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Analysis of the Effect of Winding Wire Cross-sectional Area and Rotating Speed on the Efficiency of 18 Slot 16 Pole Permanent Magnet Synchronous Generator

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Abstrak **– The potential of renewable energy in Indonesia is very large with a total of 3,643.0 GW. One of them is wind energy, the huge potential of wind energy which is 154.9 GW is very wasted if it is not optimized as well as possible. The biggest obstacle to utilizing wind potential is low wind speed in some areas in Indonesia. So an effective generation system is needed to produce efficient output. A permanent Magnet Synchronous Generator (PMSG) is very suitable for use in areas of potential low-speed winds because low rotation can produce good efficiency. The output value of the Permanent Magnet Synchronous Generator (PMSG) is currently still low and can still be improved, for this research will analyze the broad influence of the cross-section of the winding wire on the stator on the efficiency of the 18 slots 16 poles Permanent Magnet Generator with rotational speed based on wind speed in Indonesia. Variations were carried out on a cross-sectional area of 0.6 mm^2-3.6 mm^2 winding wire and rotating speeds of 500 rpm, 750 rpm, and 1000 rpm. By using MagNet Infolytica 7.5 software based on Finite Element Method (FEM) to obtain output values in the form of voltage, current, and torque. For efficiency values, data is reprocessed using Microsoft Excel. The results of this study show that the value of efficiency increases. The best efficiency produced when the rotating speed is 500 rpm is 97.04% at a cross-sectional area of 2.6 mm^2 winding wire, for a rotating speed of 750 rpm the efficiency reaches 97.24% at a cross-sectional area of 2.4 mm^2 winding wire and at a rotating speed of 1000 rpm the resulting efficiency is 97.16% at a cross-sectional area of 2.4 mm^2 winding wire.**

Keywords: Wind, Cross-sectional area, rotating speed, PMSG

I. INTRODUCTION

Electrical Energy has become a major need in an effort to improve the quality of life and economic growth in Indonesia. To meet the needs of electrical energy, Indonesia continues to strive to meet the needs by utilizing the available potential. Based on PLN 2021 statistics, the installed electrical energy capacity in Indonesia is 64,553.04 MW and 51.85% still comes from conventional energy [1]. To reduce Indonesia's dependence on fossil energy, the Ministry of Energy and Mineral Resources targets that in 2023 the 35000 MW megaproject will soon be completed by utilizing renewable energy as the main pillar. The policy is also supported by Presidential Regulation No. 4 of 2016 (Article 14) concerning the Acceleration of Electricity Infrastructure, mandating that the implementation of electricity infrastructure acceleration prioritizes the use of renewable energy [2].

The availability of fossil energy is decreasing and the application of fossil energy has an impact on increasing greenhouse gas emissions if it continues to be the main pillar in the generation of electrical energy. The government must immediately move on and switch to renewable Energy [3]. The role of renewable energy must be optimized effectively so that the needs for electrical energy in Indonesia are met. The potential of renewable energy in Indonesia is quite large with a total of 3,643.0 GW and wind energy has the largest potential number 2 with a potential of 154.9 GW. With wind energy generation capacity-optimized by PT.PLN and private parties have only 0.2 GW or 0.1% of the available potential. The lack of utilization of energy potential is caused by economic factors and medium wind speeds in some regions in Indonesia, so optimization is needed in the output value of wind energy generation [4].

Areas with low wind speeds of 3-4 m/s such as Aceh, Lampung, West Java, and other medium-speed provinces [5]. This potential is considered uneconomical if the construction of the power plant system is carried out. Though this potential can also produce electrical energy by maximizing the performance of wind turbines to convert kinetic energy into mechanical energy [4]. The wind speed is directly proportional to the rotation speed [6]. At a wind speed of 3 m / s using the type of epoxy resin blade + fiberglass + coir nacca 4412 can produce a rotating speed of 545.29 rpm. At a wind speed of 4 m/s a rotational speed of 708.9 rpm and at a wind speed of

5 m/s a rotational speed of 928.94 rpm [7]. In addition to the blade, the generator is also a major component in the generation process.

The process of generating wind power energy requires effective components to produce high efficiency. The synchronous generator can work optimally when the efficiency value reaches 90%. For this reason, research is needed to optimize the efficiency value of the generator [8]. A permanent Magnet Synchronous Generator (PMSG) is very suitable for use because with low rotation it can produce good efficiency to overcome areas with low wind speeds in Indonesia [9]. Compared to induction generators, PMSG has a better level of efficiency because there are no excitation losses produced so it is very effective for use in wind turbines[10].

PMSG design has been carried out by previous researchers by testing the rotor and stator to produce the best output. The research will be the basis for this research conducted [11]. In the permanent magnet synchronous generator variation, 18 slots and 16 poles have the additional advantage of low cogging, which is very useful at low wind speeds because it can still produce electricity efficiently [12]. As explained in PMSG's research on rotational speed variations in generators and radial flux designs with load variations in which these variations can support the output value of the generator and affect the generator efficiency value [13]. Variations on PMSG have been done by researchers before. In this study, the efficiency affected by the generator output depends on the flux provided by permanent magnets to produce an induction voltage as generator performance [14]. The design of PMSG with the type of material, iron core, number of windings, surface area, and dimensions of magnets has been carried out by previous studies by producing better current and voltage values in each variation of PMSG [15][16]. PMSG 18 slots 16 poles research has been conducted by previous researchers on the influence of iron core thickness and type and the effect of permanent magnet material on generator characteristics [17]. For further studies on PMSG 18 slots 16 poles where the efficiency is increased by the number of turns and rotation speed with the highest efficiency at a value of 80.9% [18].

The increase in efficiency is influenced by the input power and output power of the generator, where the output power is directly proportional to the voltage produced by the generator. The cross-sectional area is directly proportional to the diameter of the winding wire which also influences the voltage produced as explained in the study on the influence of the wire diameter of the linear generator coil on the performance and characteristics of the generator. The size of the diameter affects changes in voltage and current, including power. Whereas the voltage increases it is also directly proportional to the increase in current [19]. As a support, this research was carried out to see the results of research on the influence of wire diameter and the number of windings where these variations affect the output of current and voltage produced by the generator [20].

Based on the explanation above about the influence of turbines and generators on wind power generation and the broad influence of the winding wire cross-section on the generator output value, this study will analyze the broad influence of the winding wire cross-section on efficiency in the 18 Slots 16 Poles Permanent Magnet Synchronous Generator with the help of the Infolytica 7.5 MagNet application using the Finite Element Method (FEM) for several rotational speeds according to the wind speed in Indonesia to harness wind potential.

II. METHODS

This research will analyze the output value of the permanent magnet synchronous generator after variation, the cross-sectional area of the stator winding wire and rotation speed using the Finite Element Method (FEM) to achieve the highest efficiency. The initial stage of this research is to conduct a literature study from previous research and reading materials with reliable sources to collect data and variables needed for research. The next stage determines the variables to be studied based on the literature review and data that have been obtained. The next stage is designing the PMSG 18 Slot and 16 Pole models with the help of the MagNet Infolytica 7.5 application. The variable in the study will be a variation in the cross-sectional area of the winding wire on the stator with a value of 0.6 mm2-3.6 mm2. Tests will be carried out with rotating speeds of 500 rpm, 750 rpm, and 1000 rpm and for testing needs in the design of PMSG 18 Slots and 16 Poles a loading circuit of 10 Ω is added. The results of the design are simulated with the FEM method, namely solving transient 2d with motion. The data in the simulation is forwarded to Microsoft Excel for manual processing. The last stage is to analyze the results that have been processed and conclude the results of the study. If the simulation does not find the best results, it will be repeated at the stage of determining variables until the best results.

1. Specifications of Permanent Magnet Synchronous Generator

Table 1. Specifications Permanent Magnet Synchronous Generator

Element	**Desciptions**
Number of Slot	18
Number of Pole	16
Dimension	220 mm x 220 mm x 80 mm
Iron Core Material Stator and Rotor	*Carpenter : Silicon Steel*
Magnetic Material	PM 12: Br 1.2 mur 1.0
Winding Material	*Copper*: 5.77e7 Siemens/meter
Air Box and Air Gap Material	*Air*
Magnet Thickness	9 mm
Number of Windings	30

2. Variations of Permanent Magnet Synchronous Generator

Variations in this study are based on the theory below. Where the influence of the winding cross-sectional area on the generator can increase the induced voltage generated. This is caused by an increase in wire resistance resulting in current flowing on the winding wire.

a. Resistance

$$R = \rho \frac{l}{A} \qquad (1)$$

R = Resistance (Ω)
ρ = Resistivity (Ωm)
l = wire length (m)
A= cross-sectional area of wire (m^2)

Based on Ohm's Law, the voltage value is directly proportional to the resistance value. Where the greater the resistance the greater the voltage.

$$V = I.R \qquad (2)$$

V = Voltage (Volt)
I = Current (Ampere)
R = Resistance (Ω)

The cross-sectional area of the winding wire can affect the induction voltage in the generator or induction. When the wire winding on the generator is increased, the induced voltage generated will also increase. This can be explained by Faraday's law and the basic principle of electromagnetic induction. The more wire windings on the generator, the larger the area exposed to magnetic flux, thereby increasing the amount of magnetic flux passing through it and ultimately increasing its induced voltage.

b. Magnetic Flux

$$\Phi = B.A\,cos\theta \qquad (3)$$

Φ = Magnetic Flux (Wb)
B = Magnetic (Tesla)
A = cross-sectional area of wire (m^2)

c. Electromotive Force

$$\varepsilon = -N\,\frac{d\Phi}{dt} \qquad (4)$$

ε = Electromotive Force (Volt)
N = Number of winding
dΦ = Changes in Magnetic Flux (Wb)
dt = Time Change (s)

Table 2. Variations of Permanent Magnet Synchronous Generator

Cross-Sectional Area of wire (mm^2)	Rotating Speed (rpm)		
0.6	500	750	1000
0.8	500	750	1000
1.0	500	750	1000
1.2	500	750	1000
1.4	500	750	1000
1.6	500	750	1000
1.8	500	750	1000
2.0	500	750	1000
2.2	500	750	1000
2.4	500	750	1000
2.6	500	750	1000
2.8	500	750	1000
3.0	500	750	1000
3.2	500	750	1000
3.4	500	750	1000
3.6	500	750	1000

4. Modeling Permanent Magnet Synchronous Generator 18 Slot and 16 Pole

The research begins with designing PMSG 18 Slots and 16 Poles to facilitate design and modeling, it will be assisted by MagNet Infolytica 7.5 software. MagNet Infolytica is designed as a 2-dimensional and 3-dimensional modeling and designing software to assist in solving electromagnetic problems. The components that can be designed in this tool are components that use windings and permanent magnets such as motors, transformers, generators, and so on [21].

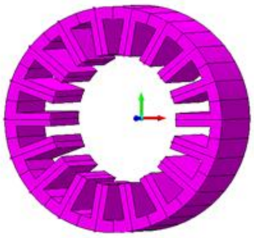

Figure 1. Stator material Carpenter: Silicon Steel and winding copper

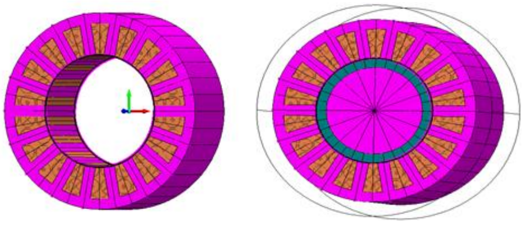

Figure 2. Permanent Magnet Synchronous Generator 18 Slots 16 Poles

This research uses the Finite Element Method (FEM) method. FEM itself means the finite element method which is defined as a numerical technique for solving problems in differential equations. The basic concept of FEM solves a problem by dividing objects into finite small parts (decrepitation). It is this small part that will be analyzed and recombined to complete the object under study [22]. FEM is a method that uses partial differential or partial derivative techniques. The partial differential theory used in this method is Maxwell's equation.

Related theories regarding the characteristics of generators produced based on tests carried out can be explained in the following theories.

a. Voltage

$$\varepsilon = -\frac{\Delta\lambda}{\Delta t} \qquad (5)$$

$\boldsymbol{\varepsilon}$ = Voltage (Volt)
Δλ = Changes to Flux Linkage (Wb)
Δt = Time Change (s)

b. Current

$$I = \frac{V}{R} \tag{6}$$

c. I = Current (A)
V = Voltage (Volt)
R = Resistance (Ω)

d. Torque

$$\tau = F.r \tag{7}$$

τ = Torque (Nm)
F = Force (N)
r = Radius (m)

e. Input Power

$$Pin = \frac{\tau \text{ x } n \text{ x } 2\pi}{60} \tag{8}$$

Pin = Input Power (W)
τ = Torque (Nm)
n = Rotating speed (rpm)

f. Output Power

$$Pout = I \, . \, V \tag{9}$$

Pout = Output Power (W)
I = Current (A)
V = Voltage (V)

g. Efficiency

$$n = \frac{Pout}{Pin} \text{x}100\% \tag{10}$$

η = Efficiency (%)
Pout = Output Power (W)
Pin = Input Power (W)

III. RESULTS AND DISCUSSION

Results of research on variations in wire cross-sectional area and rotational speed with a resistance of 10 Ω. From simulations with the help of the MagNet Infolytica application, researchers get characteristics in the form of voltage, current, and torque. However, for input power values, output power, and efficiency are obtained from manual calculations in Microsoft Excel.

1. Voltage

Table 3. Simulation results on voltage values

Cross-Sectional Area of wire (mm$^{2)}$	Voltage (Volt)		
	500 rpm	750 rpm	1000 rpm
0.6	119.3934	175.1926	225.9628
0.8	123.4691	180.2795	233.274
1	126.0377	183.4025	236.4437
1.2	127.7766	185.5022	238.2656
1.4	129.0307	187.0028	239.4075
1.6	129.9737	188.1229	240.1418
1.8	130.7053	188.9868	240.6167
2	131.2871	189.67	241.1522
2.2	131.7589	190.2211	241.7055
2.4	132.1476	190.6729	242.1512
2.6	132.4721	190.6729	242.5068
2.8	132.7462	191.3632	242.7922
3	132.9797	191.6301	243.022
3.2	133.1803	191.8578	243.2069
3.4	133.3539	192.0534	243.3554
3.6	133.5049	192.2222	243.4738

The table above shows the voltage value that is directly proportional to the variation in the cross-sectional area of the winding and rotational speed. The above results confirm Faraday's law that the amount of induced voltage produced is directly proportional to the rate of change in magnetic flux across a certain area. The rate of change of magnetic flux in the generator is affected by the rotational speed of the magnet in the rotor. In addition, the cross-sectional area of the winding wire can also affect the resistance of the wire and the current flowing in the generator. The greater the cross-sectional area of the winding wire, the greater the resistance. This can affect the magnetic flux generated in the generator and of course, it has an impact on changes in the amount of induction voltage produced by the generator.

2. Current

Table 4. Simulation results on current values

Cross-Sectional Area of wire (mm2)	Current (A)		
	500 rpm	750 rpm	1000 rpm
0.6	11.93934	17.51926	22.59628
0.8	12.34691	18.02795	23.3274
1	12.60377	18.34025	23.64437
1.2	12.77766	18.55022	23.82656
1.4	12.90307	18.70028	23.94075
1.6	12.99737	18.81229	24.01418
1.8	13.07053	18.89868	24.06167
2	13.12871	18.967	24.11522
2.2	13.17589	19.02211	24.17055
2.4	13.21476	19.06729	24.21512
2.6	13.24721	19.06729	24.25068
2.8	13.27462	19.13632	24.27922
3	13.29797	19.16301	24.3022
3.2	13.31803	19.18578	24.32069
3.4	13.33539	19.20534	24.33554
3.6	13.35049	19.22222	24.34738

Based on the simulations that have been carried out, the table above explains the influence of the cross-sectional area of the winding wire and the rotational speed on the current value. Where the cross-sectional area and rotational speed are directly proportional to the value of the current produced. The greater the research variable, the greater the value of the current produced. Of course, it supports the theory of Faraday's law where the cross-sectional area of the winding wire influences the induced voltage produced.

3. Torque

Table 5. Simulation results on torque values

Cross-Sectional Area of wire (mm2)	Torque (Nm)		
	500 rpm	750 rpm	1000 rpm
0.6	-31.196	-44.063	-55.2447
0.8	-32.3841	-45.4464	-57.006
1	-33.1744	-46.3572	-57.6883
1.2	-33.7211	-47.017	-58.0866
1.4	-34.142	-47.5267	-58.354
1.6	-34.4806	-47.9387	-58.5448
1.8	-34.7622	-48.2832	-58.6875
2	-35.0023	-48.5788	-58.8888
2.2	-35.2114	-48.8377	-59.1216
2.4	-35.3964	-49.0681	-59.3302
2.6	-35.5624	-49.0681	-59.5166
2.8	-35.7129	-49.4654	-59.6849
3	-35.8508	-49.6397	-59.8386
3.2	-35.9782	-49.8014	-59.98
3.4	-36.0966	-49.9523	-60.111
3.6	-36.2074	-50.094	-60.2331

Based on the table above explains the torque value on which each variation in the cross-sectional area of the wire winding and rotational speed. The torque value is indeed very influential on the cross-sectional area of the winding wire. Because the cross-sectional area of the wire serves as a conductor, where the greater the cross-sectional area of the winding, the higher the torque value needed. The torque on the generator serves to rotate the shaft on the generator. Based on this, the torque in the generator has a negative value because it is used to rotate while the motor has a positive value because of the power generated to rotate the torque.

4. Input power

Table 6. Simulation results on input power values

Cross-Sectional Area of wire (mm$^{2)}$	Input Power (Watt)		
	500 rpm	750 rpm	1000 rpm
0.6	1633.42	3460.7	5785.216
0.8	1695.627	3569.352	5969.656
1	1737.009	3640.884	6041.101
1.2	1765.632	3692.707	6082.811
1.4	1787.67	3732.736	6110.821
1.6	1805.401	3765.096	6130.796
1.8	1820.143	3792.154	6145.739
2	1832.718	3815.372	6166.82
2.2	1843.664	3835.703	6191.201
2.4	1853.351	3853.798	6213.046
2.6	1862.04	3853.798	6232.56
2.8	1869.924	3885	6250.193
3	1877.145	3898.693	6266.284
3.2	1883.814	3911.392	6281.088
3.4	1890.015	3923.247	6294.804
3.6	1895.816	3934.377	6307.591

The table above shows the input power on the generator. The input power value is influenced by several factors such as generator dimensions, power factor, rotating speed, and torque. The effect of rotational speed on input power and cross-sectional area of winding wire is clearly shown in Table 6. Where the greater the variation in rotational speed and cross-sectional area of the winding wire, the greater the input power on the generator. This is because the rotational speed can affect the incoming mechanical power and have an impact on the torque value as well as on the cross-sectional area of the winding wire can affect the torque value, where in theory it has been explained that torque can affect the input power value in the generator.

5. Output Power

Table 7. Simulation results on output power values

Cross-Sectional Area of wire (mm^2)	Output Power (Watt)		
	500 rpm	750 rpm	1000 rpm
0.6	1469.772	3157.958	5275.43
0.8	1571.618	3345.404	5621.742
1	1637.481	3463.451	5769.533
1.2	1682.674	3544.13	5854.227
1.4	1715.593	3602.451	5907.25
1.6	1740.51	3646.359	5941.215
1.8	1759.931	3680.445	5963.037
2	1775.421	3707.544	5988.49
2.2	1788.007	3729.502	6015.18
2.4	1798.388	3747.568	6036.674
2.6	1807.06	3747.568	6053.791
2.8	1814.382	3775.294	6067.488
3	1820.618	3786.057	6078.469
3.2	1825.97	3795.264	6087.263
3.4	1830.594	3803.188	6094.273
3.6	1834.611	3810.042	6099.814

The output power value in the table above increases with each variation in the cross-sectional area of the winding wire and rotational speed. The increase in the output power value is influenced by the value of the voltage and current generated in magnetic induction where the value increases from variations in cross-sectional area and rotational speed. Because of the influence of these two factors, of course, will have an impact on the output power of the generator. As explained in the related theory of Faraday's law.

6. Efficiency

Table 8. Simulation results on efficiency values

Cross-Sectional Area of wire (mm$^{2)}$	Efficiency		
	500 rpm	750 rpm	1000 rpm
0.6	89.98	91.25	91.18
0.8	92.68	93.72	94.17
1	94.27	95.12	95.5
1.2	95.3	95.97	96.24
1.4	95.97	96.5	96.66
1.6	96.4	96.84	96.9

1.8	96.67	97.05	97.02
2	96.87	97.17	97.1
2.2	96.98	97.23	97.15
2.4	97.03	97.24	97.16
2.6	97.04	97,24	97.13
2.8	97.02	97.17	97.07
3	96.98	97.11	97.01
3.2	96.92	97.03	96.91
3.4	96.85	96.93	96.81
3.6	96.77	96.83	96.7

Based on the graph above, the generator efficiency value displays variations in the cross-sectional area of the winding wire and the rotational speed of the generator. Efficiency is affected by input power and output power, to obtain the value of output power efficiency will be divided by input power and multiplied by 100%. For the efficiency value itself reaches the highest value in a different cross-sectional area at each rotating speed. The cause, of course, is from the output and input power values of each cross-sectional area variation that is influenced by the current, voltage, and torque produced by the generator.

IV. CONCLUSION

After conducting simulations and experiments based on the finite element method (FEM) on a permanent magnet synchronous generator of 18 slots 16 poles with variations in the cross-sectional area of the winding wire and rotational speed based on medium and low wind speeds in Indonesia, the results of efficient values were obtained at rotating speeds of 500 rpm, 750 rpm, and 1000 rpm at PMSG 18 slots 16 poles. At a rotating speed of 500 rpm, the highest efficient value is found in the cross-sectional area of 2.6 mm2 winding wire with an efficiency value of 97.04%. At a rotating speed of 750 rpm, the efficiency value is found in the cross-sectional area of 2.4 mm2 winding wire with an efficiency value of 97.24% and at a speed of 1000 rpm, the highest efficient value is found in the cross-sectional area of 2.4 mm2 winding wire with an efficiency value of 97.16%. So in conclusion, low and medium wind speeds in Indonesia can also produce high efficiency with the help of effective turbines and generators.

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