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ANALYSIS OF LOAD ON PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG) 12S8P WITH SPEED VARIATION

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Abstrak. Penelitian ini dilakukan untuk melihat pengaruh variasi kecepatan terhadap kinerja Generator Sinkron Magnet Permanen (Permanent Magnet Synchronous Generator/PMSG) yang dikonfigurasi dengan 12 slot dan 8 kutub (12S8P) untuk sistem konversi energi angin. PMSG menarik perhatian karena efisiensinya yang tinggi, desain yang sederhana, dan kemampuannya untuk beroperasi secara efektif pada kecepatan rendah, sehingga sangat cocok untuk aplikasi energi terbarukan seperti turbin angin. Menggunakan perangkat lunak simulasi MagNet, kinerja PMSG dianalisis pada rentang kecepatan 1000–6000 rpm dan variasi beban 10–50 ohm.Hasil penelitian menunjukkan fluks magnetik maksimum sebesar 0,000927 Wb, sementara tegangan rata-rata tanpa beban adalah 17,78 V pada kecepatan 1000 rpm. Selain itu, diamati bahwa tegangan dan arus meningkat secara proporsional dengan kecepatan. Kinerja torsi optimal dicapai pada beban 30 ohm pada kecepatan 5000 rpm, yang menyoroti pentingnya optimalisasi beban untuk konversi energi yang efektif. Analisis efisiensi mengungkapkan bahwa generator mencapai efisiensi tertinggi sebesar 92,96% pada beban 10 ohm dan kecepatan 5000 rpm. Studi ini juga menekankan pengaruh sifat material, desain slot-kutub, dan kondisi beban terhadap kinerja generator. Temuan ini memberikan wawasan penting untuk desain dan optimalisasi turbin angin, terutama di wilayah dengan kecepatan angin yang bervariasi. Lebih jauh lagi, penelitian ini berkontribusi pada pengembangan pemanfaatan teknologi energi terbarukan dengan menawarkan strategi berbasis data untuk meningkatkan efisiensi dan keandalan sistem.

Abstract. *This study investigates the impact of speed variation on the performance of a Permanent Magnet Synchronous Generator (PMSG) configured with 12 slots and 8 poles (12S8P) for wind energy conversion systems. PMSG has gained attention due to its high efficiency, simple design, and ability to operate effectively at low speeds, making it particularly suitable for renewable energy applications like wind turbines. Using MagNet simulation software, the performance of the PMSG was analyzed over a speed range of 1000–6000 rpm and load variations of 10–50 ohms. The results showed a maximum magnetic flux of 0.000927 Wb, while the no-load average voltage was 17.78 V at a speed of 1000 rpm. Furthermore, it was observed that voltage and current increased proportionally with speed. Optimal torque performance was achieved at a 30-ohm load at a speed of 5000 rpm, highlighting the importance of load optimization for effective energy conversion. Efficiency analysis revealed that the generator achieved its highest efficiency of 92.96% at a 10-ohm load and a speed of 5000 rpm. This study also emphasizes the influence of material properties, slot-pole design, and load conditions on generator performance. These findings provide critical* *insights for the design and optimization of wind turbines, particularly in regions with varying wind speeds. Moreover, this research contributes to advancing the utilization of renewable energy technologies by offering data-driven strategies for enhancing system efficiency and reliability..*

1. PENDAHULUAN

The ever-increasing demand for energy is a complex global challenge, especially in the midst of limited fossil energy sources and their negative impact on the environment [1], [2]. Dependence on fossil fuels not only poses a risk to the sustainability of energy supply but also contributes significantly to increased carbon emissions, which impacts global climate change [3], [4], [5]. In the face of these challenges, the development and utilization of renewable energy is an urgent solution. One potential renewable energy source is wind energy, which is known to be abundant, produces no carbon emissions, and has a relatively low environmental impact compared to fossil fuels [6],[7].

Indonesia, with its long coastline and strategic geographical location, has great wind energy potential. Based on data from the Ministry of Energy and Mineral Resources (MEMR), wind energy potential in Indonesia reaches 60.6 GW, making it one of the promising renewable energy sources to be developed [8], [9]. However, the utilization of wind energy in Indonesia is still relatively low compared to its potential. One of the main obstacles is the efficiency of wind energy conversion systems, which is highly dependent on the design and technology used in wind power plants (WPPs). Wind turbines, as the main component in a wind farm, require efficient and reliable generators to optimize the conversion of wind kinetic energy into electrical energy.

One of the main technologies widely used in wind power generation systems is the Permanent Magnet Synchronous Generator (PMSG). PMSG is a type of synchronous generator that uses permanent magnets to generate a magnetic field, in contrast to conventional generators that require excitation coils. The main advantages of PMSGs lie in their high efficiency, due to the absence of excitation losses, and their simple design [10]–[12]. In addition, PMSGs can operate at low speeds, making them particularly suitable for wind turbines in areas with significant wind speed variations. This design also allows for a reduction in generator size and weight, which is important for applications in renewable energy generation systems. However, PMSG performance is affected by various factors, such as rotor speed, load, magnetic pole design, and materials used [13]. The 12-slot and 8-pole (12S8P) PMSG configuration offers optimal performance for various operating conditions. These characteristics are achieved through slot and pole designs that allow for increased magnetic flux and reduced energy losses [14]–[16]. Technical parameters such as rotor speed, load, magnet thickness, material quality, and magnet pole position play an important role in determining PMSG performance. For example, generator efficiency is highly dependent on the permanent magnet material design that can produce high magnetic flux density, temperature stability, and resistance to demagnetization. These factors make PMSGs a top choice in renewable energy-based power generation applications, including wind turbines.

However, a key challenge in the use of PMSGs is understanding how variations in operating parameters affect generator performance, including efficiency, output voltage, current and torque. Software-based simulations, such as MagNet, provide an opportunity to analyze and optimize PMSG performance under various conditions without the need for complex and expensive physical testing. By understanding the technical characteristics of PMSGs, the design of wind power generation systems can be further optimized to improve efficiency and reliability.

This research focuses on analyzing the performance of a 12S8P configuration PMSG with variations in rotor speed and loading using MagNet simulation software. The study includes analysis of magnetic flux, voltage, current, torque, and efficiency at various operating conditions. The results of this study are expected to not only provide technical insight into the performance of PMSGs but also make a significant contribution in the development of renewable energy technology. With the data generated, this research can be an important reference in supporting Indonesia's clean energy transition and strengthening the implementation of wind power generation technology to meet sustainable energy needs.

2. RESEARCH METHODS

To obtain accurate and reliable data, this research uses MagNet software in all stages, from design to data collection. Therefore, the flow of the research process can be described through the following flowchart:

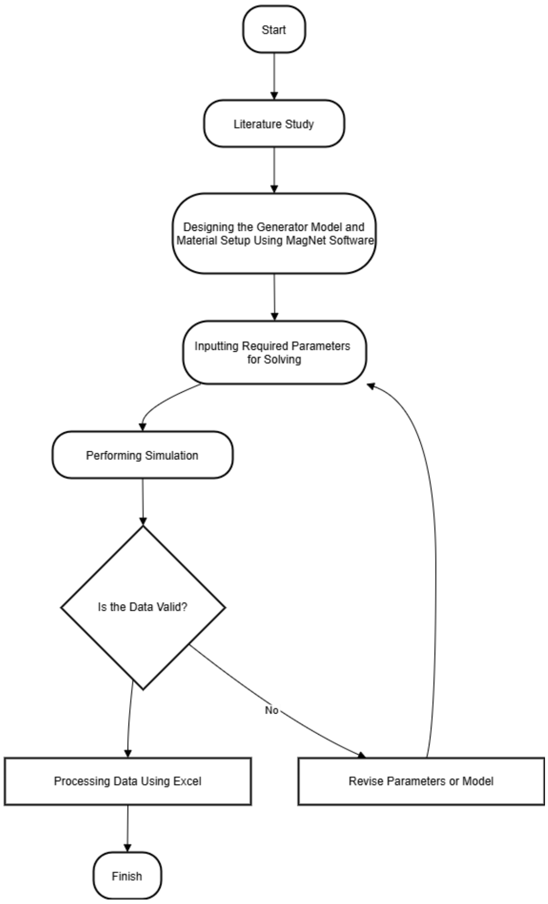

Figure 1 Research Flowchart

The initial stage of the research begins to ensure the objectives and steps of the research are clear. This is the opening step before getting into the core research process.

a. Design of *Permanent Magnet Synchronous Generator* (PMSG) Model

After conducting a literature study to understand the PMSG, the next step is to enter the PMSG model design stage. In this study, research will be carried out on PMSG 12S8P, for the size used we can see in the table below, but first set the properties to be as in Figure 2

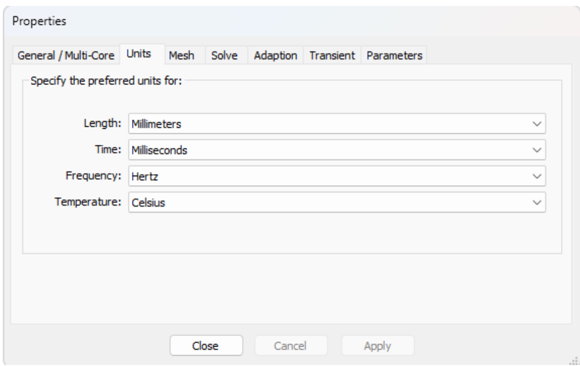

Figure 2. Setting Properties pada Software MagNet

Table 1. Size of Permanent Magnet Synchronous Generator (PMSG) Circles

No	Description	Size
1.	Stator Air Gap radius	90 mm
2.	Stator radius	75 mm
3.	Stator inner radius	67 mm
4.	Rotor Air Gap radius	50 mm
5.	Rotor Radius	46 mm
6.	Permanent Magnet radius	49 mm
7.	Permanent Magnet inner radius	46 mm

After making the size of the generator model circle based on table 1, then determine the material or material used as in table 2.

Table 2. Permanent Magnet Synchronous Generator (PMSG) component sizes

No	Description	Dimension	Material
1.	Air Gap	Stator: 15 mm Rotor: 1 mm	Air
2.	Stator	Length: 25 mm Sudut: 30°	TR52 USS Trans 52-29
3.	Coil	8 mm 100 lilitan Sudut: 15°	Cooper:5.77e7Siemens/meter
4.	Magnet	3 mm Sudut: 15°	PM12:Br1.2mur1.0
5.	Rotor	92 mm Sudut: 15°	TR52 USS Trans 52-29

b. Performing simulation

After designing the PMSG, then proceed to the simulation stage. This simulation is carried out to see the effect of torque speed on loading on the *Permanent Magnet Synchronous Generator* (PMSG) 12S8P. The torque to be tested starts from 1000 Rpm to 6000 Rpm and the load itself is 10ohm to 50ohm. The circuit used uses a rectifier and then is given a load as shown in Figure 3

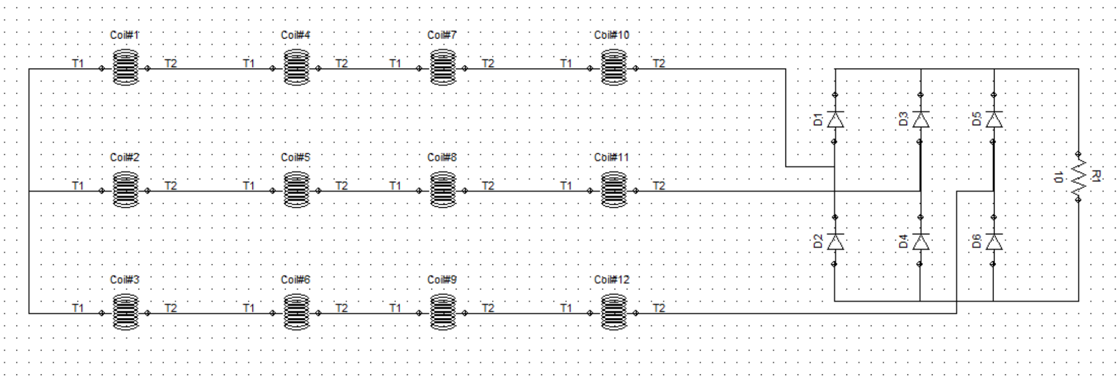

Figure 3. Loading circuit

Before simulating the solving setting first so that the data generated matches what we need, with newton tolerance at a value of 0.01 and CG tolerance at a value of 0.0001. Then setting the motion as well as the transient option to be fixed interval and for the start, stop and step for each speed will be different, can be known by using the equation below.

$$Step = \frac{3}{speed}$$

$$Stop = \frac{360}{speed}$$

Because this simulation uses a mechanical angle, the equation that can be obtained is like that and for the speed is changed from rpm to deg / s, for 1000 rpm is equal to 6000 deg / s, so that the transient and motion settings that can be obtained are

$$Step = \frac{3}{6000}$$

$$= 0.0005\ s$$

$$Stop = \frac{360}{6000} = 0.06\ s$$

Table 1. Setting Motion dan Transient

No	RPM	Degree/s	Start (s)	Step (s)	Stop (s)
1	1000	6000	0	0.0005	0.06
2	2000	12000	0	0.00025	0.03
3	3000	18000	0	0.000166667	0.02
4	4000	24000	0	0.000125	0.015
5	5000	30000	0	0.0001	0.012

After all the necessary parameters have been filled in properly, the simulation is carried out one by one based on the speed and loading that has been determined.

3. RESULTS AND DISCUSSION

MagNet software is the main role in this Permanent Magnet Synchronous Generator (PMSG) simulation research. As in the first research stage of designing or creating a Generator model according to our needs, the results will be as shown below 4

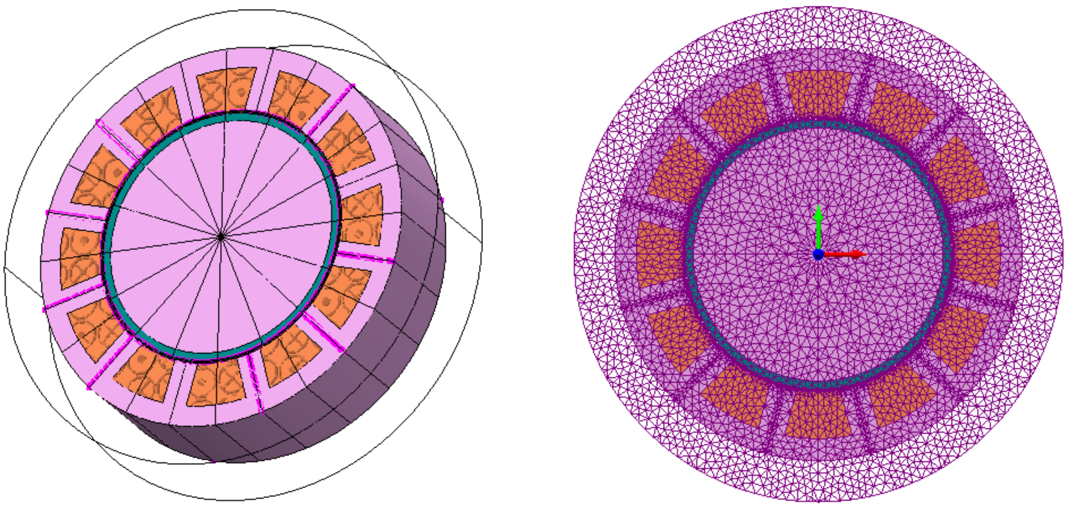

Figure 4. 12S8P generator model (left) and Mesh visualization (right)

Figure 4 shows the genetor model, in addition to modeling the size of the *Permanent Magnet Synchronous Generator* (PMSG), setting the mesh density is an important factor for the efficiency of the resulting magnetic field as shown in Figure 6 on the right. The mesh density given for the whole maximum of 1 mm while for the coil is given 3 mm, then on each side of the pair of stator and coil is divided into 30 per 2 mm mes and for the rotor airgap is given a value of 720 per 2 mm.

To find out the magnetic field produced by using PM12 material with a value of 1.2T, we can find out by using formula 3, namely:

$$B = Br\frac{lm}{lm + \delta}$$

$$B = 1.2\frac{0.3}{0.3 + 0.1}$$

$$= 0.9\ T$$

Furthermore, to find out the surface area flowed by the magnetic field can be known by using formula , namely:

$$A = \frac{\pi(ro^2 - ri^2) - (lm(ro - ri)Nm}{Nm}$$
$$= \frac{3.14(4.9^2 - 4.6^2) - (0.3(4.9 - 4.6)8}{8}$$
$$= \frac{3.14(2.85) - (0.72)}{8}$$
$$= 1.03\ cm^2$$

After knowing the magnetic field and the surface area flowed by the magnetic field, the maximum flux density value that occurs in the generator model can be known using the formula, namely:

$$\phi = B.A$$
$$= 0.9 \times 1.03$$
$$= 0.000927\ Wb$$

So it can be seen that the maximum magnetic flux value in the *Permanent Magnet Synchronous Generator* (PMSG) 12S8P is 0.000927 Wb, and for visualization of the magnetic field flow generated in the simulation can be seen based on Figure 5.

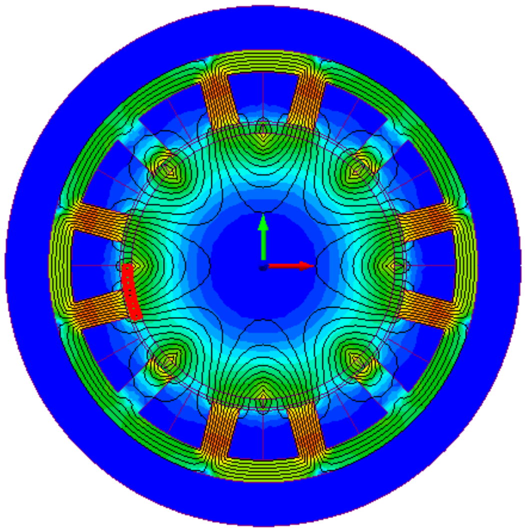

Figure 5. Magnetic Field Flow

Figure 5 shows the magnetic field flow, besides that the simulation also provides linkage flux data which we can later process to determine the average voltage of the generator as shown in Figure 6

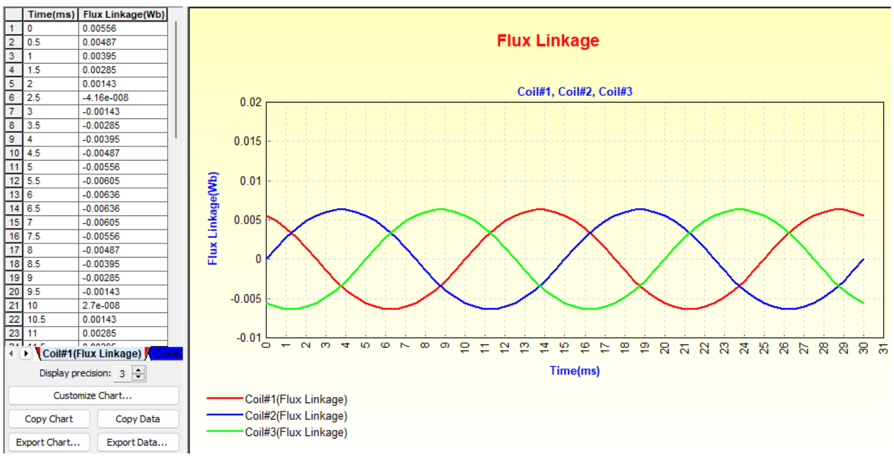

Figure 6: Flux Linkage Graph

Figure 6 shows the magnetic*flux linkage* graph against time for the three coils in the generator, Coil#1, Coil#2, and Coil#3. All three curves show a sinusoidal pattern with a phase shift of 120 electrical degrees between each coil. This pattern illustrates the characteristics of a three-phase system designed to produce an even and balanced magnetic flux distribution. The peak value of magnetic flux in each coil ranges between 0.015 Weber (maximum) and -0.015 Weber (minimum), indicating the maximum magnetic field strength sensed by each coil during magnetic rotation. The even distribution of magnetic flux with phase shifts between coils ensures high efficiency and stability of electrical output in the three-phase generator. This pattern also shows that the design and configuration of the generator successfully creates an optimal sinusoidal flux for system operation. These results confirm that the generator is capable of distributing magnetic flux well, which is important to ensure maximum performance under various operating conditions.

a. Without Load

After knowing the linkage flux generated from the *Permanent Magnet Synchronous Generator* (PMSG) 12S8P with a torque speed of 1000 rpm, data processing is carried out in excel software to determine the voltage per phase and the average Vdc generated from this generator, as shown in Figure 7.

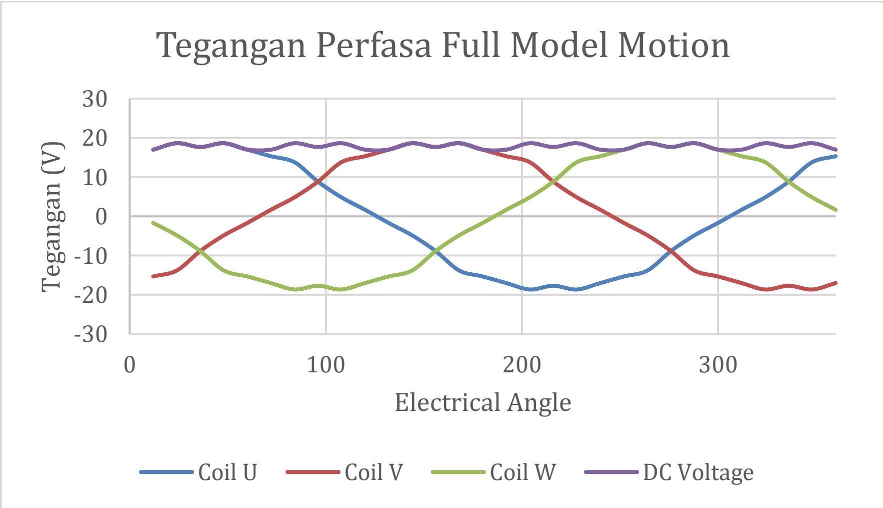

Figure 7. Average voltage and Vdc graphs

The graph above shows the voltage distribution per phase (Coil U, Coil V, and Coil W) as well as the average DC voltage (*Vdc*) generated by a **Permanent Magnet Synchronous Generator (PMSG)** with a configuration of 12 slots and 8 poles (12S8P) at a torque speed of 1000 rpm without load. The voltage per phase (indicated by blue, orange, and gray curves) forms a symmetrical sinusoidal pattern, with a phase shift of 120 electrical degrees between phases. This indicates that the generator is capable of producing balanced voltages on all three of its phases. The average DC voltage (*Vdc*), represented by the yellow line, shows a relatively constant value around **17.78 V**. This voltage is generated after the rectification process of the three-phase sinusoidal voltage. These results confirm that the design and configuration of the 12S8P PMSG has successfully achieved optimal performance in generating a stable and efficient DC voltage even under no load. The symmetrical voltage distribution per phase also indicates that the generator works well in distributing energy between its coils.

B. With Speed and Load Variations

Then the simulation is continued to the 12S8P *Permanent Magnet Synchronous Generator* (PMSG) testing stage with speed variations from 1000 rpm to 6000 rpm and load variations from 10ohm to 50ohm. This simulation is carried out to determine the effect of speed on loading on the *Permanent Magnet Synchronous Generator* (PMSG) 12S8P through 6 characteristic curves consisting of voltage, current, torque, input power, output power and efficiency of the generator. With the variation of speed, the angular velocity that must be set in the simulation also varies, to find the angular velocity can be obtained based on the formula, namely:

$$\omega = \frac{1000 \times 2 \times 3.14}{60}$$

$$= 104.7197551\ rad/s$$

So the values obtained for the speed variation are as follows.

Table 4. Angular velocities used.

No.	Rpm	Rad/s
1.	1000	104.7197551
2.	2000	209.4395102
3.	3000	314.1592654
4.	4000	418.8790205
5.	5000	523.5987756

After the simulation is carried out, the data that will be obtained is the voltage, current and torque data, then put together in a graph as shown below

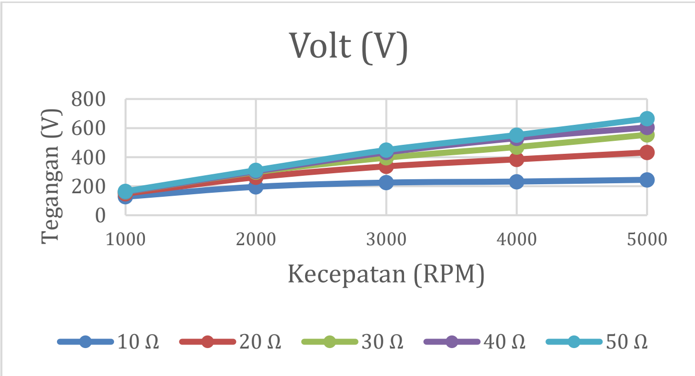

Figure 8. PMSG voltage graph with speed variation

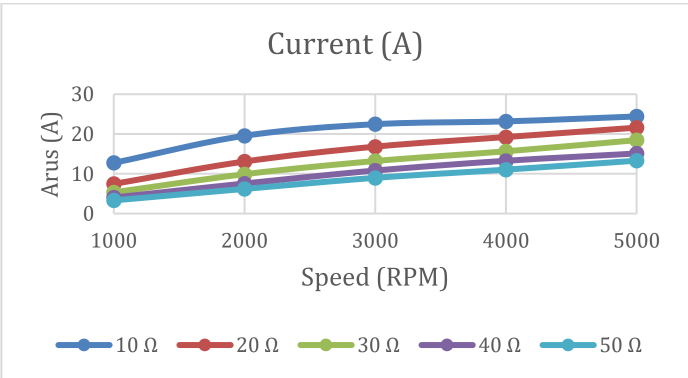

Figure 9. PMSG current graph with speed variation

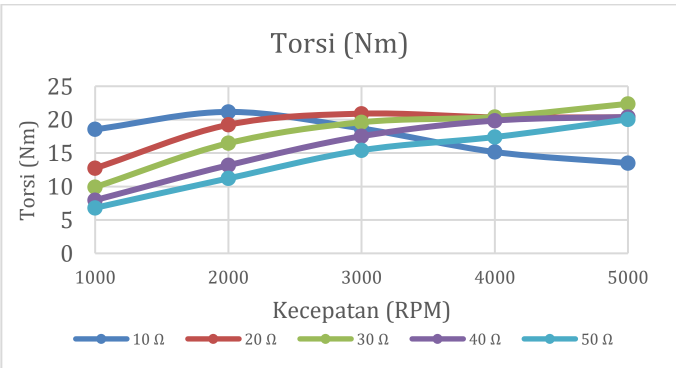

Figure 10. Graph of torque with speed variation

As for the input power value (Pin) obtained based on formula 7, namely the torque value multiplied by the angular velocity and for the output power (Pout) obtained based on formula 8 resulting from the current and voltage itself, the resulting graph can be seen in Figures 11 and 12.

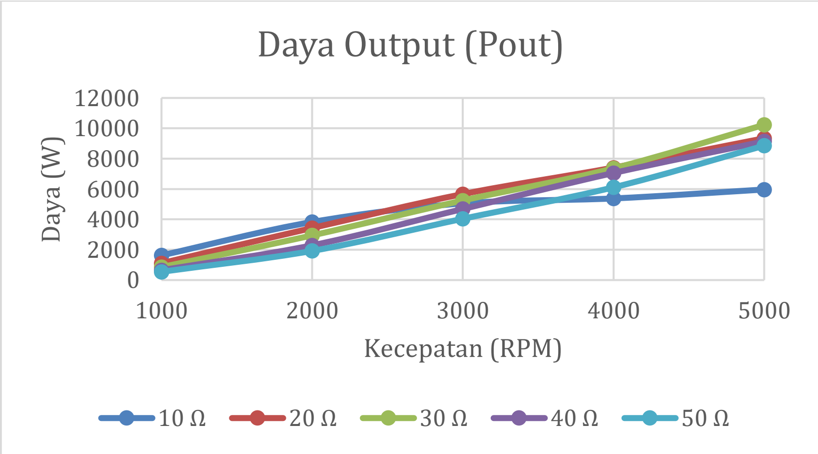

Figure 11. Input power graph (Pin) with speed variation

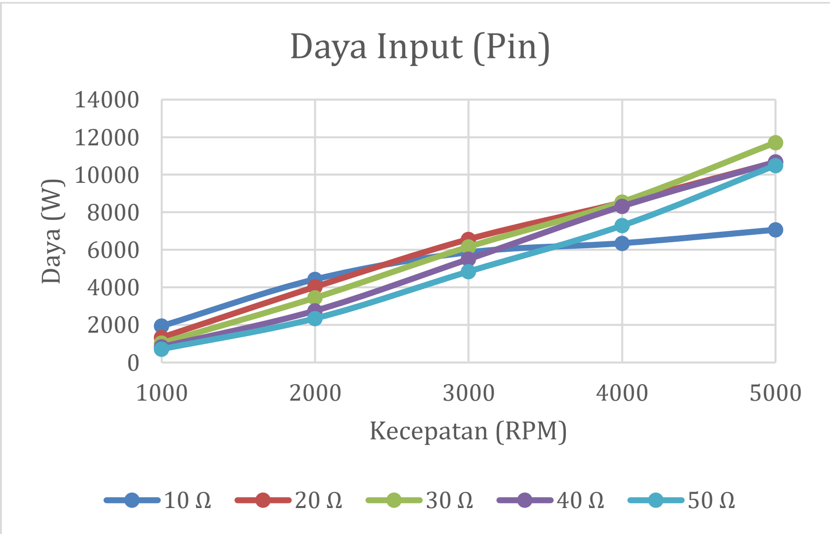

Figure 12. Graph of output power (Pout) with speed variation

After the input and output power data is known, then we can know the efficiency value through the Pin and Pout. to find out we can use the equation, namely:

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$= \frac{1627.689856}{1942.965492} \times 100\%$$

= 88.81%

This calculation is done on all experiments so as to get the data in table 5 and produce a graph like figure 13.

Table 2. Data Efisiensi tiap percobaa

	Effeciency				
	1000	2000	3000	4000	5000
10 Ω	88.81%	91.84%	90.61%	90.73%	92.96%
20 Ω	86.21%	90.15%	92.59%	92.90%	92.07%
30 Ω	85.62%	88.05%	90.06%	92.27%	92.48%
40 Ω	82.61%	85.75%	88.65%	89.63%	91.45%
50 Ω	84.31%	84.89%	86.07%	88.51%	89.12%

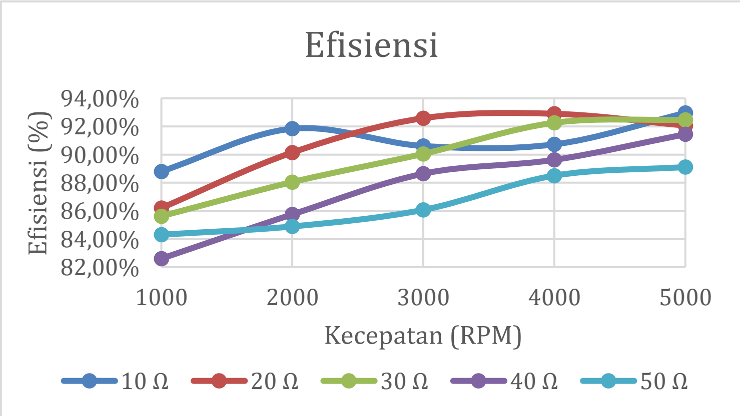

Figure 13: Efficiency graph with variation in speed

In the graph in Figure 13 we can see that each rpm has its own level of efficiency according to the speed given, because speed greatly affects the value of input power and output power produced. The greater the speed given the greater the voltage generated, but the increase in load (resistor) which is getting bigger also affects the decreasing output value, it is caused by a change in load at a fixed rotational speed

4. CONCULUSION

Based on the simulation and analysis, the following conclusions can be drawn. First, the maximum magnetic flux value generated by the Permanent Magnet Synchronous Generator (PMSG) with 12 slots and 8 poles (12S8P) configuration is 0.000927 Wb. Secondly, the average voltage (*Vdc*) generated by the 12S8P PMSG at 1000 rpm without load reached 17.782 V. Third, in the simulation with load, the voltage and current generated have a directly proportional relationship with the rotational speed; that is, both increase as the speed increases. The optimum torque was achieved at a load of 30 ohms with a speed of 5000 rpm. Finally, the generator efficiency shows a varying pattern: the greater the applied speed, the higher the voltage generated. However, the addition of a larger load also affects the output value which tends to decrease. This is due to the change in load at a fixed rotational speed. These findings provide important insights into the performance and characteristics of the 12S8P PMSG under various operational conditions.

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