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Design and Analysis of a Synchronous Generator Using Finite Element Method Based ANSYS-Maxwell

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Abstract

The most basic electrical machine that converts mechanical energy into electrical energy is synchronous machines. Synchronous machines can be operated at high speeds and low speeds for different power plants. In terms of system planning, it is important to examine the operating characteristics of the machine at idle and variable load conditions in these cycles. It is very important that generators, which are the basic components of turbines in power plants, have high efficiency when they are designed. While synchronous generators are being designed, many parameters that are compatible with each other must be arranged in an appropriate way. The efficiency of generators can vary greatly by changing very important parameters in the design. In this study, the analysis, design and analysis of the characteristic parameters of a synchronous generator are carried out with the ANSYS-Maxwell-Rmxprt integrated design and simulation program based on Finite Element Method (FEM). In this paper, parameters such as efficiency, induced voltage, phase currents and voltages and output torque of a three-phase synchronous machine were obtained depending on the electrical angle change.

Keywords: Synchronous generator, efficiency, FEM.

1. Introduction

Synchronous generators are electrical machines that are produced at different power levels from a few kVA to hundreds of MVA and are generally used for high-capacity power generation. Although their high costs seem like a disadvantage because of their large structures and capacities, their efficient work is one of their advantageous aspects. Synchronous generators, which convert the mechanical energy taken from the shaft to 1-phase or 3-phase alternating voltage, can be operated with free, special or self-excitation methods. If the synchronous generator, which consists of two basic parts, armature and inductor, is to produce low power, the armature is located in the rotating part, while the inductors of the generators that will produce high power are designed to be located in the rotating part. Since synchronous generators are generally preferred in high power generation facilities, the armature section is called the stator and the inductor section is called the rotor.

The pole structures of generators are of two different structures, cylindrical and protruding. Salient-pole synchronous generators are generally used in hydroelectric and wind power plants that require multi-pole and low speed. However, it can also be encountered in the pole structures of small power and high frequency generators [1]. The air gap distance between the stator and the rotor is one of the most important parameters for generators to produce voltages close to pure sinusoidal, and arrangements are made in the pole structures and stator windings so that the air gap flux is sinusoidal [2].

In salient pole generators, the pole legs are usually curved. Therefore, the distance between the pole legs and the stator grooves is not the same everywhere. Thus, the flux in the air gap occurs in a sinusoidal form [3]. Since the air gap between the rotor surface and the stator surface is equal everywhere in cylindrical pole generators, sinusoidal voltages can be obtained by making shortened pitch, that is, fractional windings, in the stator windings of this type of generators. These arrangements made in the stator section also ensure that a more uniform torque is produced during the operation of the generator at the engine position. In addition, measures such as placing squirrel cage system on the rotor parts and damper windings on the pole legs, ie short-circuit bars, are also frequently encountered in the literature [4]. In synchronous generators, making the stator grooves off-axis affects the total harmonic distortion (THD) value of the obtained voltage [5]. In accordance with the international harmonic standards (IEEE-519), the voltages produced by generators below 1 kV should not exceed 5% as individual harmonic distortion and 8% for the distortion limits in the voltage waveform as THD [6]. In some cases, passive filter circuits can be designed for generator voltages within acceptable limits according to the limits of the standards. In general, the situation encountered is that there are some mechanical shapings in the pole legs, but rarely in special applications, the stator grooves are made at a certain angle from the axis. Like the asymmetrical stator winding distribution, the designs of the distributed windings also affect the generated voltage waveform [7].

Synchronous generators are widely used in systems that generate electrical energy from wind energy. Many researches are carried out around the world in the field of synchronous generator design. Different types of rotors are used in the design of the Radial Flux Permanent Magnet Synchronous Generator. The performances of these rotor types used are also different from each other. The frequently used rotor types were compared with each other using the finite element method, and the advantages and disadvantages of the induced phase voltage-phase angle relationship, the cogging moment, the flux in the air gap, and the electrical angle change efficiency relationship were revealed [8,9]. Different rotor types in high speed, high efficiency, permanent magnet synchronous generator and motor system design study; They have been evaluated in terms of their output power and in terms of creating a zig emf. Again, the output powers generated by the use of different magnetic materials used in the rotor in the engine and generator design were compared. As a result, it has been mentioned that criteria such as low cogging torque, high thermal endurance, low rotor losses, high output power per generator weight, relatively high frequency and voltage, low harmonics are required for high speed and high efficiency permanent magnet synchronous generator design [10].

Cogging moment is a very important factor in radial and axial flux permanent magnet machine design. The production difficulty and high cost of the stator of axial flux permanent magnet machines require different techniques than those used in radial flux synchronous machines to reduce the cogging moment. Cogging torque minimization techniques for axial flux synchronous machines are emphasized and alternative techniques are suggested. After the analyzes with the 3D finite element method, the results were compared with the reference engine [11].

For system planning, it is important to examine the operating characteristics of the machine in idle and variable load situations. Analytical and finite element methods were used to examine the behavior of the synchronous machine by extracting these characteristics, and parameters such as the efficiency, induced voltage, phase currents and voltages, and output torque of a three-phase synchronous machine were obtained depending on the electrical angle change.

Unlike other studies, the design of a 3000W radial flux generator is aimed in this study. The dimensions of the generator were determined in the Rmxprt environment for design and analysis. Numerical analysis of this designed generator 2D-model was done with FEM. The obtained numerical data is a preliminary design for the determination of the electromagnetic parameters of the model and the applicability of the designed model.

2. Material and Method

2.1. Mathematical model

Permanent magnet synchronous generator (PMSG) is designed to operate at a nominal 250 rpm and 50 Hz frequency. The basic mathematical Equations of PMSG are presented below [5].

$$S = 11K_{w1} * \bar{B} * Ac * \left(\frac{D}{1000}\right)^2 * \frac{L}{1000}n \tag{1}$$

Here S is apparent power (VA), K_{w1} winding factor, $\bar{B}$ magnetic loading (T), Ac electrical loading (A/m), D stator inner diameter (m), L stator depth (m), n speed (rpm). It is important to choose the slot/pole combination with a winding factor higher than 0.866. For permanent magnet machines, magnetic loading is generally 0.45-0.8T, and electrical loading Ac can be taken in the range of 8000-30000 A/m [13]. Torque to volume ratio (TRV) in permanent magnet generators can be taken in the range of 14-42 (kN/m^3) [6].

$$TRV = \frac{T_{out}}{\frac{\pi}{4}DL} \tag{2}$$

Where Tout is given as output torque.

$$\frac{B_g}{B_r} = \frac{1}{1+\mu_r\frac{g}{Lpm}} \tag{3}$$

The Lpm magnet thickness can be calculated by Equation (3). Where B_g is the air gap magnetic flux density (T), B_r is the magnet flux density, g is the air gap length (m). Moreover; The leakage flux factor can be calculated from Equation (4) and Equation (5).

$$\gamma = \frac{4}{\pi}\left\{\frac{B_{so}}{2g'}\tan^{-1}\left(\frac{B_{so}}{2g'}\right) - \ln\sqrt{1+\left(\frac{B_{so}}{2g'}\right)^2}\right\} \tag{4}$$

$$K_c = \frac{\tau_t}{\tau_t - \gamma g'} \tag{5}$$

$$\tau_s = \frac{\pi D}{N_s} \tag{6}$$

Where N_s represents the number of slots and τ_s represents the slot pitch (m). The phase current of the generator can be calculated as given in Eq. (7).

$$I_{ph} = \frac{P_{out}}{mV} \tag{7}$$

Where m is the number of phases and V is the rated voltage.

J_s current density (A/m^2) and conductor cross-sectional area and conductor diameter can be calculated using Equation (8) and Equation (9).

$$A_{cu,i} = \frac{I_{ph}}{J_s} \tag{8}$$

$$d_w = \sqrt{\frac{4A_{cu,i}}{\pi}} \tag{9}$$

The stator outer D_0 diameter can be calculated by Equation (10). The pole step T_{pm} is calculated by Equation (11).

$$D_0 = D + 2 * (H_{s0} + H_{s1} + H_{s2} + T_{cs}) \tag{10}$$

$$T_{pm} = W_{pm} + W_b \tag{11}$$

Where H_{s0}, H_{s1} and H_{s2} are the slot heights and T_{cs} is the stator core yoke length. Moreover; W_{pm} is the magnet width and W_b is the spacing between the poles. The efficiency of the generator is calculated as given in Eq. (12).

$$Eff = \frac{P_{out}}{P_{out}+P_{cu}+P_{core}+P_{fw}} \tag{12}$$

Where, P_{cu} denotes copper loss, P_{core} denotes iron losses in the stator and rotor, and P_{fw} denotes wind and friction losses.

2.2. Design of permanent magnet synchronous generator (PMSG)

In this section, the design stages of the permanent magnet generator analyzed with ANSYS-Maxwell-Rmxprt are given. Analytical solutions are obtained by entering the basic sizing parameters into the RMxprt module of the ANSYS MAXWELL program. As seen in Fig. 1, the appropriate machine type, basic parameters (number of poles, reference speed, friction-wind loss, inner rotor and circuit shape) are entered, basic parameters of the stator and rotor are entered. However; Some basic parameters (operation mode, rated power, operating speed and temperature, rated voltage) need to be entered into the analysis. In Maxwell 2D, the dimension to be designed for the machine geometry is selected first. According to the calculated geometry data, the machine geometry is created or automatically assigned by RMxprt. As model parameters; boundary conditions, number of turns, resistance-inductance parameters (automatically assigned by RMxprt) are given.

The size of the designed generator is given in Fig. 1. The features of the stator of the designed model are presented in Table 1, and the features of the rotor are presented in Table 2.

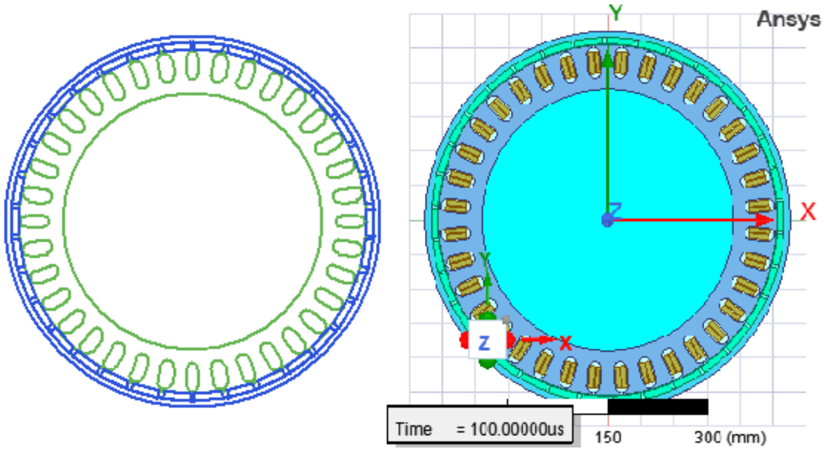

Fig. 1. ANSYS models of the designed generator

Table 1. The stator parameters of the generator model

Name	Value
"Outer Diameter"	510mm
"Inner Diameter"	380mm
Length	60mm
"Stacking Factor"	0.95
"Steel Type"	D21_50
"Number of Slots"	36
Number of conductors	24
"Slot Type"	1
Hs0	2.5mm
Hs2	25mm
Bs0	2.5mm
Bs1	20mm
Bs2	20mm

Table 2. The rotor parameters of the generator model

Name	Value
"Outer Diameter"	550mm
"Inner Diameter"	512mm
Length	60mm
"Steel Type"	D21_50
"Stacking Factor"	0.95
"Pole Type"	1
Embrace	0.9
"Magnet Type"	XG196/96
"Magnet Thickness"	10mm

In Table 3, the analysis step and output characteristics of the designed synchronous generator are listed. Losses can be seen separately through the table.

Table 3. Analysis step of the designed synchronous generator

Name	Value
"Operation Type"	Generator
"Load Type"	"Infinite Bus"
"Rated Output Power"	3000W
"Rated Voltage"	220V
"Rated Speed"	250rpm
"Operating Temperature"	75cel

3. Result and Discussion

In this part of the study, analytical and results and FEM results are presented. The graphs of the line voltage and the no-load phase voltages in the analytical calculations are given in Fig. 2. In Fig. 2, the change in phase and line voltages induced in the star connected armature according to the rotor position of the synchronous generator in the no-load condition is given. It has been determined that the total harmonic distortion in the phase and line voltages is very low in the no-load condition.

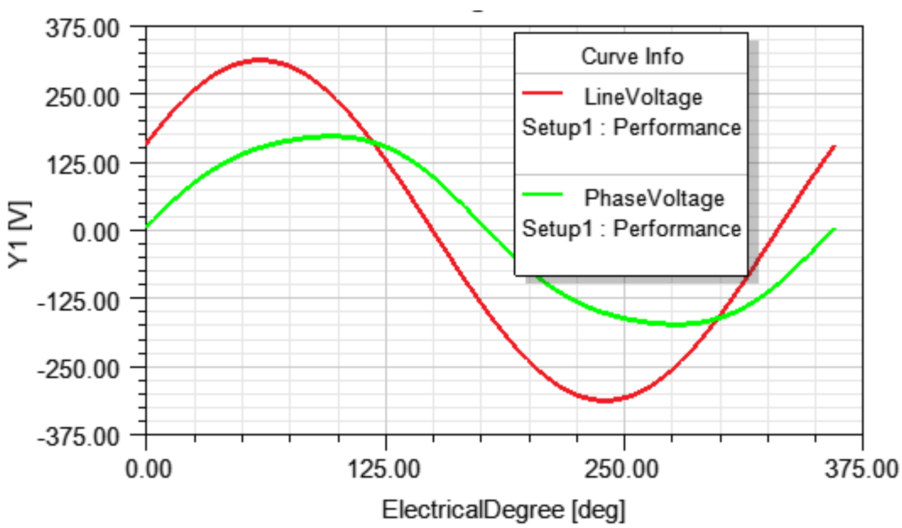

Fig. 2. No-load voltage values

In Fig. 3, the change of induced phase voltages of the synchronous generator in full load condition depending on time is given. It has been determined that the phase voltage total harmonic distortion in the full load condition is 17.84%.

In Fig. 4, the variation of the output torque of the synchronous generator with time is shown. It has been observed that the electrical output torque is at the average value of 326.4 Nm.

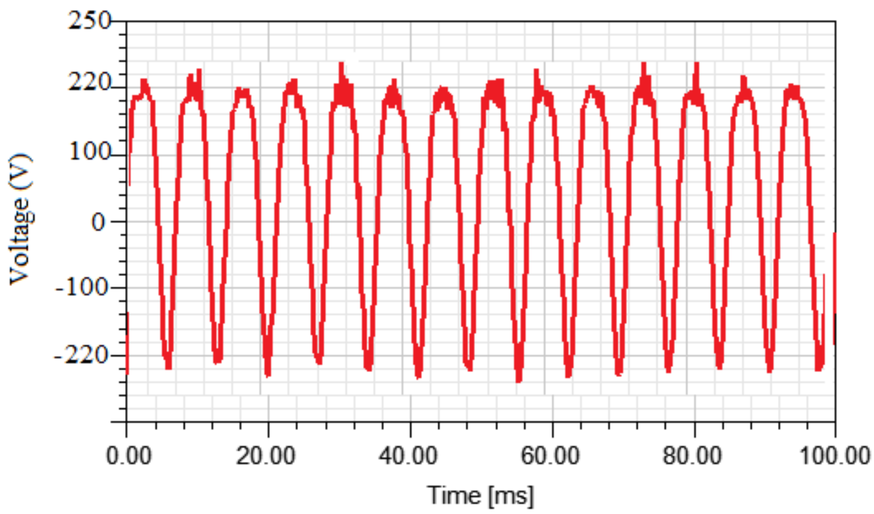

Fig. 3. Variation of induced phase voltages of synchronous generator in full load condition depending on time

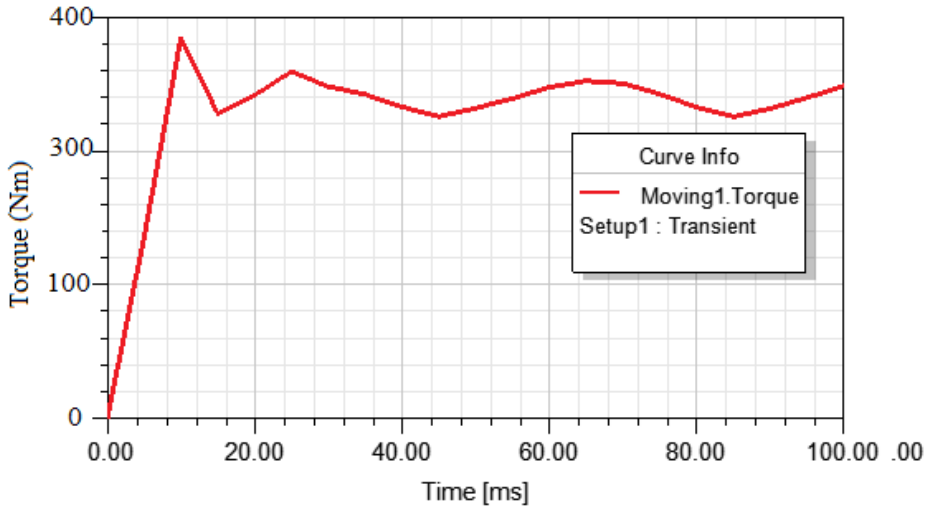

Fig. 4. Torque-time curve

In Fig. 5, the change of phase voltages depending on time is shown in the case of 0.8 back power factor of the synchronous generator analyzed according to FEM.

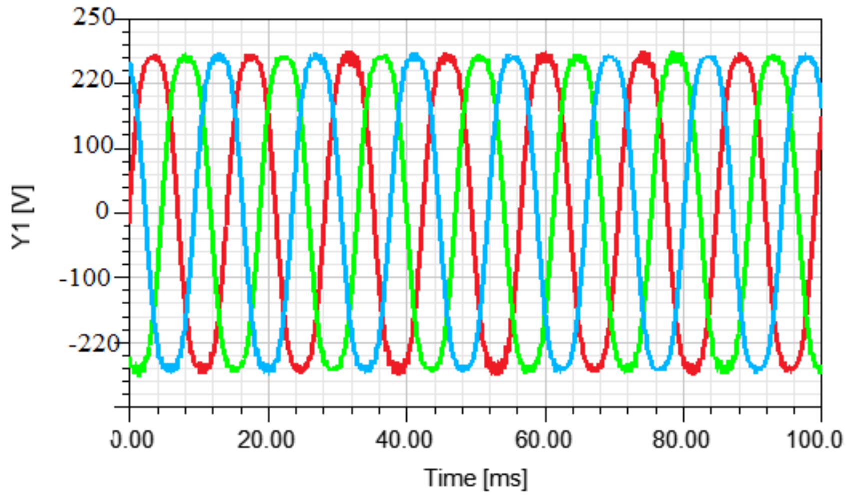

Fig. 5. Voltage-time curve

In Fig. 6, the change of phase currents depending on time is shown in the case of 0.8 reverse power factor of the synchronous generator.

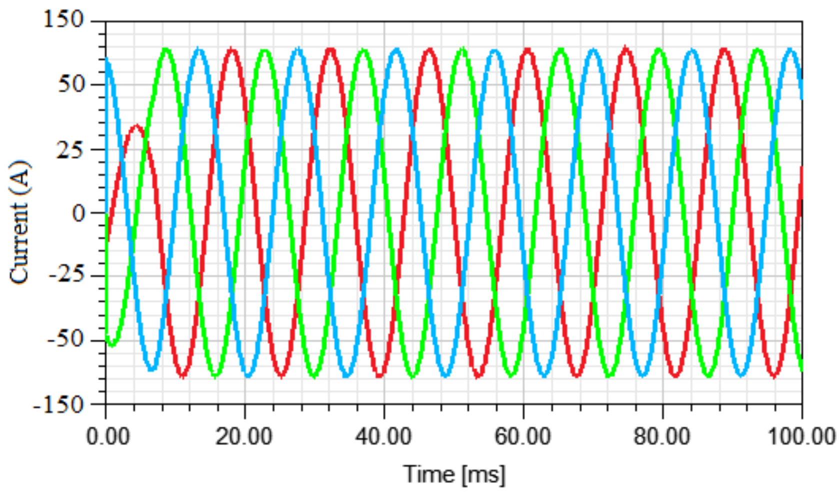

Fig. 6. Current-time graph

Fig. 7 shows the time dependent phase flux change of the synchronous generator at 0.8 back power factor.

The magnetic field intensity distribution of the designed generator model is given in Fig. 8. It is observed that the rotor saturates the magnetic material close to the windings.

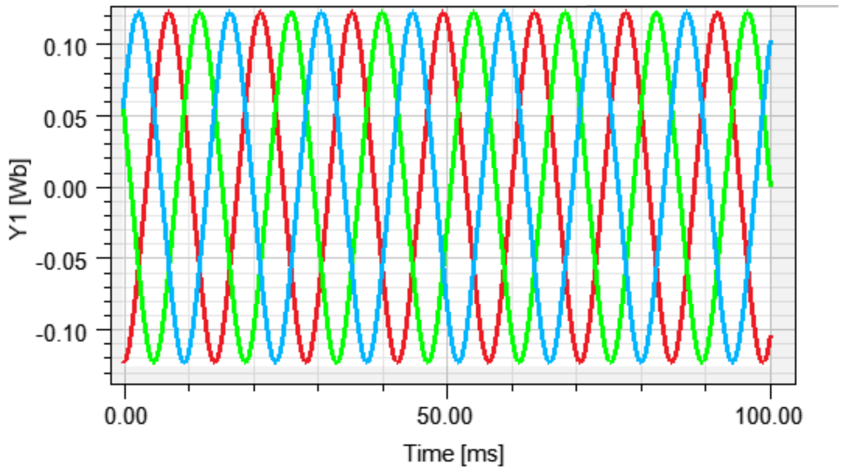

Fig. 7. Time-dependent graph of phase fluxes

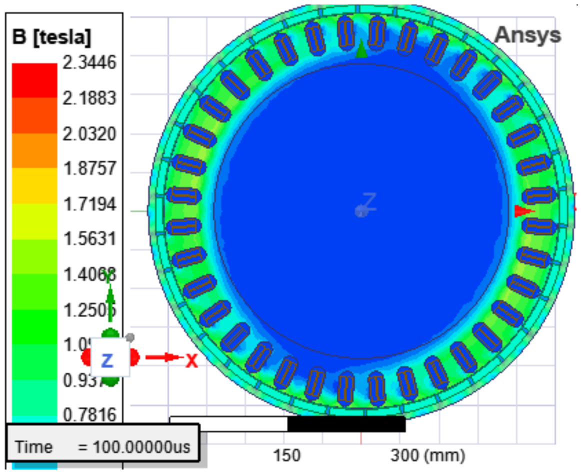

Fig. 8. Magnetic field intensity distribution of the designed generator model.

The magnetic flux line distribution of the designed generator model is given in Fig. 9. It is observed that the rotor saturates the magnetic material close to the windings.

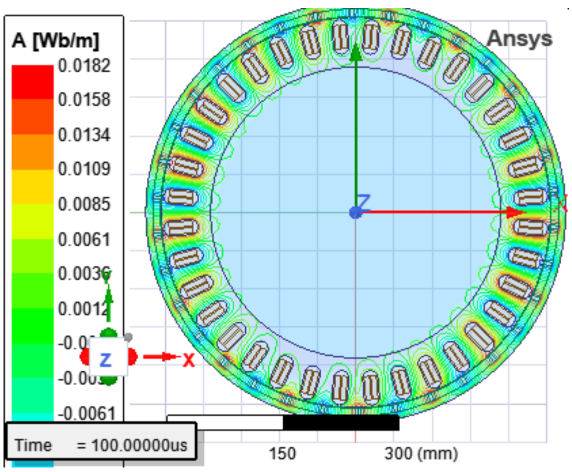

Fig. 9. Magnetic flux line distribution of the designed generator model.

The time dependent output torque variation of the synchronous generator is shown in Fig. 10. It is seen that the torque value varies in the average value of 326.4 Nm.

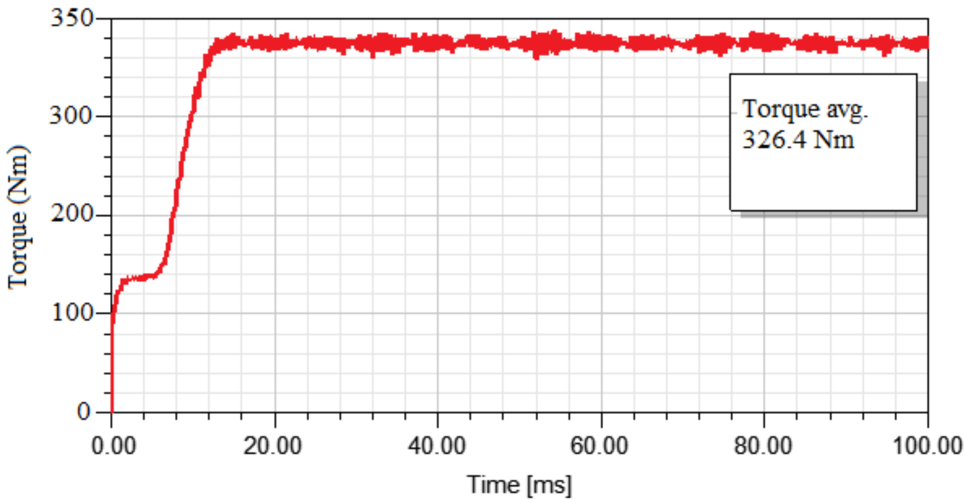

Fig. 10. Torque-time curve

4. Conclusion

In this paper, Permanent Magnet Synchronous Generator has been designed. Parametric analyzes were made in the RMxprt environment of the design. The efficiency of the designed synchronous generator, the induced voltage at the determined revolutions, the phase currents and phase voltages, the amount of torque are obtained depending on the electrical angle and time change. In addition, the magnetic flux distribution and magnetic field lines of the generator were determined by FEM, which is a numerical analysis method in ANSYS-Maxwell environment. The weak and strong points of the generator simulator, which was designed and analyzed in this integrated simulation environment, were determined. If a prototype generator model is to be developed based on this simulation model, it is necessary to pay attention to the flux density values at these points in order to prevent magnetic saturation in the core and yoke.

Acknowledgments

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