

# The Effect of Halbach Array Configuration on Permanent-Magnet Synchronous Generator (PMSG) Outer-Runner

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## Abstract

Permanent-Magnet Synchronous Generator it can provide highly reliable power generation with small in size, no copper losses in the rotor circuit, no need for external excitation. We designed and simulated the PMSG with 12 slots and 8 poles with an alternating polarity magnet configuration: NN-SS-NN-SS-NN-SS-NN-SS-NN magnetic flux per pole in the outer stator and the inner stator has been assumed to be constant, following sizes and materials described in this paper. The generator's number of poles is determined by stacking several sections of the magnet side by side and grouping opposite poles in a continuous pattern. The initial design of the PMSG 12 slots and 8 poles outer-runner compare to see how the halbach array configuration changes the output parameter, it will be included. Proportional to the load size and speed The larger the magnetic flux generated by the movement of the magnetic field, the higher the rpm, and the heavier the coil magnetic flux obtained, the higher the induced voltage. This research use five speed variations varying from 1000 to 5000 rpm and load variation from 5 ohm, 15 ohm, 30 ohm, 60 ohm, and 100 ohm. With the effect that the flux distribution is voltage generated at a 5 ohm load only increases at 1000 rpm, while the increase in torque produces an increase in the amount of input power at 30 ohm, which is equal to both the speed and the amount of torque, where the input power increases at all speeds at a load of 30 ohm. This also arises when the output power generated at a load of 30 ohm increases by a high efficiency of over 86%.

**Keywords:** PMSG, Generator, Magnetic Flux, Halbach Array, Speed Variations

## 1. Introduction

Some areas that have varying wind speeds every second, such as in Indonesia, can be sufficient for small-scales wind power plant energy to be built, the impact is using of renewable energy is therefore increasing including research about wind turbine generator[1]. A suitable generator for this situation is called a Permanent-Magnet Synchronous Generator or commonly known as PMSG[2][3]. In raising the output level of high efficiency because there is no loss of excitation produced so widely used in general, the electromagnet is the phenomenon of current through the wire to create a magnetic field that is concentrated in the center of the coil, the more and more the number of windings around the magnetic core is made of a ferromagnetic material that causes magnetic flux core focus to make the magnet stronger. Stacked magnet cores and plates fabricated of steel sheets layers are integrated into the joining, diminishing non-magnetic holes and lowering the idling current[4] [6].

PMSG is a type of permanent magnet synchronous machine used in wind power applications that has a higher efficiency and a simpler and more robust structure. The high-energy permanent magnets are buried inside the rotor component, Some of these parameters are very much influenced by the shape of the stator and rotor, type of material, type of topology, type of magnetic configuration and others that can be applied to a generator PMSG. Force magnetic field that is created by moving electric charges and magnetic dipoles, and exerts a force on other nearby moving charges and magnetic dipoles. The effect of the air-gap magnetic flux density value, permanent magnet working point, torque angle, and magnet embrace on magnet thickness and air-gap size was also studied with 36 slots and 4 poles designed including rotor-speed stability improvement although[7] [9].

The goal of this analysis was to see how PMSG's we are designed is influenced by the performance parameters. In order for it to be seen compared a synchronous reluctance generator for wind applications with adding halbach array configuration. We limitation on this paper studied is the effect of changes in the PMSG 12 slots and 8 poles outer-runner: the dimensions, and magnetic configuration on the resulting voltage, current, torque, strength, performance, and magnetic flux per pole in the outer stator and the inner stator has been assumed to be constant.



This paper studied are a concept of a PMSG with 12 slots and 8 poles with an alternating polarity magnet configuration: NN-SS-NN-SS was analyzed in this paper, which was modelled and simulated using FEM-based electromagnetic software. The topology and operating principle of PMSG outer-runner will be introduced in Methods. Result and Discussion will be devoted to the design of the PMSG outer-runner. In Conclusion we summarize the paper and points out the future research direction.

## 2. Methods

Basic simulation of electromagnetic components such as C-core, E-core, and the like is used to consider the idea of producing magnetic fields and magnetic flux in electrical components before designing the electrical components of a generator. Faraday's law, also known as the law of electromagnetic induction, states that a magnetic field that increases over time will cause an electric motive force (EMF) equal to the rate of change of magnetic flux. Faraday's law is written as equation:

$$\varepsilon = -N \frac{\Delta\phi}{\Delta t} \quad (1)$$

$$\lambda = N \cdot \phi \quad (2)$$

$$\varepsilon = \frac{d\lambda}{\Delta t} \quad (3)$$

Where  $\varepsilon$  is the induced emf (Volt),  $N$  is the number of turns,  $\Delta\phi$  is the change in magnetic flux (Wb),  $\Delta t$  is the time interval (s). The negative sign only shows the direction of the electromotive force generated. If the magnetic flux is replaced to pass through the coil or coil, and the amount of magnetic flux received by the coil which causes the emf is called linkage flux, Where  $d\lambda$  is defined as the change in linkage flux (Wb). As for when an electric charge moves at a certain distance through a magnetic field, it is subjected to Lorentz's Force law is written as an equation:

$$F = qvB \times \sin \alpha \quad (4)$$

$$\phi = B \times A \times \cos \theta \quad (5)$$

This magnetic field can create a magnetic flux in the surrounding area as it is moved at a certain speed, because the field area is not perpendicular to the magnetic field and forms an angle, the magnetic flux is expressed by equation (5). Where  $B$  is the magnetic field (T),  $\Phi$  is the magnetic flux present in the component (Wb),  $A$  is the cross-sectional area ( $m^2$ ),  $\theta$  is the angle formed by  $B$  and  $A$ . The relationship between flux density and magnetic field intensity will always exist in every other material.

This generator uses a permanent magnet-generated excitation field rather than an electrified coil-generated excitation field. This is one of the advantages of being able to minimize copper losses; as a result, permanent magnet generators can be much more effective than generators that use coils as an excitation field; in comparison, PMSG can be used in wind turbines with non-constant speeds. Since the voltage and power factor provided by the PMSG can be adjusted to suit we needs. Figure 1 shown how we construct designed of PMSG.

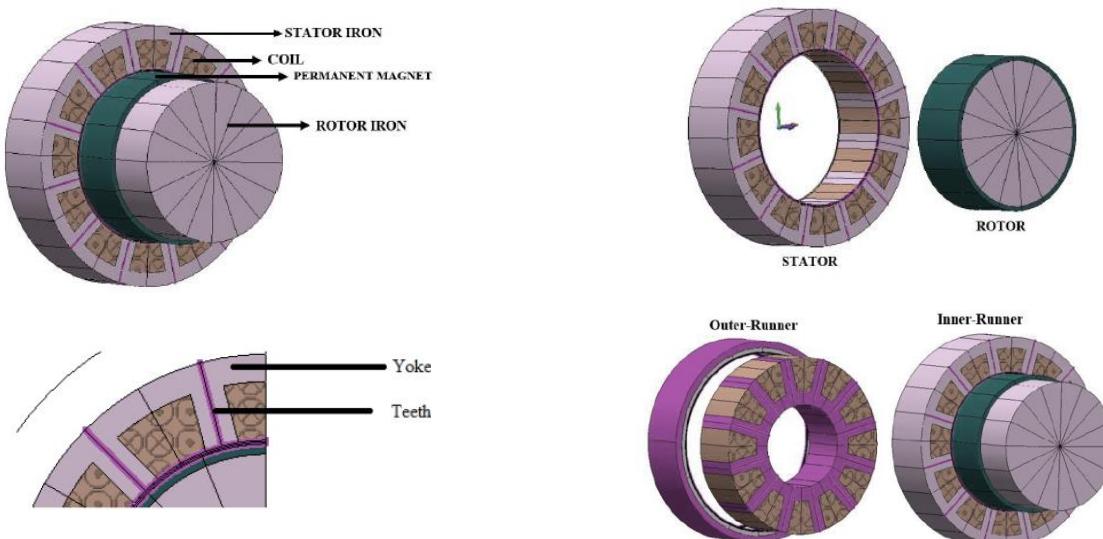


Fig 1. The Basic Construct Designed of PMSG

Since the air distance between the inner stator and the rotor is equal, the maximum magnetic flux per pole in the outer stator and the inner stator has been assumed to be constant. The flux linkage per turn in both windings has been assumed to be the same. On axial rotation, the figure above shown crankshaft will rotate the inner stator by the necessary angle[10]. The PMSG designed in this paper has the following specifications: with 12 poles and 8 slots with magnet polarity alternating configuration: NN-SS-NN-SS-NN-SS-NN-SS-NN-SS-NN- with sizes and materials described in Table 1, which is modeled and simulated using FEM-based electromagnet software. The number of poles on the generator is generated by piling several parts of the magnet side by side and arranging opposite poles in a continuous manner. The Alternating Polarity arrangement is a type of magnetic path configuration that is typically found in generators or motors. It produces a magnetic flux that is almost identical in both field directions.

Table 1. PMSG 12S 8P Outer-Runner Preliminary Design Measurement Specifications

No.	Component	Material	Magnitude	Thickness
1	Rotor Airbox	Air	Outer Diameter	180 mm
			Inner Diameter	133 mm

2	Rotor Iron	Carpenter: Silicon steel	Outer Diameter	150 mm	5 mm
3	Permanent Magnet	Neodymium Iron Boron: 48/11	Inner Diameter	140 mm	
4	Virtual Rotor Airgap	Virtual Air	Outer Diameter	140 mm	3 mm
5	Rotor Airgap	Air	Inner Diameter	134 mm	
6	Stator Airgap	Air	Outer Diameter	134 mm	0,25 mm
7	Virtual Stator Airgap	Virtual Air	Inner Diameter	133,5 mm	
8	Stator	Carpenter: Silicon steel	Outer Diameter	133,5 mm	0,25 mm
9	Stator Airbox	Air	Inner Diameter	133 mm	66,5 mm
10	Teeth	Carpenter: Silicon steel	Lenght	25 mm	10 mm
11	Yoke	Carpenter: Silicon steel	Outer Diameter	82 mm	10 mm
12	Coil	Copper: 5.77e7 Siemens/meter	Inner Diameter	62 mm	
			Turn	100 Turn	-

The magnet would develop magnetic field lines on both sides from its magnetic poles with this arrangement. The magnetic flux travels by seeking the shortest path to the opposite pole, the effect can be shown in the distribution of magnetic flux seen in Figure 2, The number of poles on the generator is generated by piling several parts of the magnet side by side and arranging opposite poles in a continuous manner. The alternating polarity arrangement is a type of magnetic path configuration that is typically found in generators or motors. It produces a magnetic flux that is almost identical in both field directions[11][12]. where there is an accumulation of magnetic flux in the rotor region, shown by the red component, which occurs due to the rotor's small area magnetic flux trajectory. Though this magnetic field stress is produced in such a way that the two plates are apart from each other, the stress occurs in definite areas. Repulsion forces are generated between magnetic poles with the same polarities, while attraction forces are generated between polarities with different polarities[13].

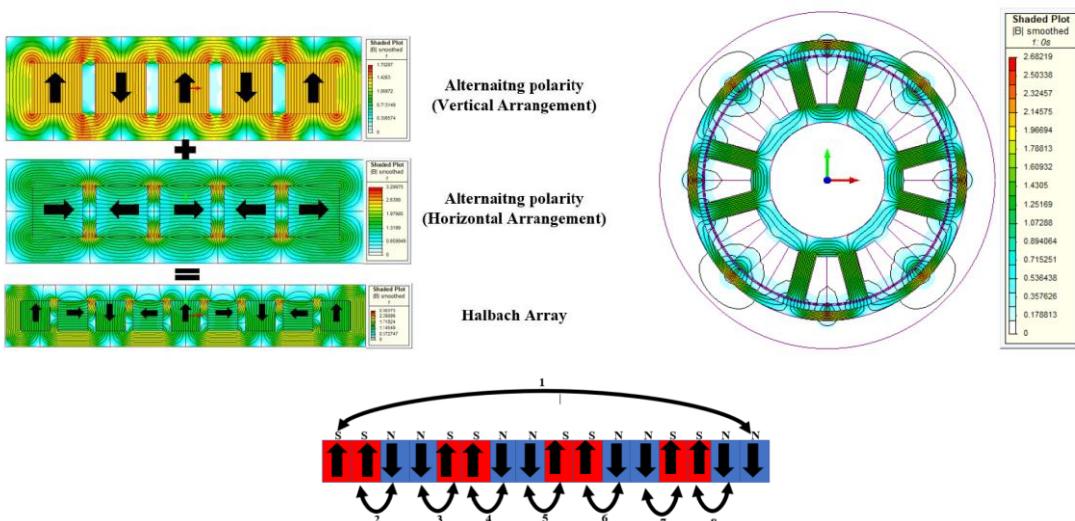


Fig 2. Halbach Array Configuration and Magnetic Flux Dispersion in PMSG

Although the waveform emitted by the generator is an alternating sinusoidal wave (AC) In fact, this is the most common magnetization pattern for this shape of magnets: first, since the air-gap flux density has a sinusoidal wave form[14] with a frequency power is converted into fixed frequency[15] that varies with the speed of the generator rotation, a controller containing filters, rectifiers, and other components is required to control the output provided by the generator. The rectifier will be modelled as an electrical circuit schematic in the simulation software shown in Figure 3, with the power input and output is expressed by equation (6)-(8), angular speed is expressed by equation (7). Where  $P$  is the generator power (Watt),  $T$  is the load torque (Nm),  $\omega$  is the angular speed (rad / s), and  $n$  is the rotation speed (rpm),  $V$  is the voltage (Volt), and  $I$  is the current (Ampere). The efficiency of the generator can be calculated using equation (9) with  $\eta$  is efficiency (%),  $P_{in}$  is input power (Watts), and  $P_{out}$  is output power (Watts). As for Table 2-4 shows the performance parameters produced in this our design.

$$P_{in} = T \times \omega \quad (6)$$

$$\omega = \frac{2\pi \cdot n}{60} \quad (7)$$

$$P_{out} = V \times I \quad (8)$$

$$\eta = \frac{P_{in}}{P_{out}} \times 100\% \quad (9)$$

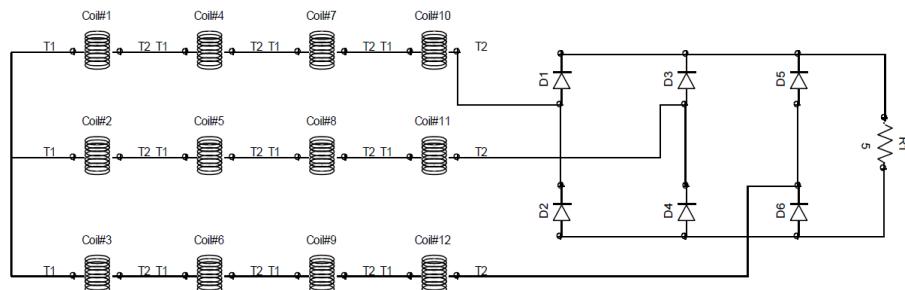


Fig 3. PMSG Schematic Circuit Modeling With a Rectifier

Table 2. The Voltage Values Generated by The Initial Design of PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	106.89	142.99	146.35	148.35	151.68
<b>15 Ω</b>	144.99	251.25	325.47	370.16	398.31
<b>30 Ω</b>	156.97	293.75	401.91	503.77	585.72
<b>60 Ω</b>	161.39	312.00	443.87	577.05	688.70
<b>100 Ω</b>	164.83	320.88	470.60	611.00	741.34

Table 3. The Current Values Generated by The Initial Design of PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	21.38	28.60	29.27	29.80	30.34
<b>15 Ω</b>	9.67	16.75	21.70	24.68	26.55
<b>30 Ω</b>	5.23	9.79	13.40	16.79	19.52
<b>60 Ω</b>	2.69	5.20	7.40	9.62	11.48
<b>100 Ω</b>	1.65	3.21	4.71	6.11	7.41

Table 4. The Power Input Values Generated by The Initial Design of PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	2696.29	4846.23	5281.75	5683.95	6652.23
<b>15 Ω</b>	1664.30	4924.48	8325.50	10843.86	12737.93
<b>30 Ω</b>	1019.32	3508.62	6670.47	10307.31	13973.33
<b>60 Ω</b>	613.78	2161.36	4428.78	7293.18	10436.16
<b>100 Ω</b>	435.95	1552.25	3282.16	5394.02	8001.78

Explanation from table 2 on the initial configuration, the voltage provided by the design of PMSG 12 Slots and 8 Poles outer-runner is proportional to the speed and large load. And the higher the rpm, the greater the magnetic flux produced by the movement of the magnetic field, and a broad coil magnetic flux obtained would result in a higher induced voltage. Because the load placed on the circuit is a resistive load one that causes much current to be blocked, the current absorbed by the load is directly proportional to the speed and inversely proportional to the load, because the load is directly proportional to the speed and inversely proportional to the load. The higher the rotational speed, the more often the coil or coil will miss lines of magnetic flux, resulting in higher induced voltage and current flows in the coils that emerge shown by table 3. In table 4 equation (6)-(8) used for the power input is proportional to the product of the torque at the load (T) and  $\omega$ , where is the multiple of  $2\pi$  with the speed in rpm divided by time, so the input power will increase as the speed increases. The power output will be lower at high loads because the amount of torque will be less, as seen in Table 5 and 6.

Table 5. The Power Output Values Generated by The Initial Design of PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	2285.09	4096.66	4301.64	4468.60	4643.32
<b>15 Ω</b>	1417.54	4214.89	7062.81	9144.71	10595.04
<b>30 Ω</b>	834.90	2905.90	5414.24	8470.91	11437.18
<b>60 Ω</b>	444.15	1649.08	3334.81	5602.21	7964.14
<b>100 Ω</b>	277.16	1058.44	2267.84	3800.09	5593.04

Table 6. The Torque Values Generated by The Initial Design of PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	27.5	23.14	16.81	13.27	11.42
<b>15 Ω</b>	15.89	23.51	26.50	25.89	24.33
<b>30 Ω</b>	9.73	16.75	21.23	24.61	26.69
<b>60 Ω</b>	5.86	10.32	14.10	17.41	19.93
<b>100 Ω</b>	4.16	7.41	10.45	12.88	15.28

### 3. Result and Discussion

#### 3.1. Halbach Array Configuration

Variations to the magnetic structure that previously used alternating polarity to use the halbach array configuration will be made to see if it affects the performance parameter that will be produced by retaining the diameter of each component, size, and type of material used in the initial design of the PMSG 12 slots and 8 poles outer-runner. Since the simulation models only use the fundamental sinewave current as the power source, it can be ignored that high-order voltage harmonics cause the thrust ripple to increase while the pole is on-load[16]. This magnetic arrangement is achieved by inserting one piece of magnet between the two previous magnets, as seen in Figure 4. For the dimension, type of material in this variation design is the same as in the initial design methodology, while the modeling form for simulation and the distribution of magnetic flux resulting from the simulation are shown. as seen in Figure 5. The following figure depicts the performance parameter data produced by this variation.

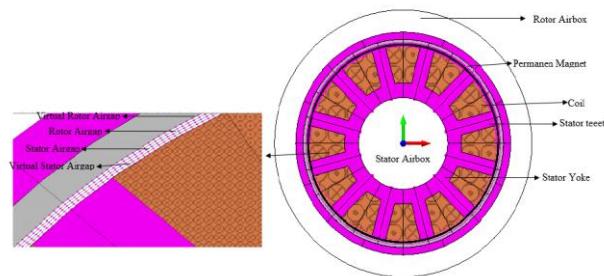


Fig 4. Design of PMSG 12S 8P Outer-Runner With Halbach Array Configuration

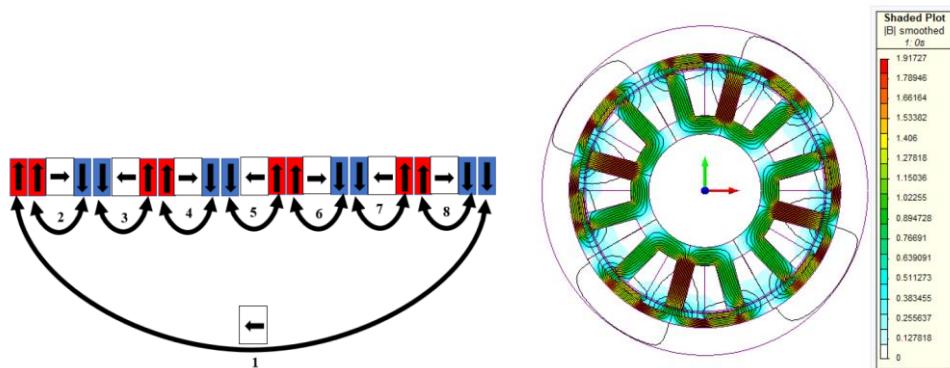


Fig 5. Magnetic Structure Variations in Halbach Array and Flux Dispersion Halbach Array in PMSG

Table 7. The Voltage Values Generated by Halbach Array Configuration in PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	114.99	130.02	133.33	137.38	138.72
<b>15 Ω</b>	165.79	284.93	342.81	352.16	378.11
<b>30 Ω</b>	185.73	335.38	459.87	554.77	621.24
<b>60 Ω</b>	199.46	374.41	530.33	673.04	810.95
<b>100 Ω</b>	207.40	399.70	571.71	739.27	885.36

Table 8. The Current Values Generated by Halbach Array Configuration in PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	23.00	26.00	26.67	27.48	27.74
<b>15 Ω</b>	11.05	19.00	22.85	23.48	25.21
<b>30 Ω</b>	6.19	11.18	15.33	18.49	20.71
<b>60 Ω</b>	3.32	6.24	8.84	11.22	13.52
<b>100 Ω</b>	2.07	4.00	5.72	7.39	8.85

Table 9. The Power Input Values Generated by Halbach Array Configuration in PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>5 Ω</b>	3021.51	3900.39	4229.55	4599.33	5272.94
<b>15 Ω</b>	2073.36	6093.28	8884.42	9531.07	10938.70
<b>30 Ω</b>	1369.70	4351.44	8246.47	11985.05	15088.96
<b>60 Ω</b>	862.43	2925.79	5788.84	9297.43	13513.07
<b>100 Ω</b>	599.64	2127.98	4332.79	7094.30	10338.88

**Table 10.** The Power Output Values Generated by Halbach Array Configuration in PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>Power Output Values (W)</b>					
<b>5 Ω</b>	2653.29	3387.90	3564.59	3788.60	3879.50
<b>15 Ω</b>	1834.27	5428.89	7860.56	8296.67	9550.71
<b>30 Ω</b>	1157.84	3753.94	7074.79	10296.97	12914.67
<b>60 Ω</b>	683.10	2352.13	4689.46	7559.78	10980.54
<b>100 Ω</b>	448.09	1627.59	3287.89	5472.53	7842.88

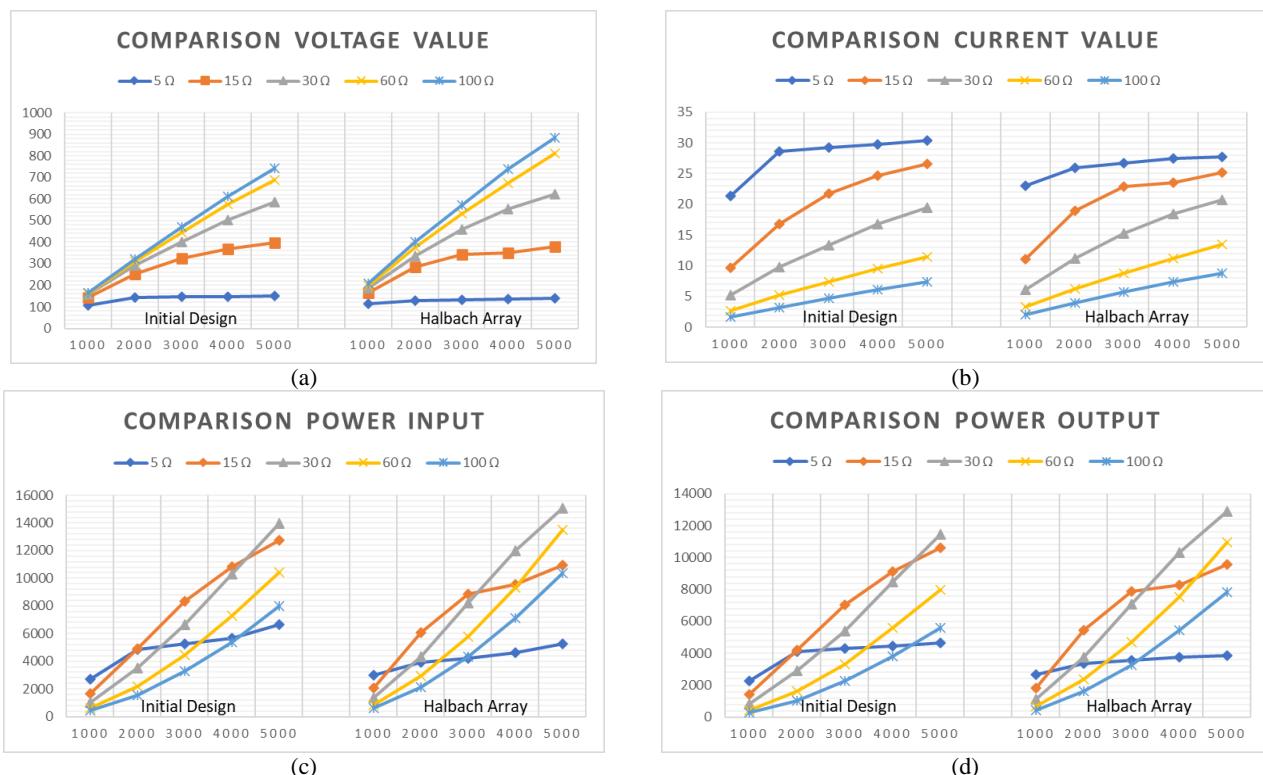
**Table 11.** The Torque Values Generated by Halbach Array Configuration in PMSG

Load	Various Speeds (Rpm)				
	1000	2000	3000	4000	5000
<b>Torque Values (Nm)</b>					
<b>5 Ω</b>	28.85	18.62	13.46	10.64	8.76
<b>15 Ω</b>	19.80	29.09	28.28	22.75	20.89
<b>30 Ω</b>	13.08	20.78	26.25	28.61	28.82
<b>60 Ω</b>	8.24	13.97	18.43	22.20	25.81
<b>100 Ω</b>	5.73	10.16	13.79	16.94	19.75

The PMSG 12 slots and 8 poles outer-runner increased voltage through different loads and speeds is increased by applying the halbach array application to the initial design used. This is when the addition of a magnetic slice between the two polarities allows the inner side of the magnet to have a greater magnetic field than the outer side, resulting in a higher linkage flux obtained by the coil, as seen in Figure 5 above, where all areas of the teeth and coil are exposed to magnetic flux lines.

### 3.2. Initial Designs PMSG Compared to Halbach Array Configuration

The following graph represents a summary between the initial design and the simulation results of the halbach array configuration. Where the voltage in the halbach array configuration has decreased when using loads of 5 and 15 ohms, as seen in Table 7 above, as well as the conditions that exist in the resulting current when using loads greater than 30 ohms, as shown in Table 8 above. The PMSG 12 Slots and 8 Poles result in increased voltage and output current due to increased output power, For more details, we present a comparison graph below.



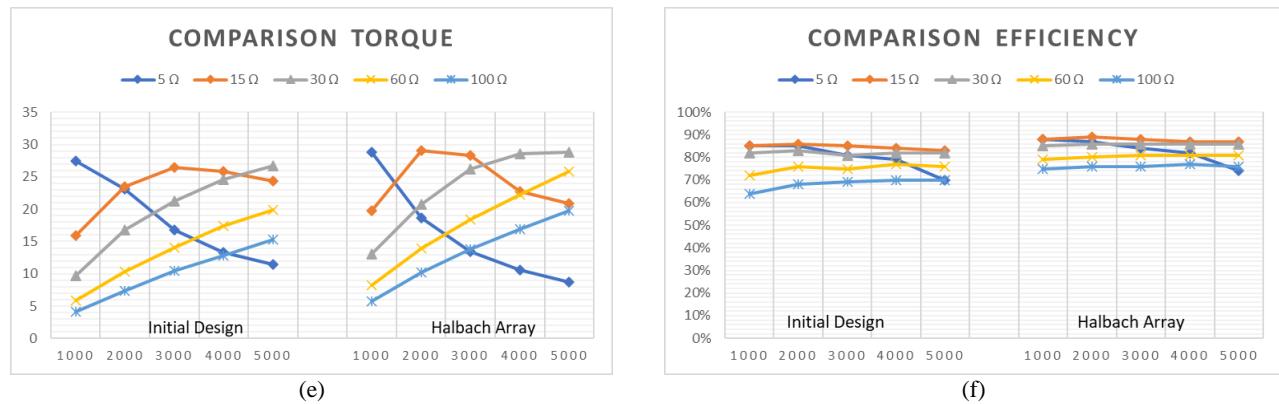


Fig 6. Comparison Result Between Initial Design and Halbach Array Configuration in PMSG

The output power provided by the PMSG 12 slots and 8 poles outer runner using the halbach array magnetic configuration is similar to the required input power, increasing the efficiency of this PMSG. Over all speeds and loads used, as seen in the comparison data above. Because of the change in magnetic configuration, there are more magnetic fields dispersed within, resulting in longer magnetic flux lines. However, as previously said, at low load, PMSG encounters a reasonably high transient condition before reaching a point of stability, resulting in a significant reduction in performance. Based on the result of this research, it can be concluded that causes radial force variations through rub between the rotor and stator, as opposed to the smooth constant rub used in simulations. The control technique will remove jump reaction modes and minimize mechanical stress considerably with minor transients at the switching instants, the induction generator's terminal voltage, stator current, rpm, active power generation, and reactive power consumption remain constant at their previous values. In order to find such materials, the electric machine must have a moderate air gap [13][17][18][19]. So, reactive power supplied by a wind-turbine system in synchronous condenser mode is the same as that supplied by a synchronous engine. Since the current magnitude is different in this mode of operations[20][21], we presume that our design PMSG can meet the reactive power compliance criterion when connected to the grid.

#### 4. Conclusion

The magnetic field within the generator can be increased by using the halbach array magnetic configuration depending on the resulting flux distribution, but the voltage produced at a 5 ohm load only increases at 1000 rpm, which results in 8.1 volts more and decreases at the same distance. Others, although the voltage rises at speeds of 1000, 2000, and 3000 rpm with a load of 15 ohms, it declines at speeds of 4000 and 5000 rpm. At 30, 60, and 100 ohm loads, the pace increases. Meanwhile, since the resulting current and torque are the same independent of voltage, the configuration of this variation is ideal for use with loads less than 30 ohm. The increase in torque causes an increase in the amount of input power, which is proportional to the speed and also the amount of torque, where the input power increases at all speeds at the load of 30 ohm. This also happens to the output power produced at the load of 30 ohm, with a percentage increase greater than the increase in input power, resulting in a large efficiency with the load of 30 ohm it over 86%. Further research suggestions are in the process of developing the PMSG required tangible form using a low-cost, as well as the availability of component content. In order to realize the actual shape of the generator, PMSG must consider other elements of the state, such as the halbach array, which, if imposed, would overheat before rush the generator itself and variations design on the stator teeth that umbrella added..

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