system in [15]. Some constraints related with the dimensions of PMSM, the maximum acceptable current density, and the non-saturable operation conditions are considered in the design. After that, the PMSM is analyzed by FEM and it is seen that it has high efficiency and power factor, non-saturable operation, low current density, cogging torque and torque ripple. The optimized design results are also compared with the other studies in the literature. Authors in [16] propose a high power density PMSM drive design with flooded stator cooling. The aim of the study is to increase the efficiency and reduce the volume of the drive. The magnet losses and AC losses are also important problems in the PMSMs. Hence, the magnets are axially segmented to decrease the magnets losses caused from the harmonics. As a result, the efficiency of the PMSM is increased by this way. A paper [5] presents an optimization of an axial-flux PMSM design at high speed. PMSM is optimized by using GA for optimal design of the because of the demanded torque with minimum current and copper losses, and dimensions. The optimum value of the air gap, permanent magnet flux density, current density, and the number of stator winding turns are determined by GA. Maxwell 3D model of the PMSM based on FEM is created to compare the analytical results and optimization results. According to the simulation results, it is seen that the rms current value and the copper losses at rated torque reduce significantly.

In this study, the rotor structure of the PMSM is optimized in order to obtain high power density at high speeds with low rotor mass. Both the output power of the motor should be increased and the motor weight should be decreased in order to achieve high power density. However, it is quite difficult to achieve this desired situation. Therefore, Multi-objective GA was used for the optimization in order to increase torque and reduce the rotor mass.

## 2. Mathematical Model of the PMSM

Dynamic equivalent circuits of the motor are presented in Figure 1 [17].




q-axis circuit (Torque) d-axis circuit (Field)

**Figure 1.** Equivalent circuit of a PMSM.

Voltage equations are obtained shown as Equation (1). Additionally, The linkage fluxes are shown in Equations (2)-(3).

$$\begin{bmatrix} u_d(t) \\ u_q(t) \end{bmatrix} = \begin{bmatrix} R_s & 0 \\ 0 & R_s \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_d(t) \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \dot{\psi}_d(t) \\ \dot{\psi}_q(t) \end{bmatrix} + \begin{bmatrix} -\omega_e & 0 \\ 0 & \omega_e \end{bmatrix} \begin{bmatrix} \psi_q(t) \\ \psi_d(t) \end{bmatrix} \tag{1}$$

where, $i_d$ and $i_q$ are $dq$-axis currents. $\omega_e$, $R_s$, $\psi_d$ and $\psi_q$ are the electrical rotor frequency, the stator winding resistance and linkage fluxes of $dq$-axis, respectively. $\psi_m$ is the flux linkage due to the rotor magnets.

$$\psi_d = L_d i_d + \psi_m \tag{2}$$

$$\psi_q = L_q i_q \tag{3}$$

The electromagnetic torque equations are shown in Equations (4)-(5).

$$T_e = \frac{3}{2} p \left[ \psi_d i_d - \psi_q i_q \right] \tag{4}$$

$$T_e = T_L + J \frac{d\omega_m}{dt} + B\omega_m \tag{5}$$

where, $T_L$, $J$, $\omega_m$ and $B$ are the load torque , the inertia, the mechanical angular velocity of the rotor and the friction coefficient.

3-types rotor structure of the PMSM is given in Figure 2 according to placement on the rotor and different shape of magnets. PMSM having surface-mounted magnets is given in Figure 2a [17]. The stator inductance of this type motor is lower than the other rotor types. Therefore, control of the surface-mounted PMSM is simple. Additionally, the reluctance effect of the motor is small enough to neglect. However, field weakening and speed control over the nominal value are so difficult for this motor. The interior-mounted rotor structure is shown in Figure 2b. Stator inductance depends on rotor position in this type motor. The operation of over nominal speed is suitable for this motor type because reluctance torque is obtained during field weakening. Additionally, durable structure is mechanically obtained in high speed applications when the magnets are placed embedded in the rotor. Buried magnet PMSM is given in Figure 2c. Flux condensation can be obtained with buried magnets given in Figure 2c. Flux density in the air gap is higher compared to that of the magnet in the buried magnet PMSM. In this study, interior mounted PMSM was designed and optimized for high speed applications. It is a motor that can be used in military applications, robotics and some industrial applications where high power density is important.

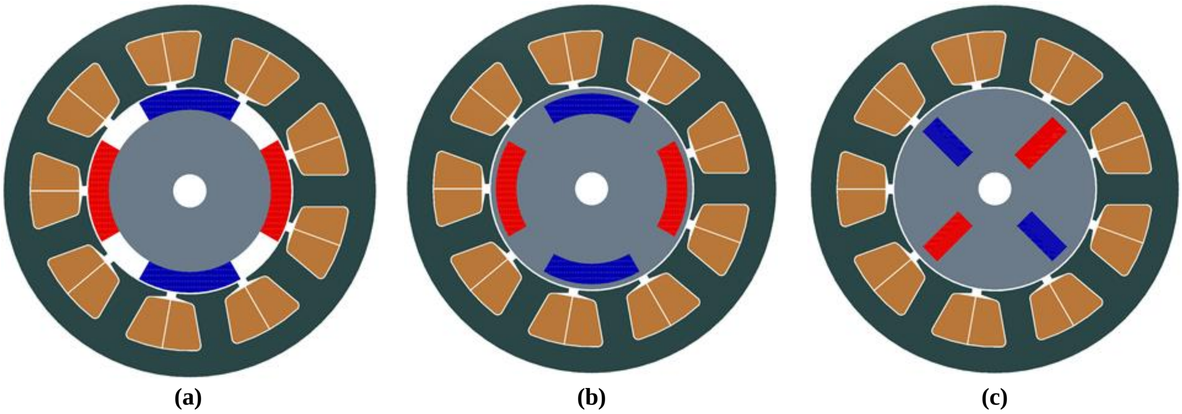



**Figure 2.** a) Surface-mounted PMSM, b) Interior mounted PMSM, c) Buried magnet PMSM.

## 3. Design and Optimization of the PMSM

In this study, an interior-mounted PMSM having 16 poles, 3 phases and 30 slots was designed by using MotorSolve/Infolytica program. Stator geometry, rotor outer radius, winding layout and pole number of the motor were kept constant for optimization. The materials of the stator and rotor cores were used as M530-50A. Values of motor parameters taken as constant are given in Table1. Rotor inner diameter, stack length, magnet insert, magnet thickness, and magnet angle were optimized in this paper. It is aimed to obtain maximum motor torque with minimum rotor mass in optimization progress. Thus, high power density motor will be obtained. Definition of the optimized motor parameters are shown in Figure 3.

Two fitness functions used for optimization are given in Equations (6)-(7). The fitness functions are optimized together by using MATLAB Genetic Algorithm toolbox and Multi-Objective Genetic Algorithm. The fitness functions were used in order to obtain maximum motor torque and the minimum motor mass. PMSM was analyzed using the Finite Element Method (FEM) -Newton Raphson iteration in the MAGNET program during the optimization steps The performance analyses of the Multi-Objective Genetic Algortihm are given in Figure 4. Each circle in the figure symbolizes an individual. During the optimization process, the motor torque was maximized as shown in Figure 4a. However, the rotor mass was slightly minimized as illustrated in Figure 4b because it is difficult to produce high torque with small rotor mass. 1092. iteration was determined for this study. Additionally, The change in the progress between motor torque-rotor mass is given in Figure 4c.

**Table1.** Values of motor parameters

| Parameter | Value | Parameter | Value |
|---|---|---|---|
| pole | 16 | slot opening width | 1 mm |
| number of slot | 36 | tooth tip thickness | 1 mm |
| stator outer radius | 55 mm | tooth width | 3.5 mm |
| stator inner radius | 35.5 mm | bottom fillet radius | 0 |
| air gap | 0.5 mm | top fillet radius | 0 |
| slot depth | 15 mm | number of turn | 6 |

$$fitness(1) = -\overline{T}_e \tag{6}$$

$$fitness(2) = M_{rotor} \tag{7}$$

where $\overline{T}_e$ is average electromagnetic torque of the motor. The reason used negative torque in the function is to convert minimization of optimization to maximization. $M_{rotor}$ is mass of the rotor.

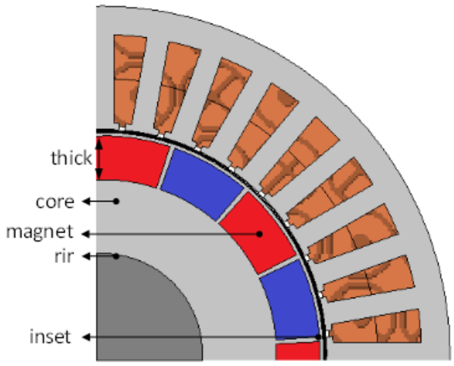



**Figure 3.** Definition of optimized motor parameter.

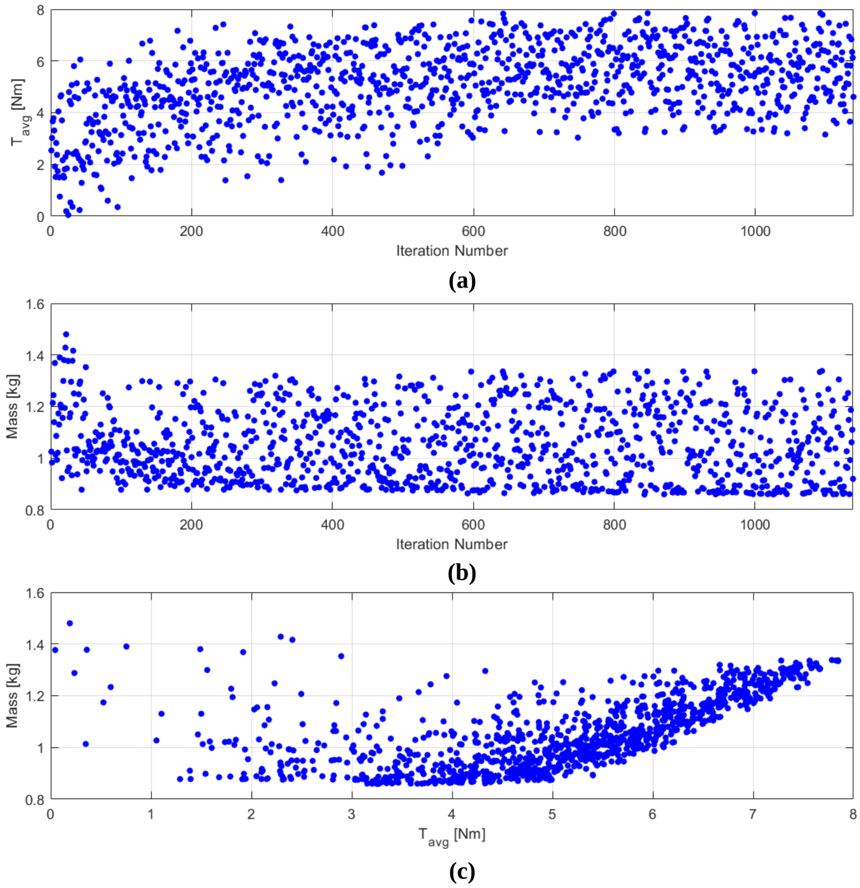



**Figure 4.** Performance analyses of the Multi-Objective Genetic Algorithm **a)** Motor torque, **b)** Rotor mass, **c)** Motor torque/Rotor mass.

The analysis results about variations in the motor power according to optimized parameters are illustrated in Figure 5. Rotor inner diameter, stack length, magnet insert, magnet thickness, and magnet angle were optimized in this study. The maximum and minimum values of the parameters to be optimized are determined as shown in Table 2 before starting the optimization step. Additionally, optimized motor parameters are given in Table 2. The rotor inner radius is optimized between 12 and 18 mm as shown in Figure 5a. High motor output power was obtained between 15 and 16 mm and the optimized rotor inner radius was chosen as 15.799 mm. It is seen that the motor output power increases as the stack length increases when the region where the individuals is concentrated are analyzed as given in Figure 5b. However, the mass of the motor increases when the stack length of the motor increases. Therefore, the motor stack length is limited between 40 and 60 mm before optimization steps. The output power decreases as magnet inset depth increases as given in Figure 5c and optimized magnet inset depth is 0.539 mm. Individuals concentrate in the region where the power increased as given in Figure 5d and optimized magnet thick are 6.917 mm. It can be seen that the output power of the motor increases when the magnet angle increases when the region where the individuals is concentrated are analyzed as given in Figure 5e. A combination of motor torque, rotor mass and motor output power are presented in 3D is given in Figure 5f. Additionally, the stator and rotor structures of the optimized PMSM are given in Figure 6.

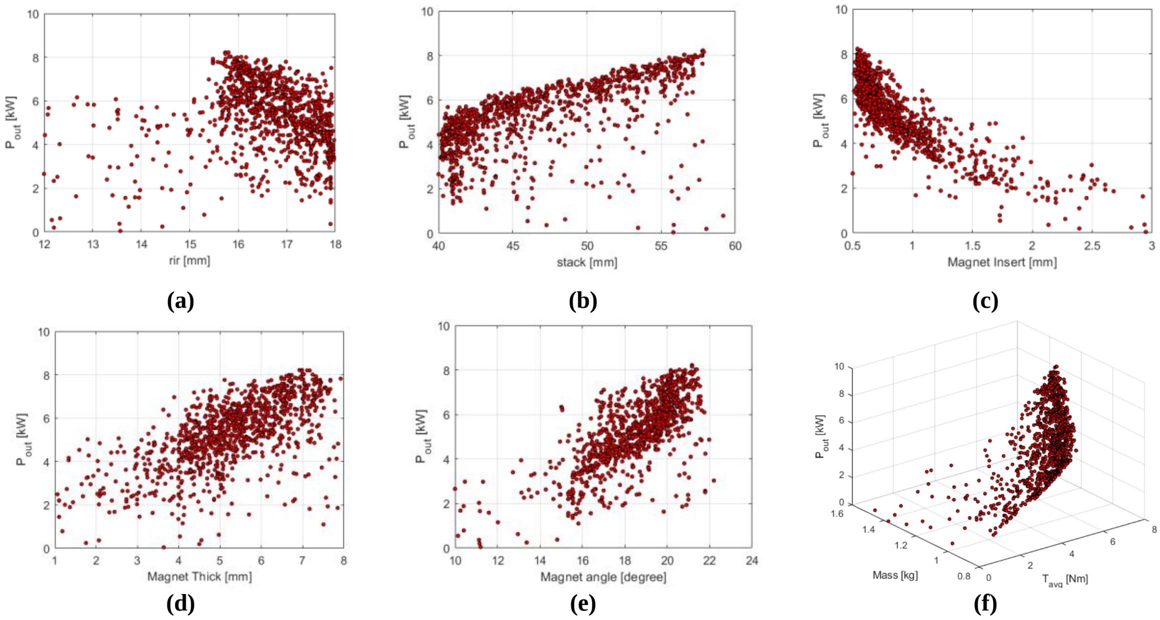



**Figure 5. a-e)** Change of optimization parameters according to output power, **f)** combination of motor torque, rotor mass and motor output power.

**Table 2.** Parameters of the optimized motor.

| Parameter | Min. value | Max. value | Optimized Value |
|---|---|---|---|
| rotor inner radius | 12 mm | 18 mm | **15.799 mm** |
| stack | 40 mm | 60 mm | **57.816 mm** |
| magnet inset depth | 0.5 mm | 3 mm | **0.539 mm** |
| magnet thickness | 1 mm | 8 mm | **6.917 mm** |
| magnet angle | 10° | 22.5° | **21.168°** |

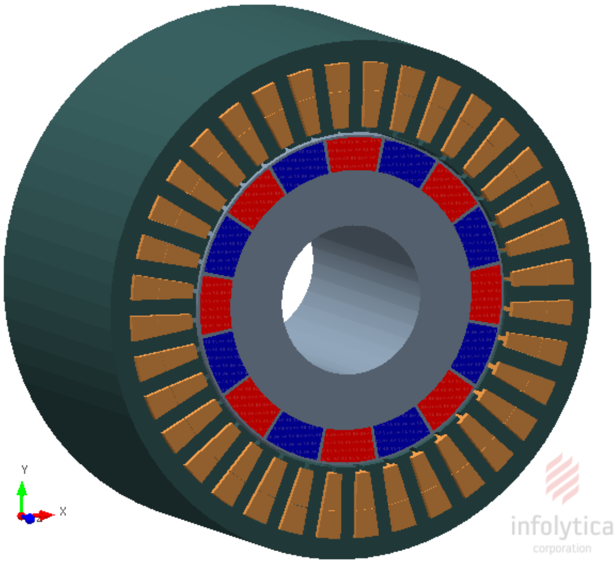



**Figure 6.** Stator and rotor structures of the optimized PMSM.

The mesh and solid view and flux density distribution of the optimized motor are shown in Figure 7. PMSM was analyzed using the Finite Element Method (FEM) -Newton Raphson iteration in the MAGNET program during the optimization steps. The maximum flux density of the motor in stator tooth and stator yoke is nearly 2.579 T.

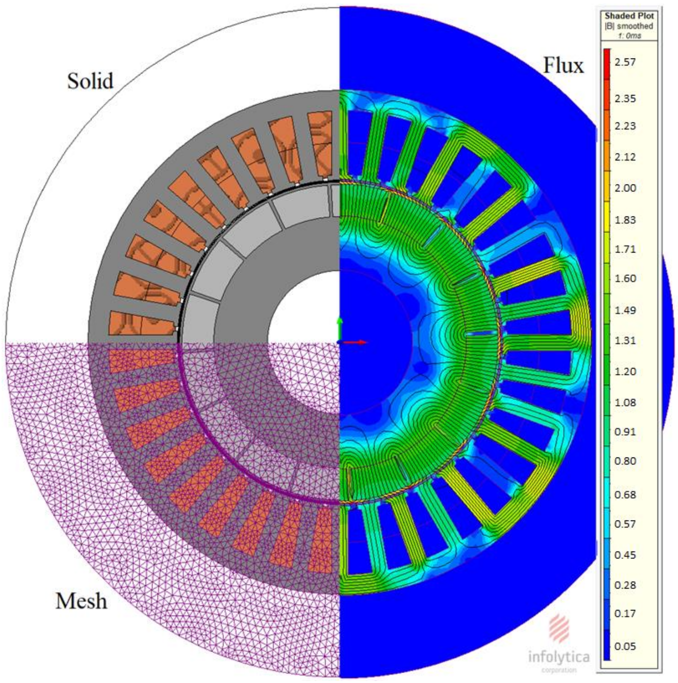
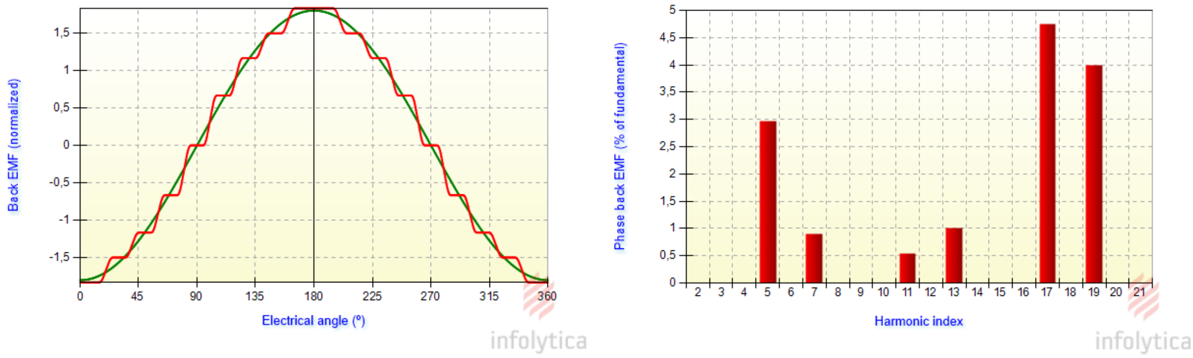



**Figure 7.** Mesh and solid view and flux density distribution of the optimized motor.

The back-EMF curve of the motor according to motor electric angle are shown in Figure 8a. A stator with a harmonic content in Figure 8b was obtained by selecting the stator 24 slots and 16-pole. It can be said that a suitable winding layout was chosen when analyzing the harmonic content.




**(a)** **(b)**

**Figure 8.** **a)** back-EMF (normalized) of motor, **b)** Harmonic content for winding layout.

The curves of torque, output power, efficiency and power factor are analyzed in Figure 9 by using MotorSolve/Infolytica program. The rated speed of the motor is 10000 rpm and the motor frequency is 1333.33 Hz. The motor is operated in the constant torque region by using Pulse Width Modulation (PWM) bridge switched 10 kHz frequency. When the results are examined, there are small differences between MotorSolve and MAGNET. This is due to the fact that the analysis was carried out with an ideal source in MAGNET and PWM in MotorSolve. The motor torque is kept up about 8.80 Nm from standstill to steady-state operation. The output power of the motor is 9.24 kW at 10000 rpm. The motor efficiency is obtained as 96.8% without the friction and ventilation losses at the rated speed. Additionally, the motor power factor is 0.848 at 10000 rpm and the rated current of the motor is 15 A.

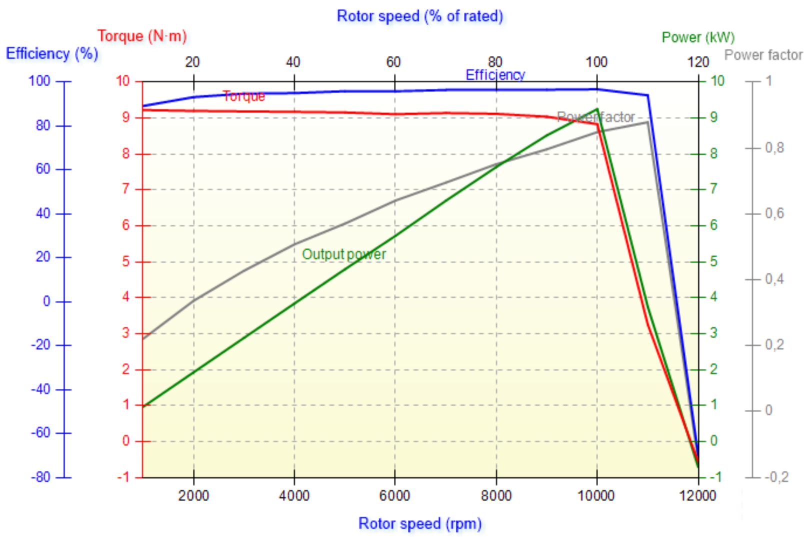



**Figure 9.** Torque, output power, efficiency and power factor of the optimized motor.

The efficiency map of the designed motor is given in Fig. 10. The efficiency decreases as the motor speed decreases at the same load torque. The efficiency of the motor is above 90% at load torque above 1.5 Nm and at rated speed. The optimized motor has an efficiency of approximately 97-98% at load torque above 5.8 Nm and at the motor rated speed.

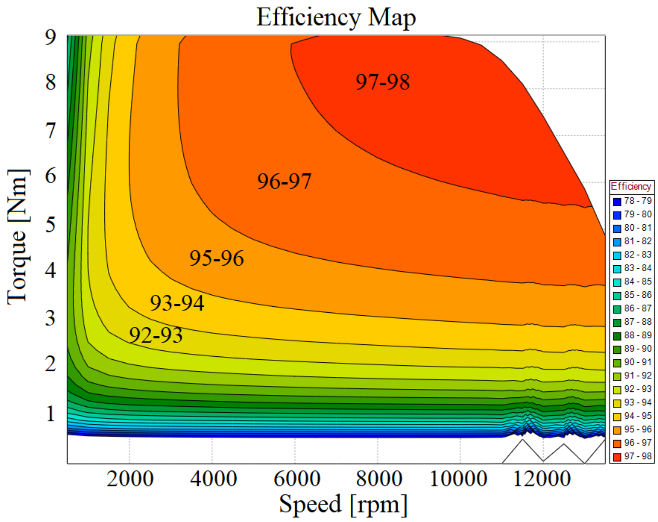



**Figure 10.** Efficiency map of the optimized PMSM.

## 4. Conclusion

The high output power and the low motor mass are desired from the motors that will be used in robotic, military and some industrial applications. Reactive power requirements of the PMSMs are as low as possible since these motors have magnets in their rotors. Therefore, it is possible to obtain much higher power density with PMSMs compared to other AC motors. Different performances can be obtained by depending on the geometry and position of the magnets used in this motor type. A PMSM having high power density is designed in this study. After the motor winding layout and stator geometry are analyzed by the MotorSolve Software, the PMSM is optimized by FEM developing an intermediate program that enables MATLAB and MAGNET Software to work together. The GA and FEM are run by MATLAB and MAGNET Software, respectively. A loop is created by giving the geometric parameters determined by MATLAB into the MAGNET Software and obtaining the motor torque and rotor weight by motion analysis and sending them to the MATLAB Software again. The number of the stator slot and pole of the PMSM are determined as 24 and 16, respectively. By keeping the stator geometry of this motor constant, an optimization study is performed on the rotor geometry. The optimization is realized by the aim of high torque and low rotor weight to obtain the desired motor by using the Multi-Objective GA method. By optimizing the rotor inner diameter, package length, magnet depth, magnet thickness, and magnet angle, the best rotor geometry is obtained as a result of a total of 1100 generations. It is observed from the optimization analysis results that the torque of the motor increases and the weight of the rotor decreases. However, it is not possible to decrease the rotor weight as the motor torque increases. Since the majority of the rotor consists of iron cores and magnets, reducing the weight is quite difficult. While the rotor weight varies between 0.9-1.4 kg, the motor torque is obtained in the range of 1-8 Nm in different generations. As a result of the optimization, it is decided that 1092th generation is the most proper motor. Thus, approximately 8 kW power could be obtained at a speed of 10.000 rpm for approximately 1.3 kg rotor weight. The package length of the optimized PMSM is obtained as 57.8 mm which is a very small value. The efficiency of the motor is also obtained as around 97% by neglecting the friction and ventilation losses. It has remained above 90% at all speed values. Therefore, it can be seen that the sizes of this designed PMSM are convenient for the robotic and military purposes.

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