IOP Conference Series: Materials Science and Engineering

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To cite this article: S S Wibowo *et al* 2021 *IOP Conf. Ser.: Mater. Sci. Eng.* **1073** 012031

Finite element modeling and analytic algorithm for electromagnetic performance of Permanent Magnet Synchronous Generator (PMSG) 24 Slot 16 poles from modification of induction motor 0, 75kw 3 Phase

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Abstract. Modification of the induction motor into a permanent magnet synchronous generator is to put a permanent magnet on the squirrel cages stator to generate the magnetic pole as a replacement for the electromagnet pole produced at a separately excitation of the conventional synchronous generator called the Permanent Magnet Synchronous Generator (PMSG). The purpose of this research is to design PMSG by modification of induction motors into permanent magnet synchronous generator with 24 slots 16 pole by using radial flux and utilizing stator. This research is a software-based FEM (Finite Element Method) for design and the magnetic Material used for permanent magnet synchronous generators is Neodymium Iron Boron (NdFeB). The PMSG on this design obtains the back EMF constant for its half-cycle of 4.902 rad/s and gets a voltage of 191.455 Vdc at 375 rpm speed and when given the loading of 100 Ω at 375 rpm speed produces a voltage of 176.73 Vdc, the current of 1.77 A and the output power is 313.24 Watt with efficiency reaching 85%. The PMSG modelling is done to have a specification of 24 slots 16 poles, changes the the characteristic Induction motor with synchrounous speed of 1500 rpm becomes as low as 375 rp. So This PMSG modification can be used as wind turbine or microhydro power palnt with low speed prime mover energy.

1. Introduction

A permanent magnet synchronous generator (PMSG) is a generator where excitation of the magnetic field on the stator is provided by a permanent magnet instead of a coil that provides an electromagnetic field. Synchronous terms refer to the fact that the rotor and magnetic field rotates at the same speed, as the magnetic field is generated through a permanent magnet mechanism that is mounted shaft and induced current into a fixed or stationary armature. The Use of PMSG are the majority source of electrical energy. They are commonly used in Wind Turbine or Micro Hydro Power Palnt. Because it doesn't need power source of DC supply for excitation

Modification of the induction motor into a permanent magnet synchronous generator is to put a permanent magnet on the squirrel cages stator to generate the magnetic pole as a replacement for the electromagnet pole produced at a separately excitation of the conventional synchronous generator called the Permanent Magnet Synchronous Generator (PMSG). Using a permanent magnet on the rotor will reduce weight, as the rotor construction from PMSG is smaller than the synchronous generator construction with the rotor from the excitation coil, which is one of the advantages of permanent magnets.

2. Theoritical background

2.1. Permanent Magnet Synchronous Generator (PMSG)

The Permanent Magnet Synchronous Generator (PMSG) is a generator whose excitation field is generated by permanent magnets instead of coils so that magnetic flux is produced by a permanent magnetic field [1,2]. This Generator has significant toughness, attracting researchers and is usually used in wind turbine applications [3-6].The permanent magnet synchronous generator is a rotating electric machine with a 3-phase classic stator that is like an induction Generator in general. Permanent magnets can be mounted on surfaces or embedded in Rotornya.

The permanent magnet synchronous generator (PMSG) based on the wind turbine can be easily connected to the grid via back-to-back converters. The PMSG has shown high efficiency in power enhancement and excellent performance to extract maximum power from the wind [3,4,6]. Low speed wind generators have a problem with cogging torque that could be improved via pole and slot. The small scale wind power dan microhydro power applications need a cost effective and mechanically simple generator for serving as a reliable energy source [6-8].

2.2. Magnet Permanen Noedymium (NdFeB)

Karakteristik magnet permanen yang paling tinggi saat ini adalah Neodymium Iron Boron (NdFeB), yang memiliki nilai produk energi maksimum sampai dengan 400 kJm3. Sedangkan NdFeB bonded memiliki nilai produk energi maksimum sampai dengan 200 kJm3. Neodyum Iron Boron (NdFeb) merupakan Bahan magnetic yang paling baik karena mempunyai densitas fluksi yang besar [1,2,4].

2.3. Buried magnets

In this configuration the magnets are put inside the rotor and therefore it is referred to as Interior Permanent Magnet (IPM) machine. There are many different ways in achieving interior magnet configuration. The magnets can be magnetised in radial direction as well as circumferential direction. The thickness of iron bridges between the magnets has to be designed carefully to avoid saturation. Again, the inductance in quadrature axes is different from that in direct axes direction..

2.4. Design considerations

For PMSG Axial flux coreless PMSG is regarded as the suitable generator for small turbine because of its simplicity of design and manufacture. The absence of cogging torque for coreless design eliminates any magnetic pull between stationary and rotating parts [3]. Most of the axial flux machines have two sided rotor configuration rather than the single sided rotor to balance the axial forces [4]. Coreless design reduces the mass and increases the efficiency as compared to the conventional design [5].

Generally, in axial flux machines length of the machine is much smaller compared with radial flux machines. Their main advantage is high torque density, so they are recommended for applications with size constraints especially in axial direction [9-11].

2.5. Analytic algoritm of PMSG design

The mathematical formula of the generator design is the basic formula for determining the value of some parameters that will be known on the Generator.

2.5.1. Calculation of rotor dimention. Calculating rotor dimensions is performed to determine the installation of magnets and water gaps to be used [12].

2.5.2. Calculation of magnetic fields. The size of the magnetic flux that goes through a field and the area of the magnetic field that will arise in the generator to obtain the maximum magnetic field.

2.5.3. Calculation of number of turn on coil. The voltage produced by the generator is very influenced from the number of turns on a coil. There must be calculations and techniques to wind a coil so that the resulting voltage is the highest result.

2.5.4. Calculation of induced voltage. In addition to magnetic flux, other factors determining the induction voltage are the winding, frequency, number of slots, and the number of phases. The calculation of induction voltage should also be adjusted with construction to be designed [13,14].

2.5.5. Calculation power and torque. The torque obtained will be a representation of the performance of the generator and will be related to the amount of input power from the generator. The power of a generator depends on the angular speed. The amount of angular speed is biased from the speed value of a generator's rotary speed. The amount of output power from the generator is worth the voltage and current [12].

$$P = D^2 L \cdot (0.5\pi^2) K_w \cdot N_s \cdot B_g \cdot ac \cdot \cos\varphi$$

Output power is the power generated by the generator in the form of electrical power. For the output power generated is

$$P_{out} = \sqrt{3} E_{ph} \cdot I_{ph} \cdot \cos\varphi$$

2.6. *Finite element modellling*

2.6.1. Inisialisasi dan desain geometri. Initialization and geometric design are one of the steps to provide naming and determination of materials used against the components in the generator as well as providing a thickness size for each of these components. Initialization and geometry design covers all parts of the generator components until nothing is notinialized. If something is not initialized, then the design will not be simulated. The components that need to be initialized for a quarter of the parts, namely initialization and geometric design of stators, rotors, magnets, coils, airgap stators, rotors, airboxes, and shafts [9,10,15-17].

2.6.2. Determination of Mesh. Infolityca magnet software is a software based on Fenite Element Method (FEM) [15,17,18]. FEM is a method used to solve problems about complex electromagnetic fields, so it is able to be solved by analysis models especially in parts related to the nonlinear properties of materials. This method essentially discretes the cross-section of the machine into small areas or volumes called fenite elements or meshes [19,20].

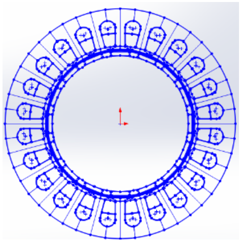
2.6.3. The boundary layer. The boundary layer is a tool on infolityca magnet software, where it is used when designing a generator 1/4 or 1/2 shape, of the full shape (360) used to reflect back the part of the generator as if in part 1/4 or 1/2 of the other part there is still the same part, so that the design of the motor can be simulated by rotating the rotor with a designated angle. Figure 6 is the giving of a boundary layer on the part of the generator [18-21].

3. Experimental dan design metodhology

3.1. *Geometrical specification of induction motor*

The induction motor to be modified into permanent magnet generator is using 3 phase induction motor with 24 slot 16 pole. The induction Motor has the following geometry dimensions in table 1:

Table 1. Dimensiions of Induction Motor



Number of slot	**-**	**24**
Diameter of outer stator	mm	121,40
Diameter of inner stator	mm	76,55
Rotor Diameter	mm	75,55
Length of rotor	mm	90
Hight of Umbrella	mm	20,5
Distance between slot	mm	6,51
Width of teeth	mm	8,10
Air gap	mm	1

3.1.1. Material data of iron core. Iron core material used in an induction motor or commonly called electrical steels is a material chosen because it has a high permeability value of materials, in which case it can increase magnetic flux density. The Material used in the induction motor is M800-50A steel. Specifications Material M800-50A steel as follows in table 2.

Table 2. Specification of iron core material.

Grade	Thickness (mm)	Density (Kg/dm^3)	Resistivity (μ Ω cm)	Core Loss (W/Kg) at 50 Hz		Magnetic Flux Density (T)	
				1,0 T	1,5 T	2500A/m	5000A/m
M800-50A	0,50	7,80	23	3,60	8,00	1,60	1,70

3.2. Analytical Algoritm on PMSG Design

In modelling of conversion from induction motor into PMSG, there are calculations based on the references from books and journals to obtain the value of the size and geometry of the generator. For the initial stage required values of the initial parameters as we want (table 3).

Table 3. Initial parameter of design.

Kecepatan Putar Rotor,$\boldsymbol{n_s}$	**375 rpm (6,25 rps)**
Medan Magnet Relatif, $\boldsymbol{B_r}$	1,2 T
Intensitas Magnet, $\boldsymbol{ac}$	12000 A/m
Faktor Belitan, $\boldsymbol{k_w}$	0,945
Faktor Daya, $\boldsymbol{\cos\varphi}$	0.85

3.2.1. Combinations of slot and pole. To determine the number of slots and poles to be used in general stator refers to the dimensions of the induction motor is 24 slots. For pole selection to be used based on the desired working frequency of the generator, the 50 Hz is then calculated using the following equation:

$$Np = \frac{120.f}{n} = \frac{120.50}{375} = 16\,Pole$$

So the number of Poles that get from the calculation above is 16 pole. After gaining the number of slots and pole is 24 slots 16 pole, the next stage calculates the slot degrees (θ_s) and degrees pole (θ_p).

$$\text{Number of slot } \theta_s = \frac{(2.\pi)}{N_s} = \frac{(2.180)}{24} = 15°$$

$$\text{Number of pole } \theta_p = \frac{(2.\pi)}{N_p} = \frac{(2.180)}{16} = 22.5°$$

3.2.2. Calculation of rotor dimensions of PMSG. The rotor used in PMSG is the rotor of the induction motor. The rotor has a diameter of 79.55 mm with Δ = Gap (mm) gap in equation 2.4 How to calculate rotor diameter:

Diameter of Rotor (mm) $D_r = D - 2 \cdot \delta = 76{,}55\,mm - 2 \cdot 1mm = 74{,}55\,mm$

So the required rotor diameter is 77.55 mm. The diameter will be reduced again by the magnetic dimension because the rotor will be paired with 3 stacked permanent magnets with a thickness of 2 mm. so that the rotor diameter becomes 68.55 mm after the grinding.

3.2.3. Magnetic fluks calculation of PMSG. Calculations fluks that flow on the magnet from the magnetic Pole from north to south by passing through air gap between the rotor and stator. The first step to calculate the polar area of the magnet. With a dimension of 3 stacked with each magnet measuring 30 mm x 10 mm x 2 mm, which has 16 pieces and a rotor diameter of 68.55 mm, it can be measured around the Rotor as follows:

$$\text{Circumference of rotor } K_r = \pi D_r = 3.14 \cdot 68{,}55 = 215{,}247\ mm$$

Then Caclculate the circumference to be magnetized :

$$K_{ri}\% = \frac{\pi D_r - D_f\ N_{Df}}{\pi\ D_r} \times 100\% = \frac{3{,}14 \cdot 68{,}55 - 6 \cdot\ 16}{3{,}14 \cdot 68{,}55} \times 100\% = 55\ \%$$

The percentage of magnetized area is 55% then the area of magnetic field is :

$$\text{Magnetic field area (m2) } A_{magn} = (p_m \cdot w_m)2 \cdot K_{ri}\% = (30 \cdot 10\,)2 \cdot 0{,}55 = 330\ mm^2 = 0.00033\ m^2$$

Type of magnet used is NdFeb N35 (Neodymium Iron Boron) This magnet has maximum energy product (BHmax), up to 440 kJ/m3 and relative magnetic field Br 1.2 Tesla, as well as the air gap 1mm then the calculation of magnetic field as follows:

$$\text{Maximal magnetic field (T) } B_{maks} = B_r \frac{l_m}{l_m+\delta} = 1.2\ \frac{2}{2+1} = 0{,}8\ T$$

Thus , the maximum magnetic field on one magnet is 0.8 T and at 3 stacked magnetic field maximum value of the magnetic field to 2.4 T. With maximum magnetic field = 2.4 T and the magnetic polar value of the magnet Amagn = 0.00033 m2 Then the Φ magnetic flux value can be calculated as follows:

$$\text{Magnetic Fluks (Wb) } \Phi = B_{maks}\ A_{magn} = 2{,}4 \cdot 0.00033 = 0.000792\ Wb$$

3.2.4. Calculation of number of coil. In the calculation of the number of coil, the voltage is assumed E_{ph}= 84 Vac, for magnetic flux that has already been calculated then Φ = 0.000792 Wb, because the number of slots and pole used is 24 slots and 16 pole with speed 375 rpm and frequency value f = 50 Hz, then the number of coil can be calculated as follows:

$$\text{No. of coil per winding } N_c = \frac{E_{ph}}{4{,}44 \cdot f \cdot \phi \frac{N_s}{N_{ph}}} = \frac{84}{4{,}44 \cdot 50 \cdot 0.000792 \cdot \frac{24}{3}} = 59.7\ coil$$

For proses *rewinding* , the number of coil is rounded up to 60 coils.

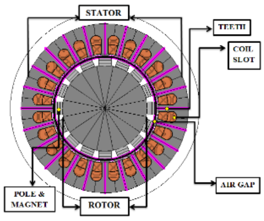
3.2.5. Calculation of generator power. The active Power produced by generator can be calculated as follows:

$$\begin{aligned} P &= D^2 L \cdot (0{,}5\pi^2) K_w \cdot N_s \cdot B_g \cdot ac \cdot \cos\varphi \\ &= 0{,}07655^2 \cdot 0{,}04485(0{,}5\pi^2)0{,}945 \cdot 6{,}25 \cdot 1{,}2 \cdot 12000 \cdot 0{,}85 = 94\ Watt \end{aligned}$$

3.3. Finite element modelling of PMSG

Modeling and determination of the material type used in each component of the generator is made using Finite Element Software based on Infolytica MagNet Software. The composed components of the magnetic permanent synchronous generator consist of a airbox, airgap, stator, rotor, magnet, coil, and shaft. Each component will be given material as in Table 4 as follows.

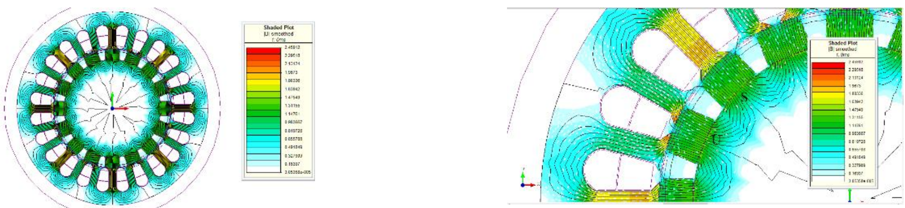
Table 4. Material for each component of PMSG.



COMPONENT	MATERIAL
Air box and *Air gap*	*Air*
Coil	*Copper:5.77e7 Siemens/Meter*
Magnet	*Neodymium Iron Boron: type N35*
Rotor	M800-50A *steel*
Stator	M800-50A *steel*
Shaft	*Air*

The design results will then be simulated in order to obtain the characteristics of the PMSG. on Infolityca MagNet software can be seen in Figure 1.

3.3.1. Modelling simulation of PMSG. Before simulating a PMSG model There are several steps to be performed i.e. setting simulation parameters such as motion creation or adjusting which parts will be rotated at the specified speed and time. The results of magnetic field distribution in the form of magnetic field direction and also flux lines in the simulation of PMSG with type Neodumium Iron Boron N35 as shown in figure 1 below.



magnetic flux lines magnetic field direction

Figure 1. Magnetic field Distribution of PMSG using NdFeb 35.

Magnetic flux density is set from 0 Tesla to 2.4 Tesla. The distribution pattern shows that the highest magnetic flux density is found in the Stator umbrella section and the teeth stator marked by a red color that ranges from 2.1 Tesla to 2.4 Tesla which means magnetic flux flows in the full part or at maximum value. In green areas ,the magnetic field density value ranges at a value of 0.9 Tesla to 1.6 Tesla which means a magnetic flux that flows in a reasonable value, then followed by the outside of the teeth is characterized by a light blue area with a magnetic field density value of a range at a value of 0.16 Tesla to 0.81 Tesla in this passage of magnetic flux that flows very minimal. For the air box area, the stator air, the central part of the rotor core, and the shaft are not traversed by the magnetic flux so that this part has a small, magnetic field density value shown in white colour.

4. Results and analysis

4.1. Setting up parameter in simulation software

In the simulation will be tried various angular velocity variations. The parameters set in Simulsi are rotor angle velocity (ω), and time. The speed that will be attempted in this simulation is speed at 100 rpm, 125rpm, 150 rpm,175 rpm, 200 rpm, 225 rpm, 250 rpm, 275 rpm, 300 rpm, 325 rpm, 350 rpm, 375 rpm, 400 rpm, 600 rpm, 800 rpm, and 1000 rpm. The Rotor is part of a rotating generator. The Rotor rotates by 360 ° for a single round. The speed in rpm (rotation per minute) means that in one minute the rotor will spin once, then it will be changed in degree units per second where in one second the rotor will spin by 360 °, with the equation as follows:

$$\omega_{(250)} = \frac{250\ rpm\ x\ 360^{\circ}}{60\ sec} = 1500 deg/sec$$

The Designed generator is a permanent magnet synchronous generator with 24 Slots 16 pole, so to form one sinusoidal wave rotor only needs to rotate for per 360 °/8 = 45 °. In this simulation the rotor will be turned per 1 °, so keep in mind the time it takes for the rotor to spin for 1°.

4.2. No load simulation of PMSG

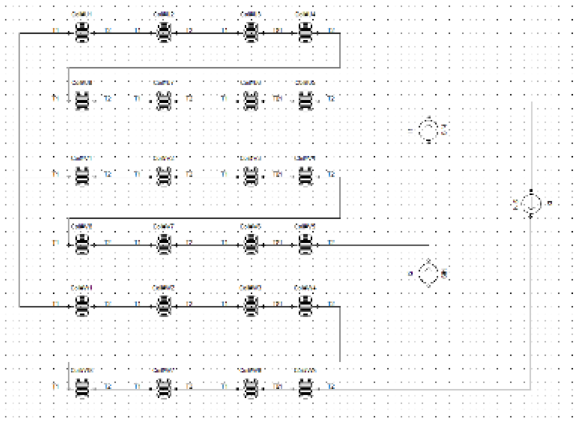


Figure 2. No load simulation circuit of PMSG.

This No Load simulation will be tested at speeds of 100 rpm until 1000 rpm. This simulation of a PMSG will result in a voltage value between phases. Where this generator is designed with 3 phases, namely phase U-V, V-W, and U-W, it will form a sinusoidal wave as in graph of speed vs Voltage.

Simulated results at a no-load 125 rpm speed will result in an inter-phase tension value. In this simulation to determine the time in which the rotor is needed when rotated per 1 ° to obtain when one wave with a speed of 125 rpm is

$$\text{Time of one step rotation} = \frac{perstep\ putaran\ (deg)}{\omega[{}^{deg}/_{sec}]}$$

$$\text{Time of one step rotation} = \frac{1(deg)}{750[{}^{deg}/_{sec}]} = 0{,}00133\ sec$$

$$\text{Time of 30 steps rotation } = 30(step).\,0{,}00133(sec) = 0{,}0399\ (sec)$$

Thus, the initial time required for the rotor speed per 1 ° of the simulation at a speed of 125 rpm is 0.00133 sec. The Rotor on the generator is rotated to 45 ° to get a single waveform, so the simulation will stop at 0.0399 sec.

In this simulation, the rotor on the generator is rotated per 1 °, with a time per 1 ° at a speed of 125 rpm of 0.00133 sec. The Rotor on the generator is rotated to 45 ° to get half the wave, so this simulation will stop at 0.0399 sec or the rotor will spin for 0.0399 sec.

Table 5. Simulation results data at a speed of 125 rpm without load.

No	Time	Flux Linkage			Tegangan Antar Fasa			DC-Voltage
	(s)	u	v	w	u-v	v-w	w-u	
1	0	0.04736	-0.02464	-0.02269	0	0	0	0
2	0.001333	0.04709	-0.01885	-0.02821	-36.38	67.84	-31.46	67.84
3	0.002666	0.045925	-0.01266	-0.03324	-44.16	67.37	-23.21	67.37
4	0.003999	0.043913	-0.00615	-0.03775	-51.16	66.12	-14.96	66.12
5	0.005332	0.041082	0.000404	-0.04148	-56.29	61.65	-5.36	61.65
6	0.006665	0.037171	0.007003	-0.04418	-63.03	55.78	7.25	63.03
7	0.007998	0.032528	0.013555	-0.0461	-67.19	50.85	16.34	67.19
8	0.009331	0.027393	0.019753	-0.04716	-68.04	43.56	24.48	68.04
9	0.010664	0.021812	0.025503	-0.04733	-68.00	35.53	32.47	68.00
10	0.011997	0.015819	0.03078	-0.04662	-67.62	27.38	40.24	67.62

The Generator rotates per 1 ° with a time of 0.00133 sec so that the recorded data is data per 1 °. The Data recorded in the simulation is an inter-phase voltage. This phase voltage is derived from the voltage of each phase, where there are phase U, V, and W. The voltage value of this phase is generated from the change of flux value of time. In table 4.7 above there is a minus voltage value, this occurs because the flux value of the generator is in and out of the rotor in the air gap. As a result, this voltage value between phases generates the following sine waves:

The output waveform shows that the rotor on the generator rotates from 0s to 0.0399 sec, indicating that the generator rotates from a rotor position of 0 ° to 45 °, resulting in half wave. The sine wave above shows that the value of t three sine waves representing the voltage between the U-V, V-W, and W-U.

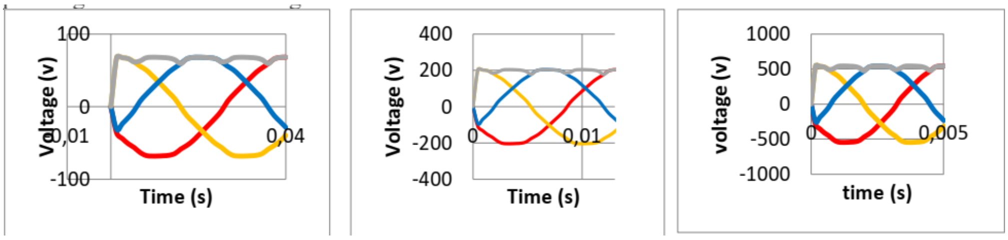


Figure 3. The output waveform of phase to phase voltage and DC output at the speed of 125 rpm.

The output voltage are rectified using three phase rectifier giving results of DC voltageThe result is shows that at no load with the average speed of 125 rpm ,PMSG will generate the peak voltage at 63.285 volts. The average voltage value will be used to calculate the EMF back constants (to) value in Equation as follows:

$$\omega = 125 \text{ rpm x } 2 .\pi \div 60 = 13{,}02083 \text{ rad/s}$$

To obtain constant of *back EMF* (Ke) in equation 2.15 is as follows:

$$K_e = \frac{Vdc}{\omega}e = \frac{63{,}285}{13{,}02083}e = 4{,}902 \text{ rad/s}$$

From the results of the whole calculation dan simulation, the Ke of PMSG will produs=ces Ke at any speed as shown in table 6.

Table 6. Simulation data of noload volage of PMSG.

No.	RPM	Vdc Ave	Ke (rad/s)
1.	100	51,063	4,902
2.	125	63,825	4,902
3.	150	76,591	4,902
4.	175	89,353	4,902
5.	200	102,117	4,902
6.	225	114,892	4,902
7.	250	127,661	4,902
8.	275	140,417	4,902
9.	300	153,198	4,902
10.	325	165,956	4,902
11.	350	178,705	4,902
12.	375	191,455	4,902
13.	400	204,265	4,902
14.	600	306,396	4,902
15.	800	408,402	4,902
16.	1000	510,727	4,902

In table 6 shows that the faster the rotation of the rotor generator, the voltage of each round is getting bigger. At this no load voltage simulation produces only voltages and does not produce currents, since generators are not connected with loads. In table 6 It is known that there is a value to or Electromagnetic Force (EMF) Back constants generated due to the change in magnetic field flux in a time that remains constant shows this generator is the same generator with different speed tests.

4.2.1. The PMSG simulation results at resistive load. The equivalent circuit of PMSG with resistive loads through three phase rectifier is drawn in the software first before doing simulation process, as shown in figure 4.

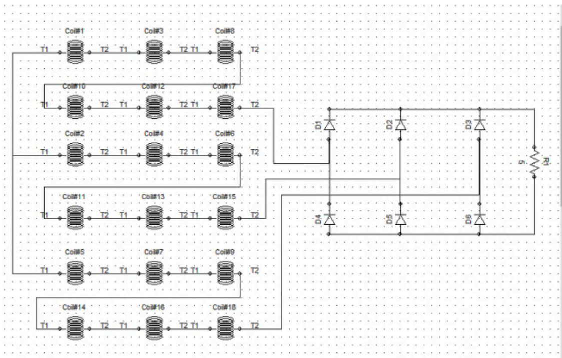


Figure 4. Simulation circuit of resistive load of PMSG.

PMSG will be given a resistor loads of between 20 Ω and 100 Ω. with a variation at a speed 100 rpm until 1000 rpm with. The Generator will get results from tests that generate multiple values at a voltage, current, torque, input power, power output ,and efficiency, as follows:

4.2.2. The Torque vs speed characterestif of PMSG. The results are then tabulated as shown ini table 7.

Table 7. Simulation data of torque vs speed with load variation.

rpm/Ω	20 ohm	40 ohm	60 ohm	80 ohm	100 ohm
100	9.84	5.92	4.32	3.438	2.88
125	11.98	7.24	5.29	4.202	3.51
150	14.01	8.54	6.25	4.97	4.14
175	15.94	9.79	7.18	5.70	4.76
200	17.77	10.99	8.08	6.43	5.37
225	19.51	12.15	8.97	7.15	5.97
250	21.24	13.27	9.83	7.85	6.56
275	22.76	14.36	10.67	8.54	7.14
300	24.47	15.41	11.49	9.21	8.39
325	25.95	16.43	12.29	9.87	8.28
350	27.51	17.41	13.07	10.52	8.84
375	28.90	18.37	13.83	11.16	9.38
400	30.35	19.46	14.66	11.87	10.00
600	38.28	26.28	19.93	16.32	13.89
800	41.01	31.17	25.24	20.56	17.50
1000	42.38	36.29	28.92	24.01	20.55

The characterestics of Torque vs spped is then drawn as as shown in Figure 5. With load variation between of between 20 Ω and 100 Ω.

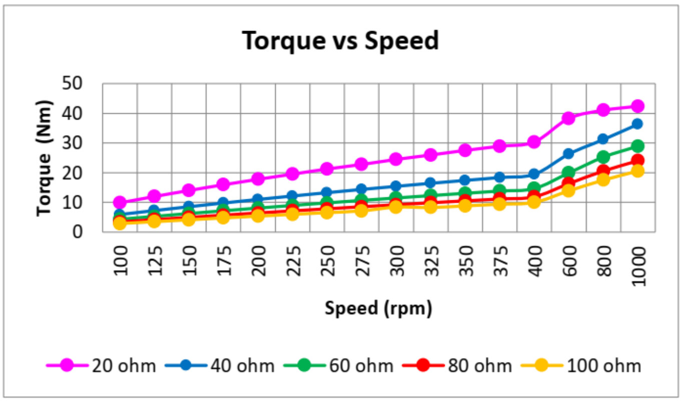


Figure 5. Characterestic of torque vs speed with load variation.

The characteristic shows in figure 5 that the more speed applied to the shaft of PMSG the more input torque produced as a primemover of PMSG. As the the load increases then the torque decreases accordingly.

4.2.3. The speed vs voltage characterestif of PMSG. PMSG will be given a resistor loads of between 20 Ω and 100 Ω. with a variation at a speed 100 rpm until 1000 rpm with. The PMSG will genereate the voltage as shown in figure 6.

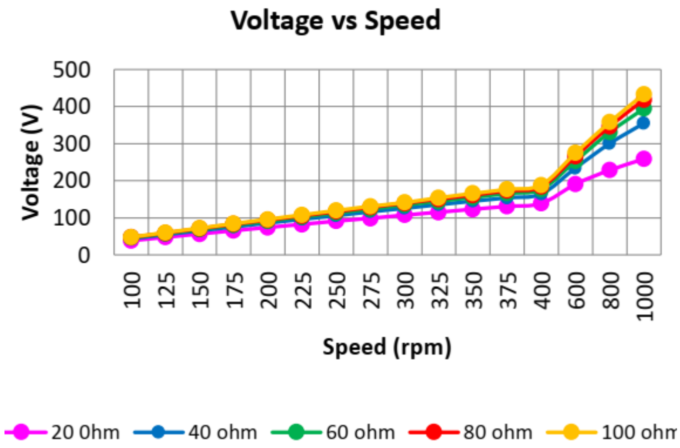


Figure 6. Characterestic of speed vs voltage with load variation.

The result shows in figure 6 that the more speed applied to the PMSG shaft , the higher the voltage will be produced. As the load is increased the voltage is ot getting down even the voltage becomes higher. This is because the more the load is increased near the nominal rating the higher the efficiency, therefore the high the output voltagr will be. From the graph shows that the lowest at 20 Ω load with speed of 100 rpm will produces the voltage of 38,2 V, whereas the highest voltage at 100 Ω with speed of 1000 rpm will produce the voltage of 433,44 V.

4.2.4. The speed vs power output Characterestif of PMSG. PMSG will be given a resistor loads of between 20 Ω and 100 Ω. with a variation at a speed 100 rpm until 1000 rpm. The PMSG will genereate the power output. The PMSG do not produce the VAR power instead it will produce WATT power because PMSG does not need excitation voltage From the graph shows that the lowest at 100 Ω load with speed of 100 rpm will produce the power output of 23,15 Watt , whereas the highest voltage at 20 Ω with speed of 1000 rpm will produce the power output of 3350,45 Watt.

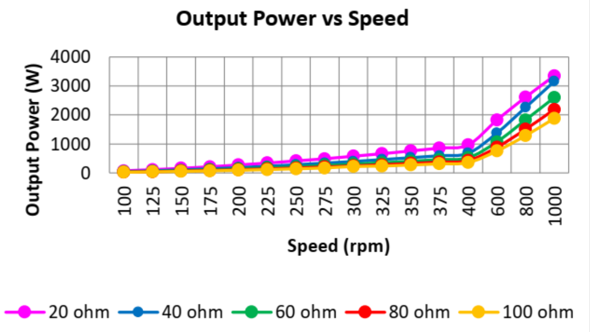


Figure 7. Characterestic of power ouput vs speed with load variation.

The graph shows that at the same load ,The output power will increases as the the speed of PMSG shat is ncreased. While the more load is applied then power output produced decreases .

4.2.5. The speed vs efficiency characterestif of PMSG. Efficiency is a measure of the level of power usage of an energy process delivered during business over a period of time. In the simulation results have been obtained the output values of voltage, and torque, so that the input power value and output power value are obtained. Then it was calculated to get the efficiency of the modified design of the PMSG created. Here's the data obtained:

Table 8. Simulation data of speed vs effivciency with with load variation.

rpm/Ω	20 ohm	40 ohm	60 ohm	80 ohm	100 ohm
100	0.72	0.78	0.79	0.80	0.80
125	0.73	0.79	0.81	0.81	0.81
150	0.73	0.80	0.82	0.82	0.82
175	0.74	0.81	0.82	0.83	0.83
200	0.75	0.81	0.83	0.83	0.83
225	0.75	0.82	0.84	0.84	0.84
250	0.76	0.82	0.84	0.84	0.84
275	0.75	0.83	0.84	0.85	0.85
300	0.76	0.83	0.85	0.85	0.85
325	0.76	0.83	0.85	0.85	0.85
350	0.76	0.84	0.85	0.86	0.86
375	0.76	0.83	0.86	0.86	0.86
400	0.77	0.84	0.86	0.86	0.86
600	0.77	0.84	0.87	0.88	0.88
800	0.77	0.85	0.88	0.89	0.89
1000	0.77	0.84	0.87	0.88	0.89

It can be found from Table 8 that the lowest efficiency of 72% is found at 20 Ω loads with a speed of 100 rpm , while the highest efficiency is 89% at 100 Ω loads with a speed of 1000 rpm

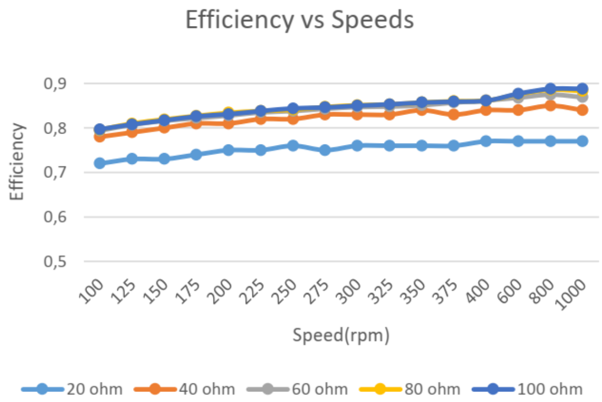


Figure 8. Characterestic of Speed vs Effivciency with with load variation.

In Figure 8 it is known that this power efficiency value indicates the level of reliability of the PMSG in converting energy. The efficiency value of this generator is fickle due to the effect of the fickle speed input value resulting in permanent magnetic synchronous generator torque also changing to a point where the value is relatively stable. And the higher the load value used, the lower the efficiency value generated. In addition in converting into electricity there are losses in the form of eddy currents and iron losses in stator and rotor materials.

4.2.6. Voltage regulation. From the simulation of the voltage test of a PMSG can be calculated the voltage regulation with the equation, as follows:

$$V_{reg} = \frac{V_{DC\ no\ load} - V_{DC\ load}}{V_{DC\ load}} \times 100\%$$

In the uni-directional voltage system, the voltage regulation value of the voltage data has been averaged as shown in the following table 9.

Table 9. Volage Regulation at the speed of 125 rpm.

Loads	**Speed of 125 rpm** load Voltage (V)	Noload Voltage (V)	Voltage Regulation (%)	**Speed of 1000 rpm** load Voltage (V)	Noload Voltage (V)	Voltage Regulation (%)
20 ohm	47,45	63,825	34	258,59	510,727	97
40 ohm	54,44	63,825	17	355,09	510,727	43
60 ohm	57,47	63,825	11	394,58	510,727	29
80 ohm	59,124	63,825	8	418,18	510,727	22
100 ohm	60,08	63,825	6	433,44	510,727	17

The data in the table 9 shows that at lower speed the voltage regulation is not as good as in high speed. At the speed of 125 rpm the increasing load is less than 50% and become worst as the load increase, Whereas the best voltage regulation is at speed 1000m rpm with lighter load of 20 Ω. As the increase the voltage regulation also decreases.

5. Conclusion

Based on the design, measurement results and analysis that have been done in this permanent magnetic synchronous generator modification design research, as follows

- The PMSG in this design from the modeling results has a specification of 24 pole 16 slots, changes the the characteristic Induction motor with synchrounous speed of 1500 rpm becomes as low as 375 rp. So This PMSG modification can be used as wind turbine or microhydro power palnt with low speed prime mover energy.

- The PMSG in this design results in an EMF back constant for half its waves of 4,902 rad/s and produce a voltage of 191,455 Vdc at a speed of 375 rpm and when given a load of 100 Ω at a speed of 375 rpm produces a voltage of 176.73 Vdc and output power of 313.24 Watts with efficiency reaching 85%.
- The variation in load and speed affects the voltage, current, torque, output power, and efficiency generated by PMSG. When the generator is charged 20 Ω at a speed of between 100 and 1000 rpm the voltage goes up.

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