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Analysis of Back Electromotive Force Voltage and The Effect of Geometry Changes in Teeth Stator Quarter PMSG 12S8P Model using Finite Element Method Software

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Abstract: *There is a need of creating new energy resource which is clean and environmental friendly, because electricity now a day still consume a lot of consumable fossil resource. Wind turbine could become the option of alternative renewable energy resource. Indonesia characteristic is unique because there is a gap in the rural area which is not reached by electricity but have a highly land potential to get a wind energy. Windmill power plant system need a synchronous generator. Synchronous generator is a machine to convert mechanical energy to become electrical energy. Mechanical energy could be formed using wind, water, gas and another fluid material resource. Good design of generator make an energy conversion become optimal. Generator performance could be simulated and planned using a special software. FEM is a software that very useful to simulate generator model, material, currents, voltage, and efficiency. This research has been done on PT. Lentera Bumi Nusantara which is using Permanent Magnet Synchronous Generator. The steps in designing a generator start from knowing the shape of the design and the materials to be used. The conclusion from this research is that the wider the teeth of the stator, the higher the resulting voltage, starting from a variation of 5 mm resulting in an output DC voltage of 12.2847 volts. The voltage continues to rise when the width of the teeth stator increased to 10 mm at 18.5749 volts. The increase of the teeth's width could expand the magnetic flux path that enters the stator, so there is larger flux that would be captured and converted to voltage.*

Keywords—Windmill, Generator, Teeth, Efficiency

1. Introduction

Electricity and renewable energy is take a part in the role of industrial and technological advancement both on a small scale to a large scale. The power consumption in every area in Indonesia is varies and uneven for each consumer. Some area need a lot of electric power, some area is not reached by electricity distribution. The need for electrical load need to be maintained so a large capacity power plant and distributed power plant need to be provided [1].

Most of the power plant in Indonesia comes from PLTU (Steam Power Plant). PLTU needs a turbine that require a very large steam pressure from burning coal. Renewable energy could come from PLTA (Hydro Power Plant), PLTB (Wind Power Plant), PLTMH (Micro-Hydro Power Plant), and also PLTS (Solar Power Plant). Renewable energy sources have advantages, such as environmentally friendly and the unlimited resource that could come from potential distributed area in Indonesia. In the future, it will be very good if there is a new finding of renewable energy that could support the electricity availability.

One of the potential renewable energy power plant that exist in Indonesia is PLTB. Indonesia as a country that is crossed by the equator has a great opportunity to get wind sweeps throughout the year, namely the west monsoon winds and the east monsoons [2]. PLTB need a synchronous generator to convert wind to electrical energy. Generator need to be modelled first. Modelling is to design the variation of teeth rotation according to the rotor and stator part. Synchronization of electrical and magnetic field could create the optimal flux that could generate maximum power supply [3].

PLTB uses a kind of permanent magnet synchronous generator. The synchronous generator needs a modelling of the shape of the generator and the composition of material to be used for rotor and stator parts. This modeling is very important, because it could make the generator have the required voltage output value. Based on that background, this research tries to design an optimal permanent magnet synchronous generator model to determine the back EMF and kinetic energy output voltages using Finite Element Method based software [4].

2. BACKGROUND

2.1 Wind Turbine

Wind Turbine is a tool for converting wind energy into mechanical energy. Wind energy itself is the result of half the density of air (ρ) with the cross-sectional area of the wind turbine (A) and the power of three of the wind speed (V3). The little difference in wind speed could make the different of energy generated become larger. The use of wind turbines is divided into several scales of height and capacity, such as large, medium, small and micro scales. The bigger the scale, the greater the capacity that can be produced by a wind turbine [5].

Currently the construction of wind turbines still cannot compete with fossil based power plants. Wind turbine is still being developed because in the near future humans will be face with the problem of a shortage of non-renewable natural resources as a basic material to generate electricity. Wind turbines can be divided into *two* main categories, namely: horizontal axis wind turbines and vertical axis wind turbines [6].

The main parts of a wind turbine are a generator, blade, cone, fin and tail [7]. The TSD-500 is a horizontal axis wind turbine with three propeller blades. The efficiency level of TSD-500 is 40%. This turbine starts rotating at a wind speed of 2.5 ms and starts producing electricity at a wind speed of 3 m / s. The maximum power that can be generated by a wind turbine is 500 Watt peak (Wp) at wind speeds around and above 12 m/s [8]. This tube can make a constant wind speeds of 33 m/s.

The turbine blades are made from pine wood. Apart from being light and strong, this material is easy to find in Indonesia (for local production development) and is also relatively affordable compared to other materials. The TSD-500 wind turbine is installed at a height of 4 to 6 meters above ground level [9]. This is what makes the turbine installation process easier to learn and safer.

The blade rotation makes the generator rotate and produces a 3-phase AC voltage which represents the wind direction vector, which is u, v, and w. Then it flows to the controller (security technology and energy conversion) and the output of this controller is DC voltage (it has been converted from AC to DC because the energy storage medium is in the form of DC). After that, it is streamed back to the data logger for data recording and then stored into the battery or accumulator. Before being used to loads (AC electrical equipment), this stored energy must first be converted through an inverter (DC voltage to AC).

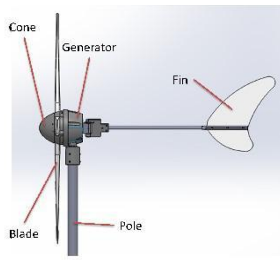

Fig. 1. *Wind Turbine TSD-500*

2.2 Generator

A generator is a device that can convert mechanical power into electrical energy. Mechanical power can come from heat, water, steam, and another fluid. The electrical energy generated by the generator can be AC (alternating electricity) or DC (direct electricity) electricity. This depends on the construction of the generator used by the electric power plant.

Generators are closely related to Faraday's law. The Faraday’s law says that if a piece of electrically conducting wire is in a changing magnetic field, then the wire will form an Electric Motion Force. The voltage drop is caused by the resistance in the conductors or the connections leading to the electrical load. There are many causes for resistance in the conductor path. The voltage drop could cause by mechanical energy that makes the rotor in the generator rotate also makes the magnet move.

2.3 Magnetic Field

The effectiveness of magnetic fields in use is often determined by the magnitude of the magnetic flux density, the wider magnetic flux, the lower the density and the weaker the field intensity. On a narrow surface the magnetic flux density will be strong and the field intensity is higher. Magnetic flux density (B) or magnetic induction is defined as the flux per unit cross-sectional area. The unit for magnetic flux density is Tesla (T).

There is H beside B, the magnetic intensity, which is often called the magnetic field. In a vacuum, B and H are proportional to each other. The SI unit for measuring the intensity of the magnetic field (H) is the ampere per meter (A / m). The magnetic intensity at a magnetic field point is the magnitude of the force at a unit of polar strength at that point in the magnetic field mm is the polar strength that causes the magnetic field in Ampere-meters [10].

The basic concept of magnetic flux is the magnetic field which is described as the vector B. And magnetic flux (Φ_m) is the size or amount of magnetic field (B) that passes through a certain cross-sectional area. The unit of magnetic flux is weber (Wb, Weber derivative of volt-second). In a two-dimensional image represented by curved lines. The curved lines are known as flux lines which indicate the direction and magnitude of the magnitude B. The direction of the line shows the direction of B, while the gap between the lines shows the size of B, that is, the smaller the gap from one line to another, the greater the value of magnitude B [11].

Flux Linkage is very important in considering Faraday's law, which states that the time variation of the Flux Linkage induces a voltage. The concept of Flux Linkage will be important when we analyze inductors as circuit elements. We could consider a simple one-turn coil of wire with a current passing through it in terminology of flux linkage. The current in the wire creates a magnetic field, which can be represented by magnetic field lines.

2.4 Permanent Magnet Synchronous Generator

This permanent magnet type generator is a generator whose excitation field is generated by a permanent magnet instead of a coil, so that the magnetic flux is generated by a permanent magnetic field [12]. These generators have significant advantages, have attracted the interest of researchers and are commonly used in wind turbine applied in PLTB. Permanent magnet synchronous generator is a rotating electric machine with a classic 3-phase stator which is like an induction generator in general. Permanent magnets can be attached to the surface of the rotor or embedded in the rotor.

2.5 Finite Element Method

FEM is a computational method with the concept of breaking the calculated area into smaller areas and then calculating the various parameters one by one in each area. This Finite Element Method (FEM) based software can also perform various analyzes of the ability and performance of electromechanical machines, from generators, motors, magnetic levitation, transformers, induction heating, and others [13].

3. Experimental Setup

3.1 Geometry Modeling of Quarter PMSG 12S8P

Modelling simulation of ¼ PMSG 12S8P is performed on FEM-based software, the fixed materials used are shown in the Table 1.

Table 1: Quarter PMSG Modelling

Name	Material
Air Box	***AIR***
Coil	***Copper 5.77e7 siemens/meter***
Air Gap	***AIR***
Permanent Magnet	***4.914***
Stator. Rotor Core	***Carpenter: Silicon steel***

The Figure 2 shows quarter generator design model in PT. Lentera Bumi Nusantara with the number of conductor turns of 12 and 8 pairs of magnets (12S8P). The 12 conductor turns are part of the coil on the coil with 12 parts and 8 pairs of magnets that are part of the rotor and the magnet consists of 8 magnetic poles N and S.

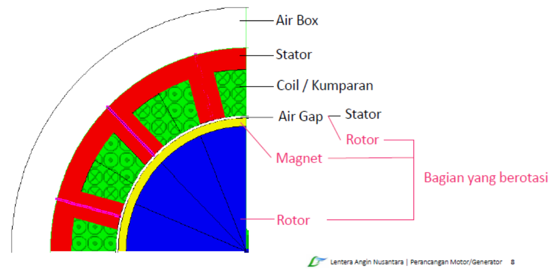

Fig. 2. *Solid Model*

3.2 Flux Linkage

Flux linkage is the induction of electromotive force (GGL) on the coil. Flux linkage could be modelled in "MagNet" software. The data could be save in excel format. Each experiment uses the mechanical angle and electrical angle parameters to get the value of the flux linkage. Flux linkage model showed in Figure 3.

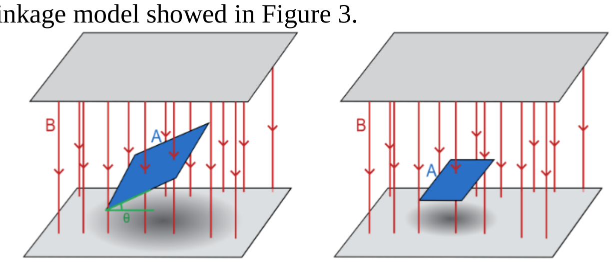

Fig. 3. *Flux Linkage*

In this research, there is variation at dimensions of the teeth width to obtain the flux linkage which is processed to obtain the value of the one coil phase voltage, four coil phase voltages, inter-phase voltages, and the average output DC voltage. The simulation done in the quarter model PMSG12S8P with wide variations of teeth, which is 5 mm, 10 mm, and 15 mm.

3.3 Variations with a Teeth Width of 5 mm

In the variation of the width of the teeth 5 mm on the generator model, it takes three numbers of teeth, each of the teeth is 20 degrees, so that in the quarter model there are 3 teeth. Whereas in the full model, there are 12 teeth per slot according to the name of the PMSG 12S8P generator.

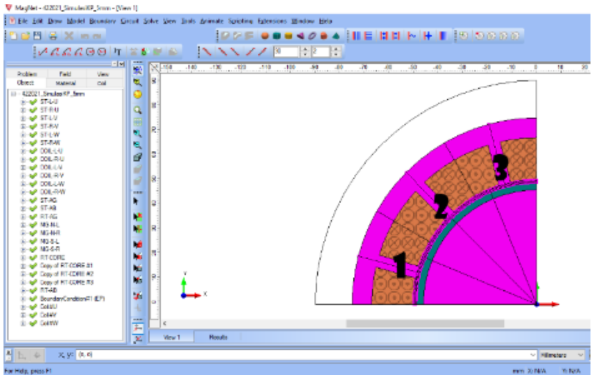

Fig. 4. *Solid Model*

In Figure 4 there are symbols of the stator section in the generator design; In part 1 there are ST-LW and ST-RW (Stator section W phase), section 2 has ST-LV and ST-RV (Stator section V phase), section 3 has ST-LU and ST-RV (Stator section U phase)), which can be edited in the tools section according to the symbol.

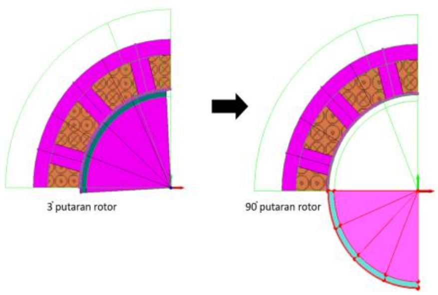

Fig. 5. *Rotor Rotation Model*

When the specifications for the magnet had been determined, the experiment was then carried out by rotating the rotor per-3° 31 times like in the Figure 5. Flux linkage value is described in the Table 2. From the Table 2 could be drawn in the Figure 5.

Table 2: Flux Linkage

Number	Elevation Angle	Flux Linkage		
		U	V	W
1	0	0.0038	0	-0.038
2	12	0.0035	0.0011	-0.1934
3	24	0.0028	0.0021	0.0002
.		.	.	.
.		-.	.	.
31	360	0.0038	0	-0.038

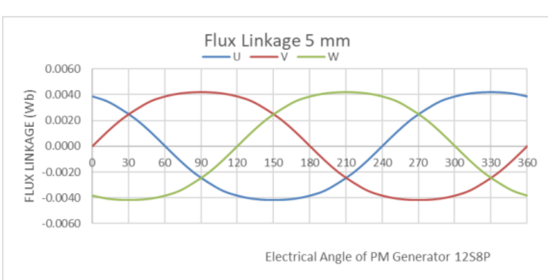

Fig. 6. *Flux Linkage graph*

Figure 6 shows that the flux linkage has a different value at each rotating position, it is influenced by the position of the magnetic poles. This is affect magnetic poles when generating a magnetic field which then received by the stator slot to be passed through the coil per phase. Figure 6 is the graph come from the data in Table 2. The y-axis is the height of the wave in Weber units (Wb) and the x-axis is the change in rotor rotation. When the position of the rotor is in 0 ° condition, the resulting wave height of coil U = 0.0038 Wb, coil V = 0 Wb, and coil W = -0.0038 Wb. When the rotor position changes in 90 ° condition, the resulting waveform of coil U is 0.0038 Wb, coil V is 0 Wb, coil W is -0.0038 Wb. Furthermore, from this value we are able to find the value of the phase voltage in each coil with the equation (Un-Us) / t. The result of simulation showed in Table 3. The graph of the Table 3 shown in Figure 7.

$$Phase\ Voltage\ of\ One\ Coil = \frac{Un - Us}{t} \quad (1)$$

Un = the value of linkage flux in n experiments Us
Un = the flux linkage value after n experiments
t = times to rotate every 3 ° (t = 0.0005 s)

Table 3: Flux Linkage

Number	Phase Voltage of One Coil		
	U	V	W
1	-0.7496	2.1883	-0.4617
2	-1.2738	1.9473	-0.1934
3	-1.5301	1.5303	0.0002
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31	-0.7466	2.1888	-0.4652

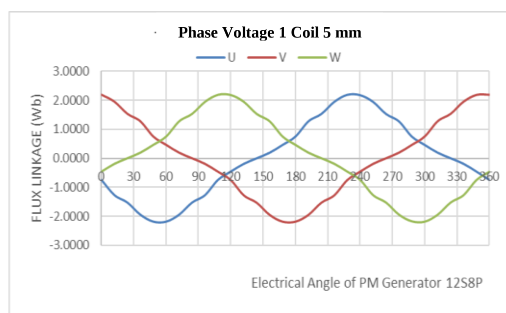

Fig. 7. *Phase Voltage of One Coil Graph*

Figure 7 shows that the voltage per phase of one coil is obtained from the calculation (Un-Us) / t. When the position of the rotor is in 0° condition, the resulting wave height of coil U = -0.7496 V, coil V = 2.1883 V, and coil W = -0.4617 V. When the rotor position changes in 90° condition the resulting waveform is for coil U = -7.6873 V, coil V = -0.0001 V, and coil W = 7.6872 V. Then the value at the phase voltage 1 coil can be found the phase voltage 4 coil, with the following formula.

$$Phase\ Voltage\ of\ 4\ coil = 4(Phase\ voltage\ of\ 4\ coil) \quad (2)$$

Phase Voltage 4 Coil 5 mm

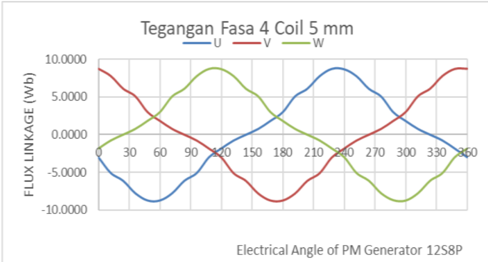

Fig. 8. *Phase Voltage of Four Coil Graph*

Figure 8 shows a calculation of four coils arranged in series, the calculation is formulated by the phase voltage of one coil multiplied by four, according to the number of coils per phase. The graph above describes the phase voltage resulting from the 3mm variation of the turns in phases U, V, and W. It can be seen that the voltage in each phase is four times that of the phase 1 coil voltage. This is because the voltage being measured is the voltage from the series results of the four coils. Then from these results can be found the stress between the phases with the formula.

$$Voltage\ of\ U - V = Phase\ voltage\ 4\ coil\ (U - V) \quad (3)$$

$$Voltage\ of\ V - W = Phase\ voltage\ 4\ coil\ (V - W) \quad (4)$$

$$Voltage\ of\ W - U = Phase\ voltage\ 4\ coil\ (W - U) \quad (5)$$

Table 4: Voltage between Phase

No	Elevation Angle	Phase Voltage (Volt)			DC Voltage
		U-V	V-W	W-U	
1	0	-11.7519	10.6004	1.1516	11.7519
2	12	-12.8843	8.5627	4.3215	12.8843
3	24	-12.2414	6.1204	6.1210	12.2414
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.	.	.	.	.	.
31	360	-11.7415	10.6160	1.1254	11.7415

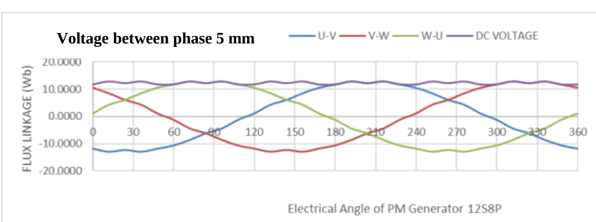

Fig. 9. *Graph between Phase Voltage*

Figure 9 that the value of the inter-phase voltage and DC voltage for each rotation of the rotor has been obtained, the calculation is obtained from the formula (3), (4), and (5). From Figure 9, it can be seen that the resulting inter-phase voltage is greater than the four coil series phase voltage. This is in accordance with the line-to-line voltage formula.

$$Vll = Vln\sqrt[2]{3} \quad (6)$$

From the three V line to neutral data, it can be taken the value of the voltage or DC voltage, which is the largest value of each V line to line. The average DC voltage for this variation is 12.2847 volts, so the electromotive constant (EC) value could be derived from this formula. The EC value for the 5 mm variation is 0.01228.

$$EC = \frac{Averge\ DC\ Voltage}{RPM} (7)$$

In the variation of the teeth width of 15 mm on the generator model, 3 numbers of teeth are needed, each of the teeth is 20 degrees, so that in the quarter model there are three teeth. Whereas in the full model there are 12 teeth per slot according to the name of the PMSG 12S8P generator. The average DC voltage for this variation is 18.5749 volts which is higher than in the variation of 10 mm. The EC value for the 10 mm variation is 0.0186. The average DC voltage for this variation is 22.5025 volts which is higher than in the variation of 10 mm. The EC value for the 10 mm variation is 0.0225.

3.4 Comparison of Output Voltage Value for each Variation

From several simulations of several variations, by widening the dimensions of the teeth from the sizes of 5 mm, 10 mm, and 15 mm, the respective output DC voltages were obtained as in the Table 5.

Table 5: Comparison of Voltage Value for each Variation

No	Variasi lebar teeth (mm)	Tegangan DC (V)	KE
1	5	12.2847	0.01228
2	10	18.5749	0.0186
3	15	22.5025	0.0225

Table 5 shows that the wider the teeth of the stator, the higher the resulting voltage, starting from a variation of 5 mm resulting in an output DC voltage of 12.2847 volts, the voltage continues to rise to a point on the width of the teeth stator 10 mm at 18.5749 volts. After that, when the width of the teeth stator dimensions is increased to 15 mm, the resulting voltage increases to the highest point, which is 22,5025 volts. The voltage at the 15 mm variation increases because the increase in the width of the teeth per slot will expand the magnetic flux path that enters the stator, so that more flux will also be captured and converted to voltage.

4. Conclusion

1. In the simulation of the generator 12S8P with quarter model, the width of the stator teeth is very influential on the efficiency value of the generator design.
2. For the stator material used in the 12S8P with quarter model, the material that has been simulated is Carpenter which is silicon steel
3. For modeling quarter model PMSG 12S8P used variations in the width of the teeth 5 mm, 10 mm, and 15 mm. The three variations have the same iron material, but the output DC voltage of each variation is different, when the 5 mm variation

of the resulting voltage is 12.2847 volts, the 10 mm variation is 18.5749 volts, and the 15 mm variation is 22.5025 volts.

4. In modeling quarter model PMSG 12S8P model with three variations, which is 5 mm, 10 mm, and 15 mm, produces different stresses. At 5 mm variation the stress is lower than 10 mm variation. Then at 15 mm variation, the stress is higher than 10 mm variation. This is because the wider the teeth dimension, the more flux will be captured by the stator.

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