Performance Analysis of a Permanent Magnet Synchronous Generator with Parametric Solution Software

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***Abstract*—The popularity of permanent magnet synchronous generator (PMSG) has increased in recent years. Small and medium-sized wind generators can be found in the smart grid structure, and synchronous generators without gearbox are used at different wind speeds thanks to their connections with power electronic circuits in grid integration. In this study, simulation studies are carried out for a small power scale PMSG with finite element analysis (FEA) software with different wind speed and design parameters. Thus, the performance analyzes of the generator depending on the number of stator winding turns, core material and load values are presented with graphic and numerical data. It has been tried to draw attention to the importance of parametric solver in generator performance analysis and the usefulness of the results obtained for researchers.**

Keywords—PMSG, smart grid, parametric solution, FEA.

I. INTRODUCTION (*HEADING 1*)

Wind energy, which is considered one of the cleanest renewable energies, has been attracting more and more attention in recent years. In some developing countries, the use of wind energy is increasing rapidly with the supportive policies of the governments. In regions with good wind resources, many wind power plants with large-scale wind turbines have been built to supply electrical energy to the grid, and the installed power values are increasing day by day. However, in some remote but potentially windy areas where the grid is not available, small, low-speed stand-alone high-efficiency wind generators can be very attractive for electrical appliances and outdoor monitor equipment [1-2].

On the other hand, given the recent pressure to harness wind power for power generation on an industrial scale, the need to reduce CoE is driving more and more researchers to focus on optimizing existing powertrains. The different known wind generator drive concepts are direct drive (DD) aka low speed (LS) drives, medium speed (MS) drives and high speed (HS) drives, with the last two falling into the gear drivetrain category. Generally, the classification of wind generator drivetrains is made possible by the presence or absence of a gearbox. MS gear drives describe systems with one- or three-stage gearboxes, while HS drivelines are gear systems with three or more three-stage gearboxes. LS systems, on the other hand, are the absence of a gearbox system called direct drive systems. The pros and cons of each generator drivetrain are summarized as shown in Table I [3]:

TABLE I. GENERAL COMPARISON OF WIND POWER SYSTEMS

Variable	**High Speed**	**Medium Speed**	**Low Speed**
Speed interval	800-3000 rpm	100-800 rpm	<100 rpm
Number of poles (50 Hz)	2-6	8-64	>64
Mechanical losses	Highest	Middle	Lowest
Gearbox	Yes	Yes	No
Cost	Higher	Middle	Lower (only generator)
Power Level	Higher	Middle	Lower
Turbine system	Horizontal	Horizontal/Vertical	Vertical

The focus on high efficiency, renewable energy and applications in smart grid structures such as electric vehicles (EVs) or hybrid electric vehicles (HEVs) has drawn more attention to the field of electrical machinery design in terms of generator and motor design. This attention has brought with it a renewed effort in the study and classification of electrical machine topologies, and also popularized the use of power electronics interface circuit structures for integration in microgrid grid structures at the permanent magnet synchronous generator (PMSG) design point without gearbox [4]. Especially in PMSG designs without gearbox, AC electrical energy with different frequency depending on different wind speed is firstly converted to DC electrical energy and then converted to a certain grid frequency (50/60 Hz) value and converted back to AC electrical energy with the power electronics interface [5]. In this context, power electronics integration circuits have an important role in micro smart grid structure.

With analytical and finite element analysis (FEA), electrical and electromagnetic distributions can be obtained by parametric simulation studies according to the changes in the relevant design parameters. In a study conducted in the past literature, while the jogging torque was 522.7 mNm in the first design, it was reduced to 49.1 mNm in the generator optimized by parametric analysis, thus an improvement of approximately 90% was reported [6].

In addition, in recent years, core materials with higher specific performance and higher flux density and electric motor or generator designs have gained intensification. Thus, a more compact and low-loss high-performance electrical machines can be designed [7].

In this study, parametric simulation studies are carried out for a small power scale PMSG without gearbox design with FEA software. Thus, the performance analyzes of the generator, depending on the number of stator windings, core material type and load values, are handled comparatively. In these comparisons, the design variables and operating conditions of the generator were tested with certain steps and different variations. Performance analyzes are performed with the obtained numerical and graphical data.

II. SIMULATION MODEL

The outline followed in electromagnetic modeling with finite element analysis software is given in Figure 1. The generator's design variables and output variables are defined in the RMxprt module of the FEA software. Thus, it can be monitored whether the generator provides input-output parameters and optimum criteria.

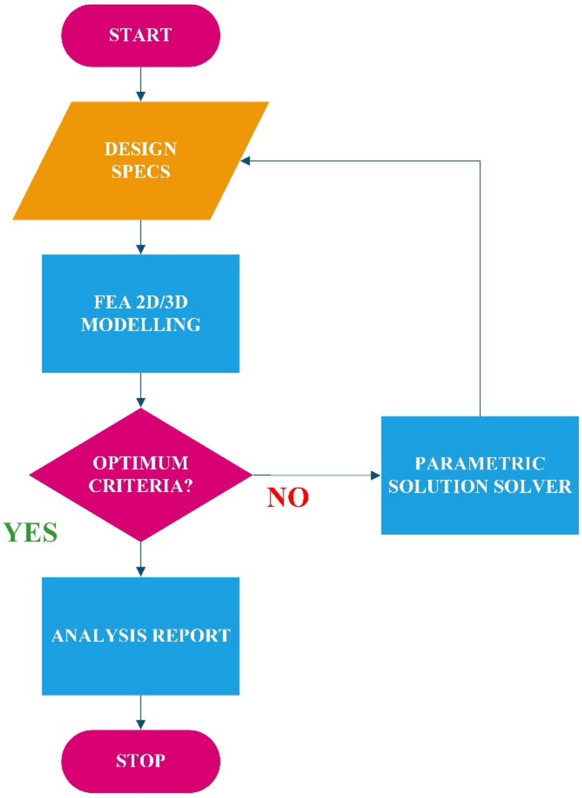


Fig. 1. The outline followed in electromagnetic modeling [8].

A. Factors affecting generator efficiency

Basically, one of the most important issues affecting the efficiency in electrical machines is core losses, keeping the temperature rise at a certain level and cooling requirements. In this context, the specific performance of the core material in the design of electrical machines greatly changes the generator and motor performance, both in mechanical dimensioning and electrical efficiency and losses.

Considering the basis of the stator phase electromotor force (EMF), Eq.1 is used for the basic equivalent circuit approach to obtain the generator terminal line-to-line voltage.

$$V_{ph} = \sqrt{3}\left[E-(R+jX)I\right] \qquad (1)$$

where E is the EMF, R is the winding resistance, I is the line current, and X is the synchronous reactance [9]. The inductances required to calculate the synchronous reactance are obtained from the classical formulas. However, simulation facility with FEA-based software can calculate such calculations more accurately and effectively.

Thus, the stator winding current cannot be calculated directly since the electrical output power and generator efficiency are not known in advance. However, the stator phase current according to the rated power value (P_e) and the phase-to-neutral terminal voltage (V_{ph}) values are obtained as given in Eq.2: [9].

$$I = \frac{P_e}{3V_{ph}PF} \qquad (2)$$

where, PF is the power factor and it changes according to the load type of the generator. On the other hand, the mechanical power Pm (W), of the wind turbine is given by Eq.3[10]:

$$P_m = \left(1/2\right)\rho C_p A v^3 \qquad (3)$$

Where ρ is the air density factor (kg/m^3), C_p is the wind power factor, A is the rotor blades sweep area (m^2), and v is the wind speed (m/s).

Generators can be analyzed as an electric motor and the efficiency is calculated as seen in Eq.4: [11].

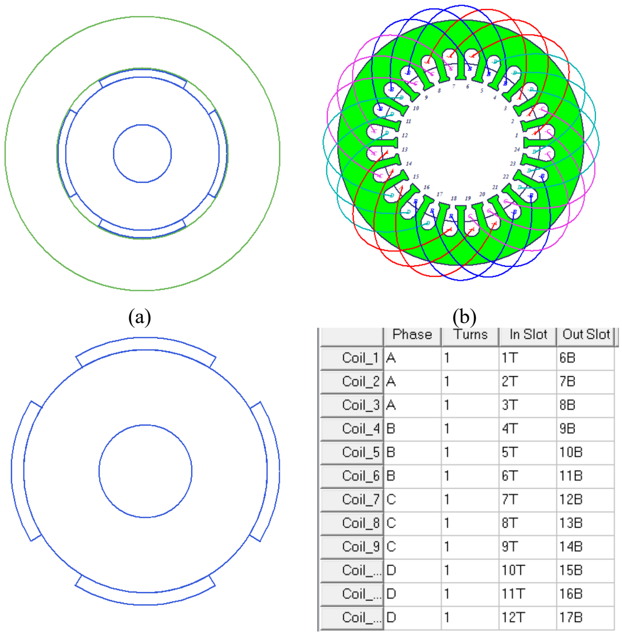
$$\eta = \frac{\omega_m T - P_{core}}{\omega_m T - P_{copper}} \times 100 \qquad (4)$$

where T is the average torque (Nm), P_{core} is the core losses (W), ω_M is the rotor speed (rad/s), and P_{copper} is the winding losses of the generator [11].

Thus, the wind speed values and indirectly the generator speed have a significant effect on the power produced and system efficiency.

B. PMSG design specs

The simulated PMSG is designed as 4-pole and 4-phase. The stator and rotor parts of the generator modeled in Ansys-RMxprt software [12] are shown in Figure 2.


(a) (b)

(c) (d)

	Phase	Turns	In Slot	Out Slot
Coil_1	A	1	1T	6B
Coil_2	A	1	2T	7B
Coil_3	A	1	3T	8B
Coil_4	B	1	4T	9B
Coil_5	B	1	5T	10B
Coil_6	B	1	6T	11B
Coil_7	C	1	7T	12B
Coil_8	C	1	8T	13B
Coil_9	C	1	9T	14B
Coil_...	D	1	10T	15B
Coil_...	D	1	11T	16B
Coil_...	D	1	12T	17B

Fig. 2. The stator and rotor parts of PMSG, a) generator, b) stator winding, c) rotor part with permanent magnet ploes, d) winding editor of FEA software.

The design spec information of this generator is given in Table 1. Thus, it is dimensioned with the FEA software and the modeling process can be started for parametric analysis.

TABLE II. TECHNICAL SPEC INFORMATION OF PMSG

Design Parameters	**Value**
Number of phases	4
Operating frequency	50 Hz
Speed	1500 rpm
Power Level	0.55 kW
Number of poles	4
Voltage Level	127 V
Number of stator slots	24
Winding Pitch	5 (1-6)
Number of coil windings	10 turns
Stator outer diameter	120 mm
Stator inner diameter	75 mm
Stator length	65 mm
Rotor outer diameter	74 mm
Rotor inner diameter	26 mm
Air-gap length	1 mm
Core stacking factor	0.95
Core lamination thickness	0.35 mm
Core material	M19_24G/M330-35A
Type of Magnet	XG196/96

C. Parametric solution study

In order to carry out parametric simulation studies, the generator speed was changed with 250 rpm linear steps in the range of 500 - 2000 rpm, and the generator temperature was changed with 5 cel linear steps in the range of 50-80 cels. In addition, the number of conductors in the stator grooves has been changed to 1 turn in the range of 5-10 turns. Thus, a short parametric analysis can be performed. For further parametric simulation, the definition and value ranges of the design variables can be changed.

The parametric 3D graph obtained for the output power change depending on the number of turns (Wn) and operating temperature (Ta) values of the stator windings of the generator is shown in Figure 3. Thus, the power losses and temperature rise values in the windings can be determined beforehand.

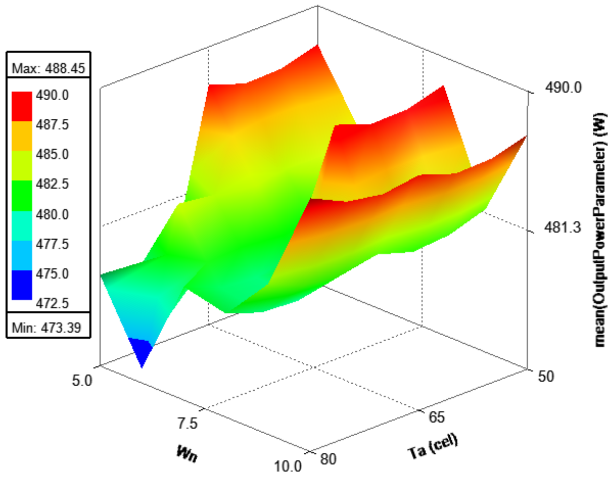


Fig. 3. The parametric 3D graph obtained for the output power change.

The relationship between the input and output power values of the generator is mainly explained by the losses. In addition, since the power values will change depending on the number of revolutions of the generator, the 3D parametric graph given in Figure 4 is given for easier understanding of this relationship.

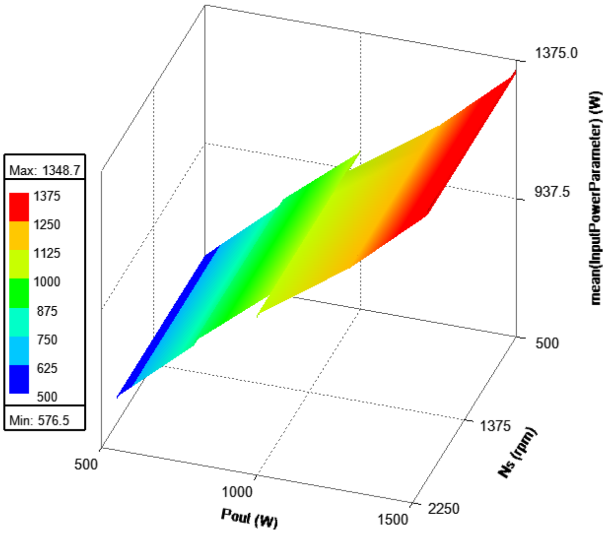


Fig. 4. The relationship between the input and output power values of PMSG.

D. Electromagnetic FEA simulation study

In order to link the 2D electromagnetic modeling, the 4-phase PMSG designed in the RMxprt software was dimensioned in the Ansys-Maxwell software as shown in Figure 5, and advanced performance analyzes were performed.

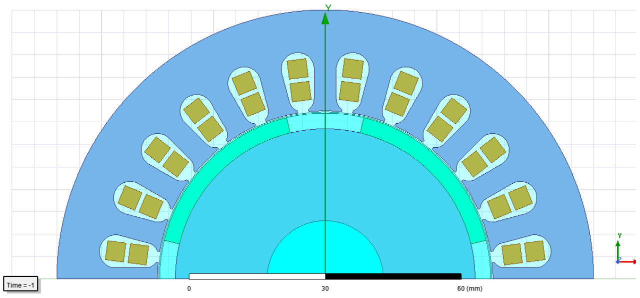


Fig. 5. Two dimensional modelling of the generator.

Analysis reports of the electromagnetic model run with 200 ms duration and 0.2 ms time steps in Ansys-Maxwell software are provided. Thus, the generator torque curve is shown in Figure 6. Torque ripple values and transient torque fluctuation can also be monitored in this curve.

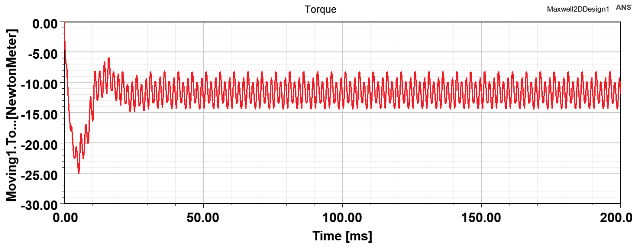


Fig. 6. Generator torque curve.

Generator stator phase voltages and phase currents are given in Figure 7 and Figure 8, respectively. Thus, the amount of decrease due to the voltage drop in the stator phase impedance under full load, that is, the regulation, can be determined.

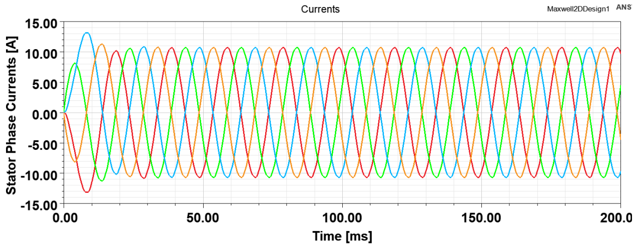


Fig. 7. Stator phase voltages.

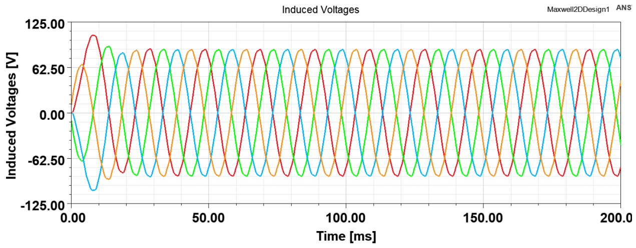


Fig. 8. Stator phase currents.

According to the flux linkage graph given in Figure 9 for the magnetic flux distributions of the stator windings and the inductance effects of the 4-phase design, the steady state flux distribution is balanced in the stator core.

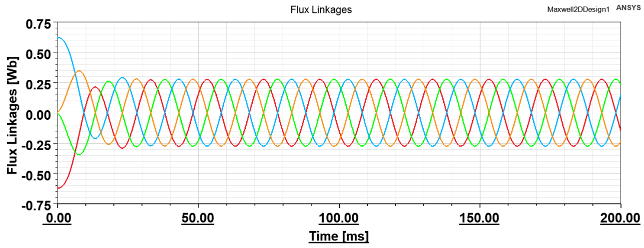


Fig. 9. Flux linkages of the stator windings.

In this study, core loss graph is given in order to make an easier performance comparison according to core material type. Thus, the core losses for PMSG designed with M19_24G core material [13] are shown in Figure 10. According to this loss graph, a power loss of approximately 5.70 W/kg occurs in the stator and rotor core parts. Considering that the stator and rotor weigh approximately 4.5 kg, a total core loss of approximately 25 W occurs.

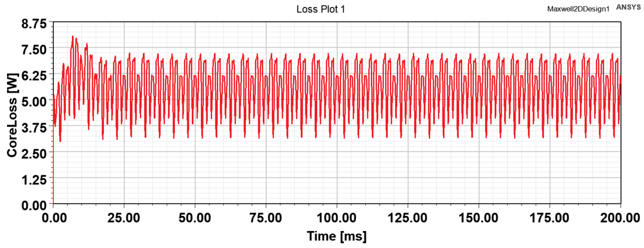


Fig. 10. The core losses with M19_24G.

The flux distribution of PMSG modeled as 2D is given in Figure 11 for a maximum of 1.7 T. The saturation zones in the tooth parts of the stator slots are clearly visible. These saturation regions can cause excessive temperature rise and cause harmonics in induced voltages.

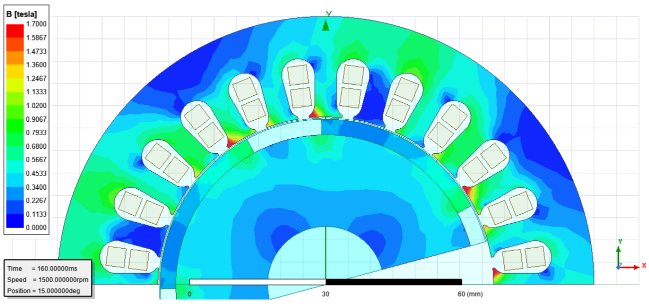


Fig. 11. The flux distribution of PMSG with M19_24G.

E. The effect of core material type on PMSG performance

If the PMSG modeled in this study is designed with JFE-supercore (10JNEX900) such as 6.5% SiFe and approximately 2 T flux density, 0.10 mm lamination thickness [14], both energy efficiency and more compact performance can be achieved. Thus, approximately 3 times thinner lamination compared to M19 core material significantly reduces eddy current loss. On the other hand, hysteresis loss is significantly reduced with 6.5% silicon additive. Thus, core losses are smaller and a more efficient generator can be produced in terms of energy efficiency.

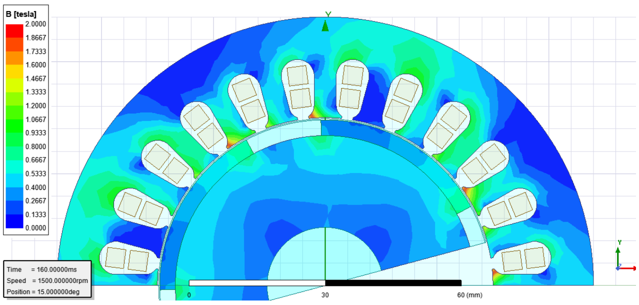


Fig. 12. The flux distribution of PMSG with JFE-supercore.

Thus, since the saturation flux density value of JFE-supercore material is about 2 T according to the flux distribution given in Figure 12, the saturation zones in the slot teeth also decreased. Compared to the M19 core material, the core loss is about 2.03 W/kg and 2.8 times less core loss occurs as can be seen in Figure 13.

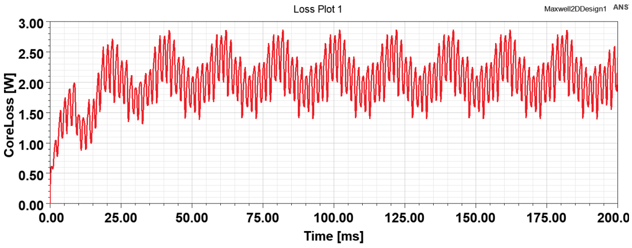


Fig. 13. The core losses with JFE-supercore.

III. CONCLUSION

In this study, performance analysis of the generator is carried out for a 4-pole and 4-phase small scale PMSG using parametric simulation and then electromagnetic modeling using FEA software. Three different variables such as temperature, generator speed and number of stator windings are defined for parametric solver settings and the relationship between the obtained 3D graphics and input and output powers is explained. In electromagnetic modeling studies with FEA software, the current, voltage, power loss and torque values of the generator and flux distributions are examined and the effect of especially the core material type on the power losses is shown. Thus, the same PMSG simulation was simulated under the same load conditions with the JFE-supercore material with 6.5% silicon additive, which has been popularly used in the designs of electrical machines in recent years. In terms of core losses, it has been reported that approximately 2.8 times less core loss occurs compared to the 3% silicon added M19 core material. As future work, it may be possible to reduce PMSG dimensions with JFE super core material and to design with a more compact structure.

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