Analysis of the Effect of Core Thickness and Rotational Speed on the 24 Slot 16 Pole Permanent Magnet Synchronous Generator on PMSG Characteristics

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Abstract **– Electrical energy has become a basic need that cannot be eliminated in everyday life for Indonesian people, where the source of electrical energy is currently still fossil fuels. One way to overcome excessive exploitation of fossil fuels is to utilize renewable energy sources, namely wind energy. Wind has a great potential for generating electrical energy with the conversion that occurs in the Permanent Magnet Synchronous Generator (PMSG). PMSG is one of the components in a wind power plant (PLTB). Current wind conditions in Indonesia cause low efficiency in PMSG, where many things affect this, one of which is power losses in the generator, copper losses caused by the copper winding on the stator getting hot, and iron losses because the generator has bearings. get hot. Many factors can cause efficiency to increase, such as the core speed and core thickness used in PMSG. In this paper, an image of the 24 slot, 16 pole PMSG model will be created with variations in rotational speed and core thickness using the MagNet Infolytica software by simulating the software using the Finite Element Method (FEM). Variations of speed used are 250 rpm, 500 rpm, and 750 rpm, with variations in core thickness of 40 mm, 60 mm, and 80 mm. The simulation results that occur in variations in current, voltage, torque, input power, and input power all increase according to Faraday's law. The highest efficiency value was obtained at 82.20% at a core thickness of 40 mm and a rotating speed of 500 rpm, with a current value of 9,926 Amperes, a voltage of 99,263 Volts, a torque of -22,904 Nm, an input power of 1198.64 Watts, and an output power of 985.28 Watts.**

Keywords: Permanent Magnet Synchronous Generator (PMSG) 24 slots 16 poles, Core Thickness, Spin Speed, Finite Element Method (FEM), Efficiency

I. INTRODUCTION

Electrical energy has become a basic need that cannot be eliminated from everyday life for Indonesians. The need for electrical energy directly increases every year along with the growth of the existing population [1]. The source of electrical energy comes from two sources: renewable energy and non-renewable energy sources. Currently, the average source of electrical energy uses non-renewable energy sources. Non-renewable energy is energy that takes a long time to form, has very limited availability, and is also damaging to the environment. If energy is non-renewable and is exploited continuously, it will run out and take a long time to be utilized again. [2].

There are various examples of non-renewable energy, one of which is coal. Coal is in the second rank, which dominates its use in Indonesia. This is because most of the existing power generation sectors use coal as fuel in power plants to produce electricity [1]. While the use of coal fuel has a direct impact on the environment, the resulting carbon dioxide emissions damage the surrounding environment. Power plants that use coal as fuel can produce radioactive substances that can damage human health 100 times more than nuclear power plants [3].

While there are still energy sources that can be used to generate electricity, for example, renewable energy sources, Renewable energy sources are energy sources that come from nature and can be used freely. These renewable energy sources can also be renewed indefinitely. To help meet Indonesia's increasing demand for electrical energy, renewable energy sources can be utilized to the fullest. Indonesia has not yet made full use of renewable energy sources. Examples of renewable energy sources are solar, water, geothermal, wind, and so on. [3].

Wind energy is an alternative energy source that has good prospects because it is always available in nature and is a clean and renewable energy source [4]. Wind energy has great potential in Indonesia, but it has not been fully utilized as a source of electrical energy. There are several things that affect the existence of wind energy, such as weather, ambient temperature, altitude above sea level, and so on. Wind energy is also fluctuating because conditions are always changing. By utilizing wind energy, it will solve the problem of using non-renewable energy such as coal, oil, and so on [5][6].

To convert wind energy into electrical energy, a generator called Pembangkit Listrik Tenaga Bayu (PLTB) is needed. In the conversion process using a tool called a generator. The types of generators that can be used are: Permanent Magnet Synchronous Generator 24 Slot 16 Pole (PMSG) capable of producing magnets quickly. The problem that occurs in Indonesia itself is that the potential for wind energy is low, causing the efficiency that occurs in PMSG to also be low. In PMSG, wind speed affects the output values of torque, current, and voltage, where increasing or adding rotational speed causes the current and voltage to increase quickly. The resulting magnet will be bigger according to Faraday's law. Not only the rotational speed, which can be used as a benchmark for increasing the value of torque, current, and voltage, but there are still many variables that can be changed to increase the efficiency value of PMSG, one of which is the thickness of the iron core in PMSG. The thickness of the iron core in PMSG can also be a factor in increasing the values of torque, current, and voltage, which is also related to Faraday's law: the thicker the iron core, the better the output value that occurs in PMSG [2], [5].

Permanent magnet Synchronous Generator 24 Slot 16 Pole is a generator that has a permanent magnet that has a slot or coil on the generator as much as 24 slot space for coils, and also 16 pole here is the number of magnets in pairs with 8 magnets pointing south and 8 magnets also pointing south. Generators are also tools that help convert mechanical energy into electrical energy using electromagnetic induction generated from the permanent magnets in the generator [5]. At PMSG 24 slots, 16 poles own cogging less the low. Cogging less means we can generate electricity at low wind speeds. Cogging less on PMSG 24 slot 16 pole has a torsional deflection caused by the interaction of a permanent magnet with the ability of a material to transmit magnetic flux. Cogging less low can cause low sound and vibration [2], [5].

PMSG efficiency is obtained by comparing the output *(Pout)*, which will be compared with the input power *(Pin)* on generators. There are many things that can affect the efficiency of the generator, such as the material used in designing the generator, the load or power used, and the low speed, which causes the turbine to not move. In addition to the factors that increase efficiency, there are also those that can reduce the efficiency of the generator, such as power losses in the generator, which can reduce efficiency; copper losses caused by the copper windings on the (Pin) stator getting hot; and iron losses due to the generator's bearings getting hot. The way to get efficiency is to compare the power output with the power input, which is the input power (Pin), which is obtained from the results of torque data or the rotation of the rotor, which rotates according to a predetermined speed and angle. As for the output power (Pout), it is obtained from the current and voltage generated due to changes in mechanical energy that rotate in the generator between the stator and the rotor. The higher the efficiency, the better the quality produced by the generator [5].

Performance from the *Permanent Magnet Synchronous Generator* depends on the magnitude of the magnet generated from magnetic induction with the rotor, where the magnet located at the end of the rotor induces a voltage in the winding that is on the stator. Therefore, the thickness of the core and the rotational speed of the permanent magnet synchronous generator (24 slots, 16 poles) The more it is increased, the better the current and voltage will be, thus affecting the characteristic values, namely current, voltage, power input, one output, and efficiency, on a permanent magnet synchronous generator with 24 slots and 16 poles [7].

Research related to PMSG to increase efficiency has been done. In the discussion raised regarding the effect of the number of turns and rotational speed on efficiency in permanent magnet synchronous generators (18 slots, 16 poles) in 2022, research is being carried out regarding the addition of windings and rotational speed to increase the efficiency that occurs in PMSG using the Finite Element Method (FEM), where the speeds used are 500 rpm, 1000 rpm, and 1500 rpm with variations of 50, 75, and 100 turns, and the load used is 10 ohms for each variation used. The results of the research carried out with the highest efficiency were found in 75 coils with a speed of 1500 rpm; the efficiency value was 80.9% [5] [8]. Subsequent research was carried out by varying the thickness of the iron core to the output power of 1 kW; the thickness variations used were 37mm, 52 mm, and 80mm. The thickness of the iron core of the rotor and stator can affect the output value depending on the characteristics of the generator. The effect of the iron core on the output power arises due to the formation of a magnetic field and magnetization ability. This magnetic field will increase the electric field generated from a piece of wire that is in a changing magnetic field. The results of the study show the largest values of current, voltage, and torque produced at 80 mm thick, with values of 17.44 A, 52.31 V, and 24.84 Nm. Incoming power produces a large comparison; it is proven that at a thickness of 52 mm, it produces 766 watts, while at a thickness of 80 mm, it can produce 1300 watts. The highest output power is 1 kW with a thickness of 80 mm [2].

The magnetic material also influences the characteristics of the PMSG. As research has been carried out in 2022, many magnetic materials can also be used, where the magnetic material has different properties. Permeability is directly proportional to the speed of the magnetic flux, and the better the material used in the magnet, the better the permeability produced. The permeability value for each material is different. As shown, there are research results where the highest output power and efficiency are produced by PM12 material: Br 1.2 nut 10, where the output power value is 1312.19 watts with an efficiency of 91% [8].

In 2021, has anyone researched the effect of the number of turns on the PMSG? Where the number of turns in the stator coil is increased, the resulting output also increases. In the study, the number of coils used was 10, 50, and 75. Where each winding produces a different value, and the value of the electric power of the big propeller is obtained in coil 75 with a value of 756.2 Watts [9].

In making and designing the generator in this study using the *software*-based *Finite Element Method* (FEMS), FEM is a method used to solve problems such as differential and integral by calculating the parameters one by one for each part of the object to be analysed in the smallest part. In carrying out FEM, there are several processes, namely discretizing, which divides into several parts or several elements; creating an estimation function to see the potential of the elements; estimating the matrix value of the elements; estimating the value in the system; and getting a calculated system solution. *Finity element method* (FEM) is in software at *MagNet Infolityca*, which is used to carry out generator designs by varying the materials used, analysing electromagnetic field problems, and getting the generator design as desired [10].

In the research that will be carried out using the material *Remko pure iron* for stator and rotor, materials *Remko: soft pure iron* has a high permeability; on *coil*, using materials Cooper: 5.77.c7siemens/meter; and on magnet, using PM12 material: Br 1.2, Nut 1.6, with a total of 65 turns and a load of 10 ohm, and the same for each variation. For variations in core thickness ranging from 40 mm, 60 mm, and 80 mm with variations in rotational speed of 250 rpm, 500 rpm, and 750 rpm.

II. Methods

In the research that will be carried out this time using the experimental method by modeling the PMSG 24 slot 16 pole and simulating PMSG, followed by calculating the data from the simulation results to get the optimal efficiency value, Figure 1 shows the research flowchart to be carried out.

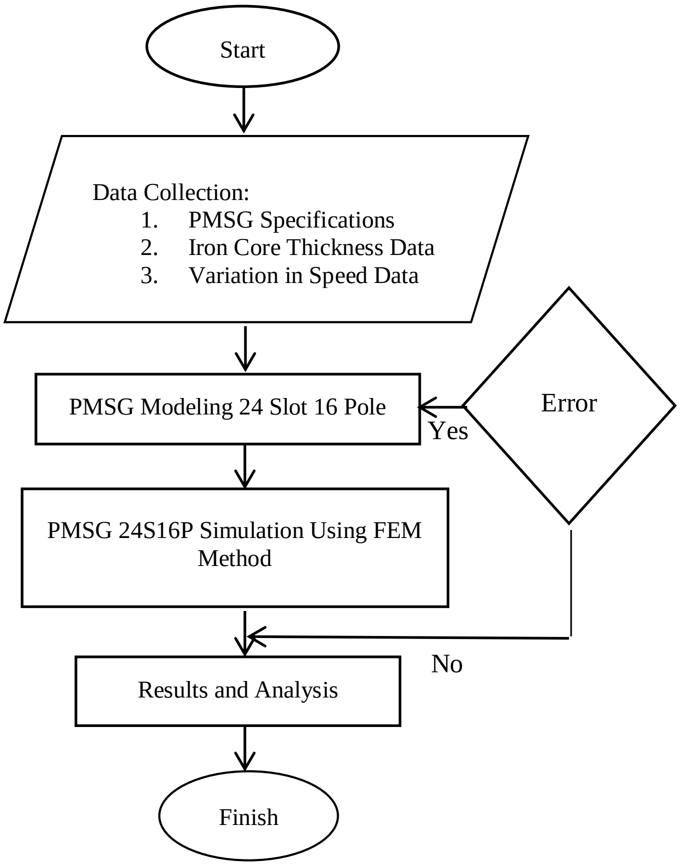


Figure 1. Research Flow Chart

The Flow chart above states the flow of research carried out, which begins with a study of literature sourced from journals that have been published, followed by collecting the required data. Starting from the specific data for modeling the generator to the component data on the generator such as the stator, rotor, magnet, and airbox. Data on core thickness and rotational speed are also needed in order to be able to run simulations in research. After getting the required data, proceed with modeling a permanent magnet synchronous generator on the software MagNet Infolityca. The next process will be modeling PMSG 24 slot 16 pole, starting with designing the stator, rotor, airbox, and permanent magnets, then entering the variables used in this study, which use iron core thicknesses of 40 mm, 60 mm, and 80 mm, and variable rotational speeds starting from 250 rpm, 500 rpm, and 750 rpm. The next step is to enter the load value and the number of windings used, where the load value and the number of coils can be said to be the same variable for each core thickness, as well as the rotational speed in this study. The load value used is 10 ohms, and the number of turns is 65. The material used for modeling PMSG 24 slot 16 pole is Remko Pure Iron: Soft Pure Iron, on the magnetic part, PM12: Br 1.2 Mur 1.6, for the air gap and airbox, Air.

In conducting research, the initial step is to collect the required data from related journals or generator specification papers that will be designed according to the wishes of the user. *software, MagNet Infolityca*. The specific generator to be designed and simulated is as follows:

Table 1. Specifications *Permanent Magnet Synchronous Generator* (PMSG) [2][5][11].

No	Specification	Description
1	Number of *Slot*	24 *Slot*
2	Number of *Pole*	16 *Pole*
3	Dimensions	150x150
4	Number of Coils	65 Coils
5	Coils Material	*Cooper: 5.77e7 Siemens/meter*
6	Material Magnet	*PM 12: Br 1.2 Mur 1.6*
7	*Air Box* Material	*Air*
8	*Air Gap* Material	*Air*

Tabel 2. Specification for Core or Iron Core Thickness and Rotational Speed of PMSG 24S16P [2][5].

No	Iron Core Material	Core Thickness (mm)	Spin Speed (Rpm)
1	Remko: Soft Pure Iron	40	250, 500, 750
2	Remko: Soft Pure Iron	60	250, 500, 750
3	Remko: Soft Pure Iron	80	250, 500, 750

The thickness will be related to the magnetic flux, where there are 3 ways to increase the Electric Motive Force (EMF), such as increasing the magnetic field, expanding the area, and increasing the number of coils turns. The magnetic flux itself is the amount or size of the magnetic field that will pass through a certain variable cross-sectional area. According to Faraday, the induction emf in the coil is proportional to the rate of change of the magnetic flux enclosed by the coil, where the faster the change in magnetic flux occurs, the greater the induction emf that arises [2] [12].

A. PMSG Modeling 24 *Slot* 16 *Pole*

MSG 24s16p is a generator that has 24 coils and a total of 16 magnetic poles, where each magnet has 8 leads north and 8 leads south. For modeling done using software from MagNet Infolityca, the total number of turns here is 65, and the load given is 10 ohms. Here are the steps to make a model on PMSG 24 slot 16 pole:

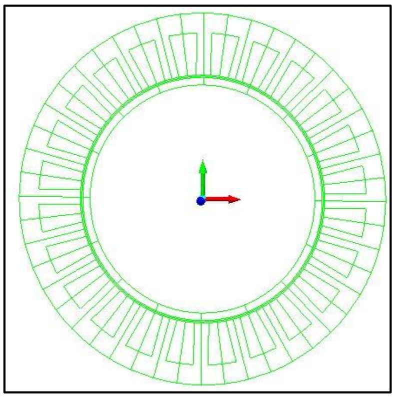


Figure 2. Line on PMSG 24s16p

The initial modeling stage for PMSG 24s16p is to establish the components in the generator, such as the stator and rotor, to be used. Determine the number of turns to be used on the coil, the magnet to be used, and the material on the air gap and air box. When this step has been fulfilled, proceed with determining the material to be used in the iron core.

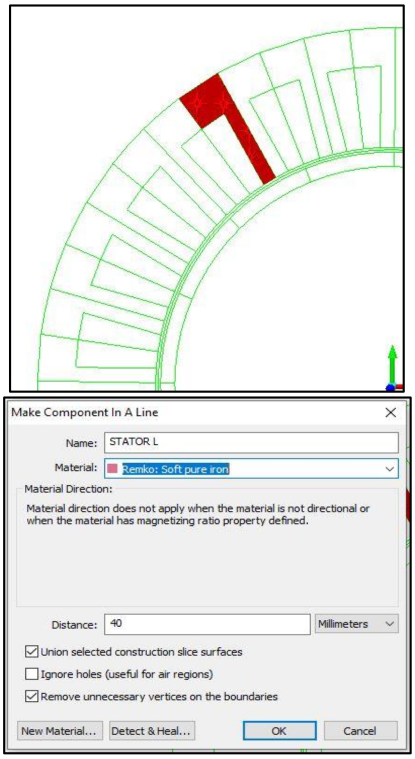


Figure 3. Making Components on the Stator and Rotor with Material *Remko: Soft Pure Iron.*

At this stage, modeling the PMSG 24 generator components slot 16 poles that will be used. The stator and rotor use the 24s16p material Remko: Soft Pure Iron, where this material has the advantage of having a high permeability value. The permeability value that exists in the material Remko Soft Pure Iron is 0,00004 Wb/Am [13] [14].

B. Determination of Core Thickness dan Spin Speed

So, the next step is to determine the thickness of the core and the rotational speed. The thicker the core used in PMSG, the better the output. The rotational speed is in accordance with Faraday's law, which states that the higher the speed, the better the output will be in PMSG. The rotating speeds used in PMSG this time are 250 rpm, 500 rpm, and 750 rpm [2] [5].

C. Determination of Number Coils and Loading

1. Determination of the number of coils

After entering the various materials required in the stator and rotor, determine the number of coils to be used. The number of turns on the stator affects the induced voltage produced, so if the number of turns on the stator coil increases, the greater the induced voltage that will be generated by the generator [11]. The number of turns used in this study is 65 on each coil.

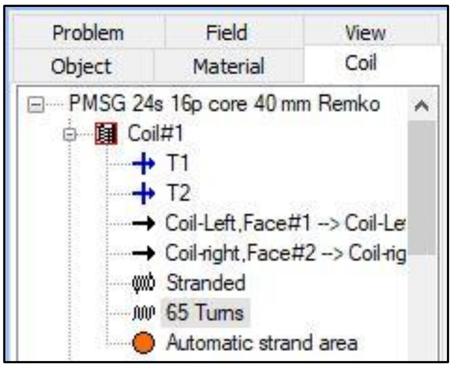
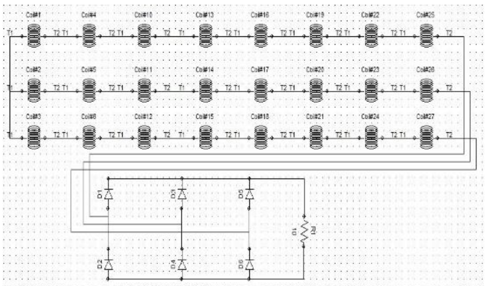


Figure 4. Determination of the Number of Coil in PMSG 24 *Slot* 16 *Pole*

2. Loading

After determining the number of coils to be used, proceed with describing the circuit phase diagram for each coil that will be loaded. To get the results, the generator must be loaded, which in this study uses a loading of 10 ohms. Loading and circuitry are shown below.:



Gambar 5. Network *Circuit* and Imposition of PMSG 24 *Slot* 16 *Pole*

D. PMSG Modeling Simulation 24 *Slot* 16 *Pole*

After doing the modeling on PMSG, the next step is to carry out a simulation and collect data from the simulation results. Data from the simulation results obtained consist of current, voltage, torque, input power, output power, and efficiency. The data obtained will be transferred to Microsoft Excel, and manual processing will be carried out, followed by a comparative analysis of the efficiency that occurs due to differences in core thickness and rotational speed in the PMSG 24 generator slot and 16 pole. The following data will be issued when running the simulation:

1. Current

The current is obtained from the comparison of the input voltage and resistance. The rotational speed of the generator affects the current value. The greater the rotational speed of the generator, the greater the resulting current value will be [7].

$$I = \frac{V}{R} \quad (1)$$

I = current (Amperes)
V = voltage (volt)
R = load (Ohm)

2. Voltage

The voltage is the result of the generator's electromagnetic induction.

$$\varepsilon = -N\frac{\Delta\emptyset}{\Delta t} \quad (2)$$

Ɛ = the induction GGL (V)
N = the number of windings
ΔØ = the change in magnetic flux (Wb)
Δt = time lapse (s)

3. Torque

Torque is generated from the tangential force and the radius where the motor is working, depending on the magnitude of the applied force and the distance between the rotational and rotary axes [7].

$$T = Fr \quad (3)$$

F = Force
R = Radius

4. Input Power

The equation used to obtain the input power (P*in*) are as follows:

$$Pin = \frac{\tau\ x\ RPM\ x\ 2\ Phi}{60} \quad (4)$$

Pin = the inlet power (W)
τ = torque (Nm)
n = the rotating speed (rpm)

5. Output Power

And to get the output power value (P*out*) using the following equation :

$$Pout = V\ x\ I \quad (5)$$

6. Efficiency

The efficiency value is obtained from the comparison of the output power (Pout) with the input power (Pin) multiplied by 100% [7].
With the following equation:

$$n = \frac{Pout}{Pin} x\ 100\% \quad (6)$$

III. RESULTS AND DISCUSSION

The results of the PMSG 24S16P study varied the thickness of the iron core and rotational speed using a 10-ohm load and 65 turns; namely, the output values for current, voltage, and torque were obtained from simulations with transient 2D motion, while the power output value input, output, and efficiency were obtained from manual calculations using Microsoft Excel. Following are the PMSG 24 Slot 16 Pole modeling results.

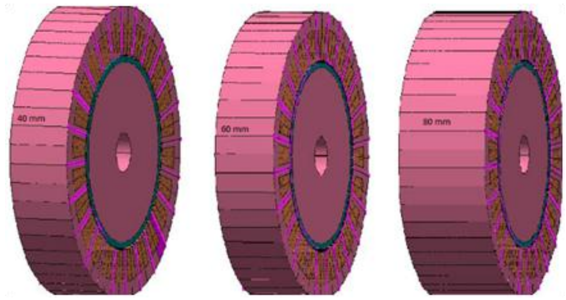


Figure 6. The PMSG 24 slot 16 pole Model with Variations in the Core Thickness

In the picture above, you can see the result of the PMSG modeling, where the thickness of the iron core used here is 40 mm, 60 mm, and 80 mm. For the thickness of this iron core, materials recommended by several journals have been used. Where thickness is one of the factors to improve the characteristics of PMSG, such as current, voltage, torque, input power, and output power. Where, according to Faraday, the induction emf in the coil is proportional to the rate of change of the magnetic flux enclosed by the coil. That is, the faster the change in magnetic flux occurs, the greater the induced emf that arises [15].

A. Results of Average Output Value in PMSG 24s16p Simulation

PMSG Average Output Value Results 24s16p at Speed 250.

Table 3. Average Output Value of PMSG 24s16p at Speed of 250 Rpm

Core Thickness	Current (Ampere)	Voltage (Volt)	Torque (Nm)
40 mm	5.482	54.818	-14.499
60 mm	7.627	76.266	-28.163
80 mm	9.279	92.794	-43.275

PMSG Average Output Value Results 24s16p At Speed 500

Table 4. Average Output Value of PMSG 24s16p at a Speed of 500 Rpm

Core Thickness	Current (Ampere)	Voltage (Volt)	Torque (Nm)
40 mm	9.926	99.263	-22.904
60 mm	12.687	126.865	-39.203
80 mm	14.757	147.568	-55.067

PMSG Average Output Value Results 24s16p At Speed 750.

Table 5. Average Output Value of PMSG 24s16p at a Speed of 750 Rpm

Core Thickness	Current (Ampere)	Voltage (Volt)	Torsi (Nm)
40 mm	13.030	130.301	-26.430
60 mm	15.823	158.232	-40.717
80 mm	17.423	174.233	-51.380

B. Power Rated Results *Input*, Rated Power *Output*, Efficiency Value

After getting the simulation results and getting the current value, voltage value, and torque value, the next step is to manually calculate the power input, one output, and the efficiency that occur in PMSG 24s16p by using Microsoft Excel to get those values. Following are the results of the data obtained on the power value input, output power, and efficiency:

Result of Input Power, Output Power, and Efficiency at Speed of 250 Rpm

Table 6. Average Output Value of PMSG 24s16p at a Speed of 250 Rpm

Thickness	Power		Efficiency
	Input	Output	
40 mm	379.39 W	300.51 W	79.93%
60 mm	736.93 W	581.68 W	78.93%
80 mm	1132.36 W	861.03 W	76.03%

Result of Input Power, Output Power, and Efficiency at Speed of 500 Rpm

Table 7. Average Output Value of PMSG 24s16p at a Speed of 500 Rpm

Thickness	Power		Efficiency
	Input	Output	
40 mm	1198.64 W	985.28 W	82.20%
60 mm	2051.62 W	1609.53 W	78.54%
80 mm	2881.83 W	2177.66 W	75.56%

Result of Input Power, Output Power, and Efficiency at Speed of 750 Rpm

Table 8. Average Output Value of PMSG 24s16p at a Speed of 750 Rpm

Thickness	Power		Efficiency
	Input	Output	
40 mm	2074.75 W	1697.82 W	81,83%
60 mm	3196.28 W	2503.70 W	78.33%
80 mm	4033.33 W	3035.65 W	75.26%

At the point of discussion, we will analyze the research results starting from the results of current, voltage, torque, input power, output power, and efficiency.

1. Current

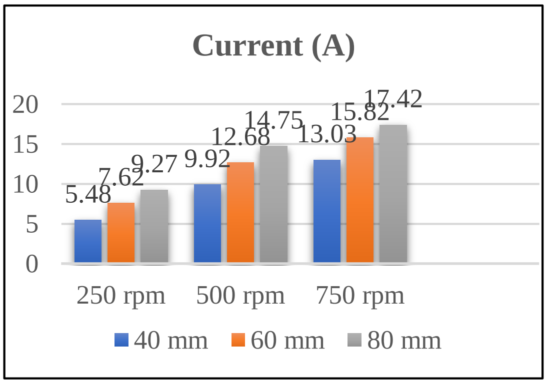


Figure 7. Current Diagram

The current value can be seen in the average value of the PMSG 24 slot 16 pole output; where the output value increases the rotational speed and increases the thickness of the core, the current value will increase. This is because the electromagnetic induction that occurs is increasing in accordance with Fareday's law regarding electromagnetic induction. The highest current value was obtained at a speed of 750 rpm with a thickness of 80 mm and a current value of 17.42 A.

2. Voltage

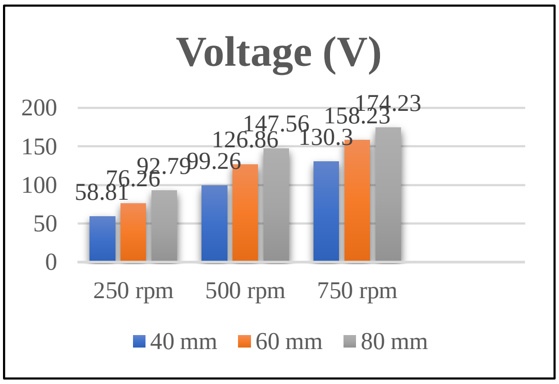


Figure 8. Voltage Diagram

The voltage value can also be seen in the average PMSG 24 slot 16 pole output value. The output voltage value is proportional to the current value; when the current value increases, the voltage value also increases because the current and voltage values are comparable. The higher the rotational speed and core thickness of the PMSG, the higher the voltage value.

3. Torque

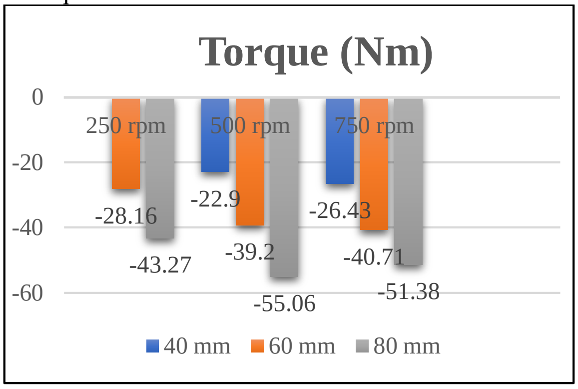


Figure 9. Torque Diagram

The torque value is seen in the average output of PMSG 24 slot 16 pole where the resulting torque value increases because the rotational speed and core thickness are also increased. In the diagram, the thicker the iron core used, the greater the amount of torque generated. The highest torque was produced at a speed of 750 rpm with a thickness of 80 mm and a value of -51.38 Nm.

4. Input Power

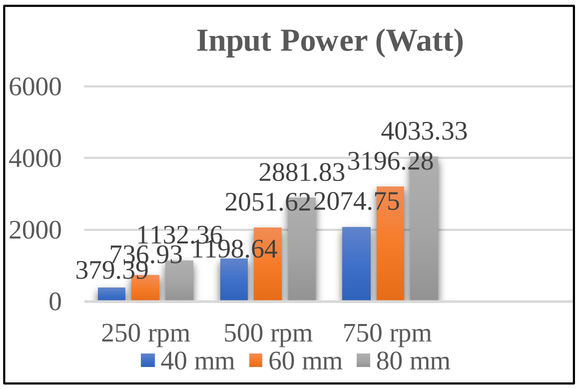


Figure 10. Input Power Diagram

The input power can be seen from the average output value on the PMSG 24 slot 16 pole; in fact, as the speed and thickness of the core are increased, the input power also increases because the input power is obtained from the multiplication between torque and rotational speed. At each input power and at each variation, the speed and thickness of the core increase because the torque that occurs in the PSMG increases.

5. Output Power

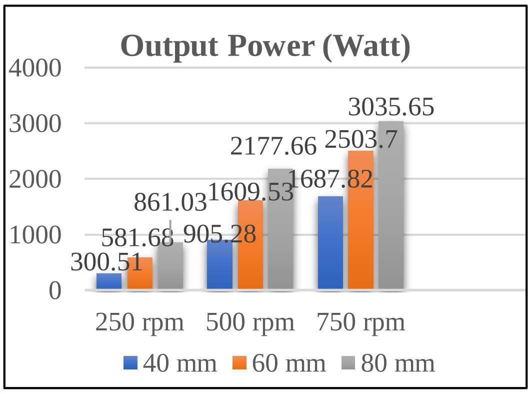


Figure 11. Output Power Diagram

The input power can be seen from the average output value on the PMSG 24 slot 16 pole; in fact, as the speed and thickness of the core are increased, the input power also increases because the input power is obtained from the multiplication between torque and rotational speed. At each input power and at each variation, the speed and thickness of the core increase because the torque that occurs in the PSMG increases.

6. Efficiency

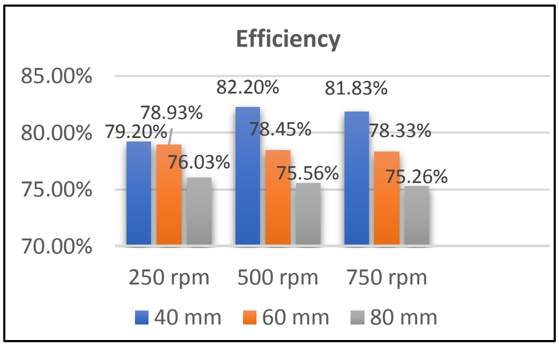


Figure 12. Efficeincy Diagram

The efficiency value to get the result is the result of dividing the output power (Pout) and input power (Pin) by 100%. The highest efficiency value in this study was at a speed of 500 rpm with a thickness of 40 mm, with a value of 82.20%. Increasing the value of the speed and core thickness given to PMSG does not guarantee an increase in efficiency because PMSG has a limit on how many expansion and widening ratios are included. The decreased efficiency is caused by several factors, including the copper losses caused by the copper windings on the stator becoming hot and the iron losses due to the generator having hot bearings.

IV. Conclusion

After simulating the results of the analysis of core thickness and rotating speed on a 24 slot 16 pole Permanent Magnet Synchronous Generator using software based on the Finite Element Method (FEM), the conclusion of this study is that the thickness of the core and rotational speed affect the value of efficiency. Because the efficiency value is obtained by dividing the output power by the input power multiplied by 100%, the output power is the result of multiplying the current and voltage. And the input power is the product of torque and rotational speed. The highest efficiency value obtained is 82.20% at a core thickness of 40 mm and a rotational speed of 500 rpm, with a current value of 9,926 amps, a voltage of 99,263 volts, a torque of 22,904 nm, an input power of 1198.64 watts, and an output power of 985.28 watts.

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