# High RPM small dimension 100 kW Permanent Magnet Synchronous Generator (PMSG) manufacturing and performance testing

To cite this article: Novias Nurendra *et al* 2023 *IOP Conf. Ser.: Earth Environ. Sci.* **1135** 012037

# High RPM small dimension 100 kW Permanent Magnet Synchronous Generator (PMSG) manufacturing and performance testing

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**Abstract.** Indonesia is an archipelagic country that is vulnerable to the effects of climate change. Climate change is mainly caused by global warming due to carbon emissions. Indonesia's energy generation sector produces 34% of Indonesia's total Green House Gas (GHG) emissions. So new ways of energy generation are needed to ensure the energy produced is clean from GHG such as renewable energy. For this reason, Hutama Karya is trying to develop core technology in the development of renewable energy in Indonesia. The core technology in question is the High RPM Small Dimension Permanent Magnet Generator. This PMSG has unique operating characteristics in the form of high RPM but low torque, making it suitable for application to renewable energy generation. The biggest challenge today is to ensure that the existing manufacturing technology in Indonesia is sufficient to produce the PMSG. Our findings indicate that manufacturing technology in Indonesia is sufficient to produce PMSG with 100 kW power capacity. It is indicated by the result of early testing that the generator can produce Electrical Coefficient (EC) value of 0.15.
**Keyword:** Generator, Generator Manufacturing, Generator Performance Test, Permanent Magnetic Synchronous Generator, Renewable Energy

## Introduction

As an archipelagic country, 150 million Indonesians live in coastal areas. This number represents about 60% of the entire Indonesian population [1]. In addition, the sea is also an important factor in realizing Indonesia's welfare. Indonesia's marine fisheries sector alone is valued at 27 billion USD, can absorb 7 million workers, and provide more than 50% of Indonesia's animal protein needs [2]. With these conditions, sea level rise and weather changes related to global warming are major challenges for Indonesia's economic and environmental sectors. Global warming is mainly caused by excess carbon emissions released into the earth's atmosphere and its impact of greenhouse effect. The energy generation sector in Indonesia accounts for 34% of Indonesia's total carbon emissions [3]. With this figure, it is necessary to make efforts to reduce carbon emissions in Indonesia, especially in the energy generation sector.
Based on the above reasons, Hutama Karya has the vision to take part in reducing carbon emissions. The vision of Hutama Karya is in the form of clean and sustainable energy generation. Therefore, it is necessary to make substantial efforts to develop core technology for clean and sustainable energy. To meet the needs of core technology, PT Hutama Karya (Persero) – PT Lentera Bumi Nusantara (PT.

LBN) has developed a Permanent Magnet Synchronous Generator (PMSG) Module with a capacity of 100 kW. This PMSG module serves to convert mechanical energy into electrical energy. Mechanical energy is obtained from Renewable Energy sources. Thus, the final goal of the PMSG development is the integration of PMSG and renewable energy. This paper will focus on the core technology manufacturing process and the generator's performance.

### *1.1. Initial Conceptual Idea*

**As one of the solutions to the rise of renewable energy needs, indigenous development of technology to support renewable energy is needed. This development is then realized by designing, developing, and finally producing the prototype of PMSG. This PMSG has a unique characteristic: it has a compact build with a relatively high-power output. With a weight of just under 100 kg and a diameter of 45 cm, this PMSG can produce 100 kW power at 6000 rpm. A generator consists of a stator that supplies the load and a rotor that provides the magnetic field. The magnetic field source is a permanent magnet. The performance of PMSG is also affected by the design of both stator and rotor [4,5]. The PMSG is chosen for its advantage in reliability, low maintenance, long service life, and compact and light design, although PMSG has its drawback in terms of material cost [6]. The main advantage of this small dimension 100 kW PMSG is low initial torque, low torque ripple, and smaller dimension compared to other systems with similar power. With this characteristic, this generator is suitable for low-medium size renewable energy systems.**

**The operating angular speed of the generator itself presented a challenge to overcome. Because for the time, the conventional renewable energy unit operates at the angular speed of around 3000 rpm. The generator is connected to the turbine via a shaft and gearbox as transmission, as shown in Figure 1. Nevertheless, in the case of this PMSG, the generator needs two times the conventional operating speed of a conventional renewable energy system to operate efficiently. Thus, a new transmission type is needed because of this constraint, especially one that can couple the system's operating speed.**

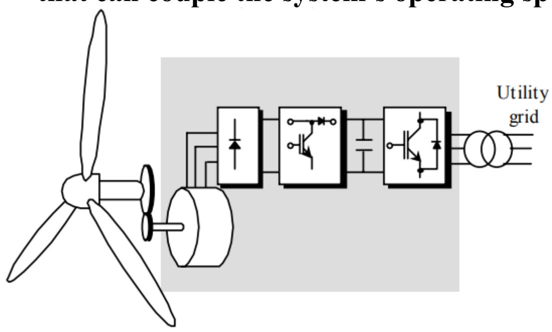



**Figure 1** Synchronous generator topologies for wind turbine system [7].

The main challenge right now is ensuring that Indonesia can afford and has the technology necessary to manufacture and test this device. The manufacturing process for this generator should be done using the available method in Indonesia, such as machine milling, welding, and cutting. Moreover, the generator's initial testing should also be done with limited tools. As such, many small manufacturers across Indonesia can easily replicate the initial testing. The final requirement is to ensure that although the manufacturing process and testing process are done using limited tools and methods, the produced generator should not deviate much from its intended performance.

### *1.2. Theory*

A. Electricity Generation in Generator

To understand the process of electricity generation in generators we need to first know about the basic theory of power generation that involves magnetic fields, which is Faraday's law. This law states that if there is a magnetic flux moving through a coil winding, there can be an induced voltage. The induced voltage that occurs is directly proportional to the rate of change in the magnetic flux through the coil in one unit of time. It is expressed as in the equation 1.

$$e = \frac{d\varphi}{dt} \tag{1}$$

Where $e$ is the induction voltage and the $\varphi$ is the flux of the magnetic field through the coil. If the coil has the number of windings (N), and in each winding occurs the same magnetic field flux then the equation can be rewritten into equation 2.

$$e = N\,\frac{d\varphi}{dt} \tag{2}$$

In practice it is impossible to apply the above equation. This is due to the magnetic field through which each coil has an unequal magnitude. If a coil has a small winding width and is tightly wrapped, then the above equation can be used to get results with a certain equation approach. But for a calculation of induction voltage that requires high precision, another form of equation is needed. In simple terms, the induction voltage on a coil winding number-i can be written with equation 3.

$$e_i = \frac{d(\varphi_i)}{dt} \tag{3}$$

If a number of N twists are found in the coil, then the above equation can be rewritten in the form of equations 4 and 5.

$$e = \sum_{i=1}^{N} e_i \tag{4}$$

$$e = \sum_{i=1}^{N} \frac{d(\varphi_i)}{dt} \tag{5}$$

Induction voltage increases in a conductor can also occur when the conductor moves through a magnetic field. This understanding is used as the basis for generator design. If a conductor, say, moves on a magnetic field with the right orientation, a voltage will be induced on the wire. The magnitude of the voltage in the event is calculated through the equation 6.

$$e = B\,l\,v \tag{6}$$

Where $e$ represents induction voltage, $B$ is magnetic field strength, $l$ is wire length and $v$ is the relative velocity between $B$ and $l$. The constant parameters in the above formula are B and l. Both define the unique characteristics of each generator. Because both represent the type of material and the amount of the winding on the stator core. Each of the above magnitudes is a vector magnitude so that everything has a magnitude and direction, for the direction of each magnitude following Fleming's right-hand rule. Both of these magnitudes are design parameters, which also are constant when considering the design of the generator.

These constant parameters are important because they function like a translator between input parameters and the amount of voltage generated from a generator. It can be said to be a translator because every mechanical input in the form of rotary speed entering the generator will be changed to induction voltage through a constant parameter. The constant parameter is the Electrical Coefficient

(EC). This coefficient is what describes the level of voltage generation in the generator. The coefficient of electricity can be expressed as the magnitude of the voltage generated by the generator each unit of speed of the relative position change between the magnet and the conductor. The equation from EC is a change from Fleming's right-hand rule equation. The Equation of the Coefficient of Electricity can be written as in equation 7.

$$EC = \frac{e}{v} = B\ l \tag{7}$$

B. Generator

Generators work using a principal invented by Michael Faraday, a principle known as electromagnetic induction. This principle states that there is an induction voltage in the transmitting wire caused by a change in the magnetic field. Along the way, this theory put forward by Faraday has provided a big picture of electrotechnics. This view has been able to give us an idea of the very important relationship between copper conductivity, the magnetic nature of a permanent magnet. This theory has also become the basis of thinking and development of electric motors and generators.
In a nutshell, a generator is a device that can convert mechanical energy into electrical energy. Mechanical energy that occurs in the form of changes in the relative position of the conductor and magnetic field per unit of time and thus there is power in the form of moving conductor. When a load is applied to the generator, this mechanical energy is converted into voltage and current which is more commonly referred to as electricity. For more insight to this power conversion, one can examine equation 8 and 9.

$$P = \omega\ \tau \tag{8}$$

$$P = V\ I \tag{9}$$

From equation 8 and 9 it can be stated that mechanical energy input for generator is in the form of rotational speed (ω) and torque (τ). Then when generator is shorted, this mechanical power will be converted to electrical power in the form of voltage (V) and current (I).
Generators have two main components, namely the rotor and the stator. The rotor is part of the generator that moves, while the stator is the stationary part. In most rotational generators, the moving part is the inside part. But these two ways can be exchanged, so it does not rule out the possibility that the outside part of the generator can act as the rotor. Both of these configurations are shown in Figure 2. In the generator there are sources of magnetic fields and conductors. As we know, these two components are needed to create induction voltage. The next important thing is to make a relative movement between the two, which can be done by placing one of the components on the rotor and the other component on the generator stator. It is this placement that makes a driven generator can produce voltage, because this placement has fulfilled the load of Faraday's Law to create an induction voltage. The requirements are in the form of a magnetic field, conductors and changes in relative position between the two.

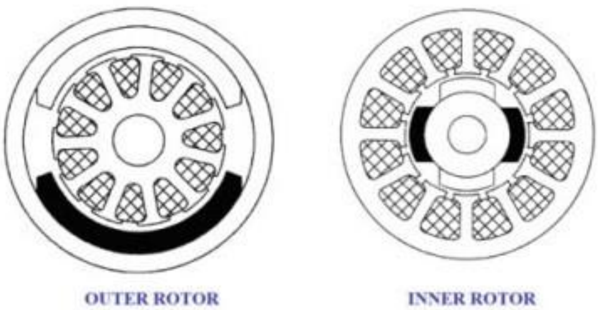



**Figure 2.** The Outer and Inner Rotor [9]

Inside the generator there is a configuration of how much winding and magnetism is needed to produce a magnitude and phase of electrical output. This configuration is commonly referred to as slots and poles. A slot is the sum of a collection of conductors winding where voltages form and poles express the number of magnetic poles. So, if there is a type of permanent magnetic generator type 12 slots and 8 poles, it means that the generator has 12 groups of windings and 8 magnetic poles. The voltage generated from a generator has a form in the form of wave flow. This waveform is caused by the difference in the magnetic field that hits the conductor. If the magnetic field that hits the conductor comes from the north pole of the magnet, it will produce a change in the magnetic field of positive value and vice versa, if it comes from the south pole, it produces a change in the magnetic field of negative value. This rotating magnetic field can be seen in a simple form in Figure 3.
The body between positive and negative magnetic field changes is also what causes the occurrence of voltages that have negative and positive values. These negative and positive values draw that the voltage that occurs has two orientations or called alternating voltage. This alternating voltage is what ultimately creates a current that has two directions or commonly called Alternating Current (AC) when the generator is connected to a load. The amount of electricity and frequency that a generator produces depends on the material, the number of windings, the relative speed and dimensions of the generator. This is in accordance with Fleming’s right-hand principle which states that to increase the induction voltage it is necessary to increase the value on these four factors. These four factors are the focus in the designing of a generator. The four things above will also determine the level of efficiency of the generator which ultimately also has an impact on the amount of power generated. In determining the amount of voltage of a generator we can use the Electrical Coefficient (EC). EC itself depends on the physical things in the generator in the form of magnetic field strength (B) and the length of the conductor (l), which emphasizes the type of material, the number of windings and the dimensions of the generator. The dimensions of the generator can also be expressed with Slots as well as Poles.

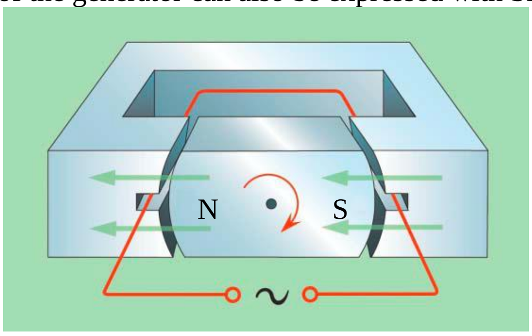



**Figure 3.** Simple AC generator [10]

The resulting phase of electrical output is affected by the configuration and number of slots and poles. The electric phase itself defines the position of an electric wave at the time reference. One cycle of electric waves is represented as 360$^{o}$ electrical. To better understand about this definition can be seen in Figure 4.

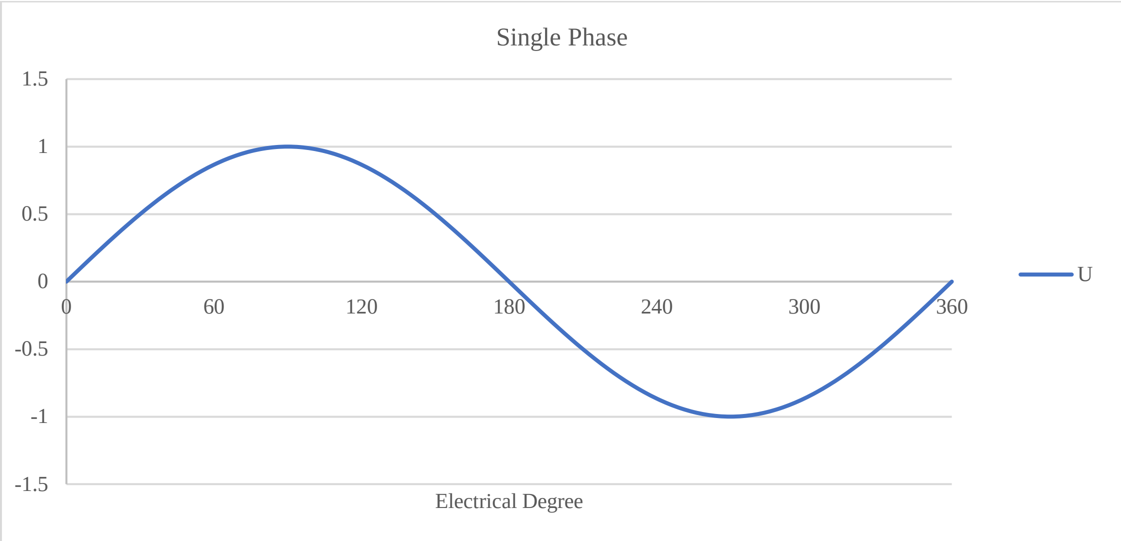



**Figure 4.** One cycle of single-phase electric wave.

If a generator is defined as a three-phase generator, there will be three waves in one $360^0$-cycle of electricity from that generator. The three waves will have the same profile but with different phases. The phase in question is the reference position to time, if there are three phases then each phase will be separated as far as $120^o$ electrical. For more details, look at Figure 5.

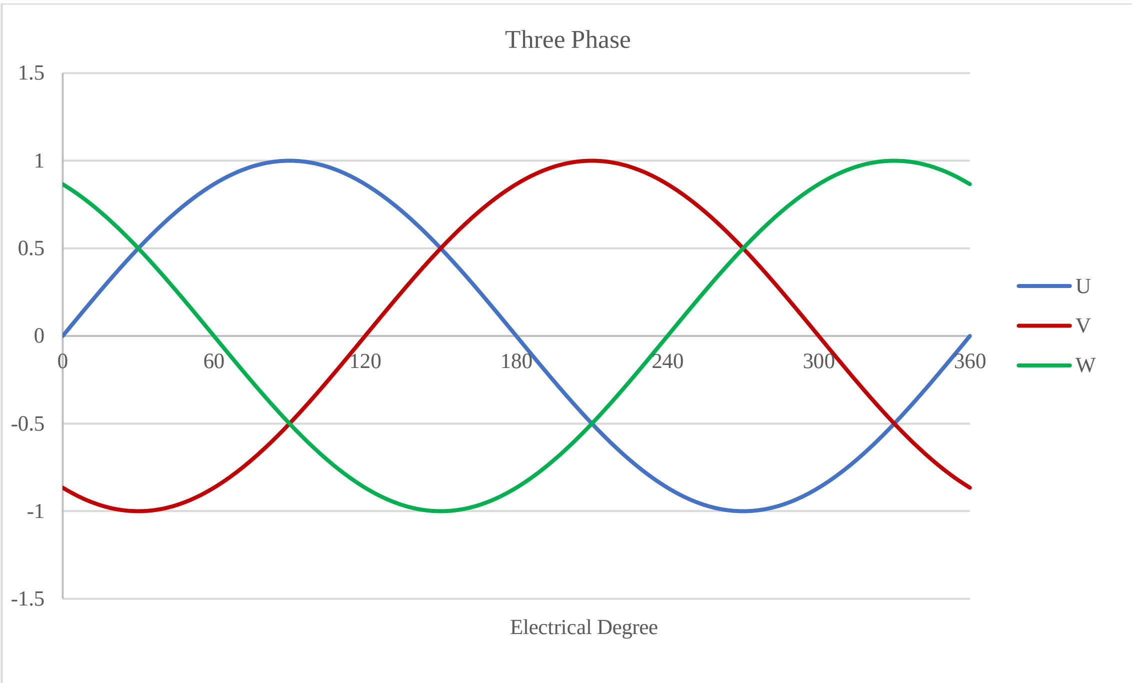



**Figure 5.** One cycle of three phase electric wave

## 2. Material and Manufacturing Method

The generator manufacturing process consists of manufacturing the generator's mechanical parts and the generator's electromagnetic parts. This mechanical part consists of a generator housing and a generator shaft. As for the electromagnetic part, it consists of a stator core and rotor, a permanent magnet, and a generator winding circuit. The manufacturing process begins with the procurement of materials according to the specifications of the 100 kW PMSG generator. The specifications of this generator can be seen in table 1. The materials needed include silicon steel plate as the material for the stator and generator core, a permanent magnet as a source of the magnetic field, copper with a diameter of 2.6 mm as a winding in the generator, aluminium block for the manufacture of generator housings and steel tubular rods as material for making shaft. Details of the materials needed can be seen in table 2. After the material is obtained, the following process is manufacturing each part of the generator. For mechanical parts, it starts with machining the generator housing from the aluminium block. The process is carried out using (Computer Numerical Control) The process is carried out using Computer Numerical Control (CNC) milling. For shaft generators, the process carried out is also in the form of a CNC milling process to form the shaft into the required dimensions. The manufacturing process of housing and shaft, along with the results, is shown in Figure 6.

For the electromagnetic part of the generator, especially the stator core and rotor parts, the process begins with cutting the material into dimensions of 400 mm * 400 mm using laser cutting. After the material is cut into suitable dimensions, the material is laminated by 350 sheets to a thickness of 122.5 mm. After the lamination process is complete, the plate stack is welded to keep the lamination from being damaged during the wire-cutting core process into the required shape. Then, the cutting process can be done to the rotor and stator core.

**Table 1.** High RPM small dimension PMSG Specification.

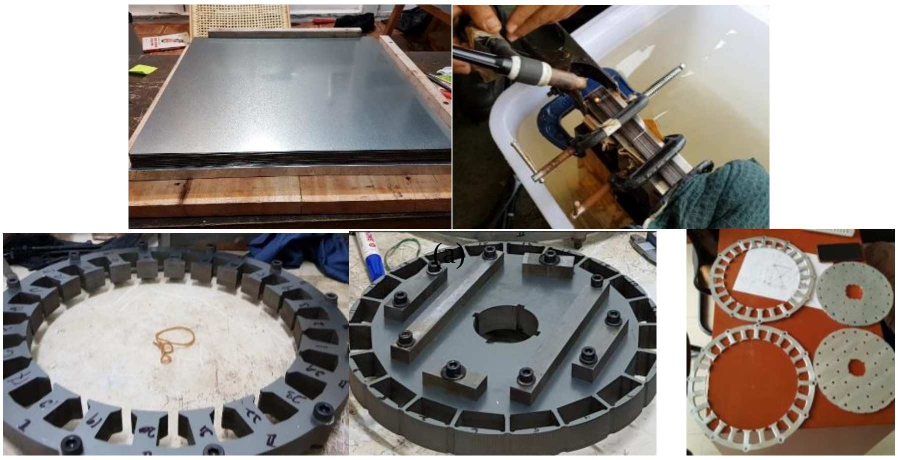
| | |
|---|---|
| Dimension (D*H) | 50 cm * 25 cm |
| Power Output | 100 kW |
| Rotation Sp. (@ rated Power) | 6000 rpm |
| Electrical Current | 80 A – 90 A (1300 Volt) |
| Nominal Torque | 200 Nm |
| Phases | 3 phases |
| Maximum Weight (Kg) | 100 kg |

**Table 2.** Material needed for PMSG manufacture.

| No | Material | Size Detail |
|---|---|---|
| 1. | Silicon Steel 25JN360 (L*W*H) | 1000 mm * 500 mm * 0.35mm |
| 2. | Permanent magnet Neodymium N48 (L*W*H) | 60 mm * 24 mm * 16 mm |
| 3. | Copper Wire (D) | 26 mm |
| 4. | Aluminium Plate (L*W*H) | 500 mm * 500 mm * 100 mm |
| 5. | Carbon Steel Tube (L*D) | 300 mm * 100mm |

**Figure 6.** Housing dan shaft after manufacturing process.

After the stator and rotor core cutting process is completed, it is necessary to manufacture the core cover from the aluminium plate. This cover helps facilitate the process of unifying the stator-rotor core sheet and winding the conductor to the stator core. The process is carried out by cutting the aluminium plate into forms such as the stator core and rotor. When finished, the cover is combined with the stator core and rotor using bolts. Then the stator-rotor core is welded using laser welding. The manufacturing process of the core can be seen in Figure 7. The next step that needs to be done is winding the conductor on the stator core, the circuit connection for the conductor, and the installation of magnets on the rotor core. The winding process begins with the installation of insulator paper on the conductor slot. After the insulator is installed, the conductor can begin to be wound on the available slots, after which the conductor is coated with insulator paint to ensure no leakage in the generator.

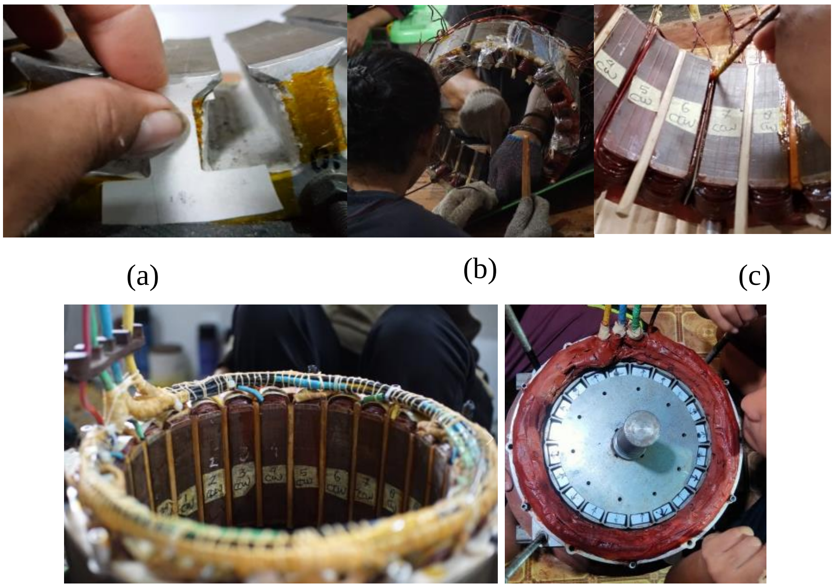


(a)

(b) (c)

**Figure 7.** (a) Lamination and welding of the silicon steel, (b) rotor and stator core after laser welding, (c) rotor and stator aluminium cover.

Before the connection between the windings is carried out, resistance, inductance, and capacitance tests are carried out on each winding. After the three parameters are deemed sufficient and meet the specifications, the process of connecting the conductors can be carried out. Finally, the stator core and rotor are put together, and a permanent installation of magnets is carried out on the rotor core. This whole process can be seen in Figure 8.

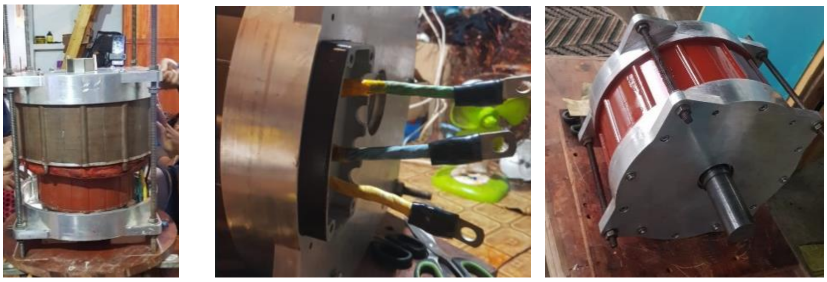


(a) (b) (c)

(d)

**Figure 8.** (a) Insulator paper installation, (b)conductor winding, (c) insultation paint application, (d) connecting the wiring and magnet installation

The last steps are assembly and finishing of the PMSG. This process begins with the installation of bearings on each housing. After bearings are installed, the rotor and shaft are joined on the rear housing, while the stator is installed on the front housing. By using a special tool, the assembly of these two main components is carried out. After the main components are assembled, the finishing processes can begin. The finishing processes started with installing the output cable on each generator phase. Then painting the insulation on the stator core is carried out to provide safety in the operation of the generator, then the generator is ready to be tested. This whole process is shown in Figure 9.



(a) (b)

**Figure 9.** (a) Assembly process, (b) finishing process-installing output cable and insulation coating.

## 3. Result and Discussion

The assembled PMSG is then going through a performance testing process. This performance test is only for back-EMF parameters, so the set-up of the required test equipment is also relatively simple. The testing tool consists of an electric motor, an oscilloscope, and a laptop as a data recorder. The set-up of the measurement tool can be seen in Figure 10.

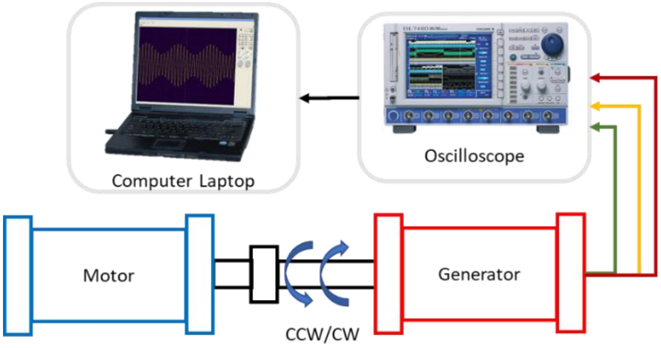



**Figure 10.** Set-up tools for PMSG performance testing.

Measurements are made by rotating the generator using a drive motor and observing the back-EMF output in each phase. The Electricity Coefficient (EC) value of the generator can be calculated by comparing the working rotation and back-EMF output. These output parameters are then compared with the output parameters of the simulation results to ensure that the generator works according to specifications. The results of the comparison of performance and generator simulation can be seen in table 3.

**Table 3.** Performance comparison between testing and simulation.

| | **Frequency** | **Rpm** | **Vmax** | **EC (Vmax/rpm)** |
|---|---|---|---|---|
| **Simulation** | 10 | 50 | 6.8 | **0.14** |
| | 600 | 3000 | 407 | **0.14** |
| **Testing** | 11.5 | 57 | 8.4 | **0.15** |
| | 12.0 | 60 | 8.8 | **0.15** |
| | 12.5 | 63 | 9.2 | **0.15** |
| | 15.4 | 77 | 11.2 | **0.15** |
| | 17.1 | 86 | 12.5 | **0.15** |
| | 19.1 | 96 | 14.0 | **0.15** |
| | 24.1 | 121 | 17.6 | **0.15** |
| | 25.2 | 126 | 18.4 | **0.15** |

The testing results indicate that the manufacturing process is adequate to produce a PMSG per specification. Between the variations of testing RPM and frequency, the generator performance consistently results in the EC value of 0.15. The consistency indicates that the generator is capable of operating reasonably consistently while only deviating about 7 percent from the computer simulation result.

## 4. Conclusion

Overall, the manufacturing process of the generator with this specific performance can be done in Indonesia using the already existing manufacturing technology, such as CNC milling, wire and laser cutting, and argon welding. The wiring, assembly, and finishing process uses manual methods, mainly using custom-made special tools. Although the overall processes are somewhat constrained to available technology in Indonesia, based on the testing, the manufacturing process is sufficient to produce the high RPM small dimension PMSG. This is proven by the testing result, which shows that the EC values of 0.15 compared to simulation EC values of 0.14. The testing value only has around 7 percent difference from the simulation result.

## Acknowledgments

Grateful acknowledgments are delivered to PT Hutama Karya and PT Lentera Bumi Nusantara as this research's funder and research support. Financial support from Hutama Karya has driven many improvements and development to the research and possible future innovation use. Moreover, the supporting data is provided by PT Lentera Bumi Nusantara, and we thank Lentera Bumi Nusantara for its cooperation.

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