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CONTROLLABLE SINGLE-PHASE SMART SYNCHRONOUS GENERATOR TOWARDS SOLAR-PNEUMATIC POWER GENERATION

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ABSTRACT
This paper presents the development of a controllable single-phase surface-mounted permanent magnet synchronous generator (SPSMPMSG) for low speed applications. Presently, the world is faced with degrading climatic conditions that may be worsen if energy need is met by fossil fuel and other conventional means of generation. On the other hand, renewable alternatives are not always of constant speed, and are usually not high enough to turn conventional alternators. There is therefore a need for the development of alternators that can generate electricity from low speed sources. The development of permanent magnet from rare-earth materials has revolutionized the electrical generator development. Permanent magnet machines are characterized by high torque, low noise, high efficiency and high power factor. The use of these magnets also made it possible to add computer based controllability making the generator a smart machine. This paper presents a CAD design of smart generator at an input speed of 500rpm to a turbine to produce a constant output of 220V. Simulation and physical test results produce an output of 220V± 1% and give a clear indication that low speed renewable energy sources can produce usable electrical power.

Keywords: *Smart generator, Permanent magnet generator, stator, rotor, Computer-aided design.*

1. INTRODUCTION

The world is presently leading a campaign of shifting from the conventional way of generating electricity to renewable sources due to the effect of the conventional sources on the climate, Nigeria as a country inclusive. The most commonly installed renewable sources are solar and wind. Solar energy is harvested by the photovoltaic cells and there is a need to store the energy and then invert it to alternating current supply. This requires huge periodical maintenance to keep the system in good shape. The wind generation system is limited due to the available speed of the wind in different area. This particular situation has limited the usage of wind turbine in Nigeria (limited mainly to the coastal region). Then, there are needs to look inward for an effective means of generating electricity for domestic and industrial consumption and at the same time do not contribute to the climatic change. This work is a part of a research on Solar-Pneumatic Energy Storage System for power generation. In the referenced research [1], energy drawn from the sun, through photovoltaic (PV) cells, is used to compress air into a cylinder from where it is used to turn an air turbine at regulated pressures. This paper is concerned with the development of a smart generator that can generate electrical energy from a very low speed such as wind, ocean tides etc.

Permanent magnet machines have been used for decades in applications where simplicity of structure and a low initial cost were of primary importance. More recently, permanent magnet machines have been applied to more demanding applications, primarily as a result of the availability of low-cost power electronic control devices and the improvement of permanent magnet characteristics [2]. The term "permanent magnet machine" describes all electromagnetic energy conversion devices in which the magnetic excitation is supplied by a permanent magnet or several permanent

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magnets on the rotor. The energy converters using permanent magnets include a variety of configurations, and such terms as motor, generator, alternator, stepper motor, linear motor, actuator, transducer, control motor, tachometer, brushless dc motor and many others. The rotor magnetic field in this generator is provided by the permanent magnet. The optimum rotor configuration, rotor electromagnetic and mechanical design, as well as the stator electromagnetic design must be matched to achieve a higher efficient machine of the desired load characteristics, high power factor, and high efficiency and performance [3].

Permanent magnet synchronous generators (PMSG), which is less noisy, highly efficient and has a long life span, have garnered considerable interest due to its high performance. It is becoming one of the most important types of alternator in wind turbine systems [4, 5]. It is known that there are two types of topology, which are axial and radial flux [6, 7, 8]. In an axial flux machine, if magnetic flux linkages run through to axial direction, maximum power density can be obtained. But manufacturing such structured machines is more expensive and several difficulties can be seen particularly over lamination of stators [7]. Radial-flux generator is made of permanent magnet poles which rotate within the stationary armature windings. Comparing these two types of machine structures, it is seen that radial flux structured machines are more available for commercial use [8]. Although, many works have been done on the development of permanent magnet generator, little work has been carried out on single-phase type of this machine. In a.c. generators, magnets are normally rotor-mounted. Rotor classification depends on how the magnets are mounted; surface mounted or exterior, if mounted as air gap magnets, and buried type or interior, if embedded within the core [9-11]. Surface mounted permanent magnet generators have lower air gap flux densities than those with buried magnets, but are easier to manufacture. Interior magnet type rotor configurations produce higher flux densities in the air gap than surface mounted topologies, but suffer from excessive end and inter-polar leakage [12]. In addition, they are costlier to manufacture due to complexity of the rotor topology. This paper is aimed at developing a single phase surface-mounted permanent magnet synchronous generator (SPSMPMSG) that can generate electricity from a low speed turbine.

2. DESIGN OF THE SINGLE-PHASE PERMANENT MAGNET GENERATOR

The design is approached systematically in an orderly progression from the user specification to the achievement of the specified outcomes. In the case of a permanent magnet generator, these include overall dimensions, slot numbers and shapes, magnet features such as type and geometry, and winding details. The design sequence is as shown in figure 1.

3. DESIGN PROCESS: INITIAL CONSIDERATIONS

The design process commences on the basis of a design specification which includes the following; Terminal voltage, V_{ph} (V), Frequency f (Hz), Rated apparent power, Q (kVA), Rotor speed, N (r.p.m.), Number of phases, m, Power factor, cos φ

The number of poles for the generator was chosen to be 12 using equation 1

$$p = \frac{120f}{N} = 12 \qquad (1)$$

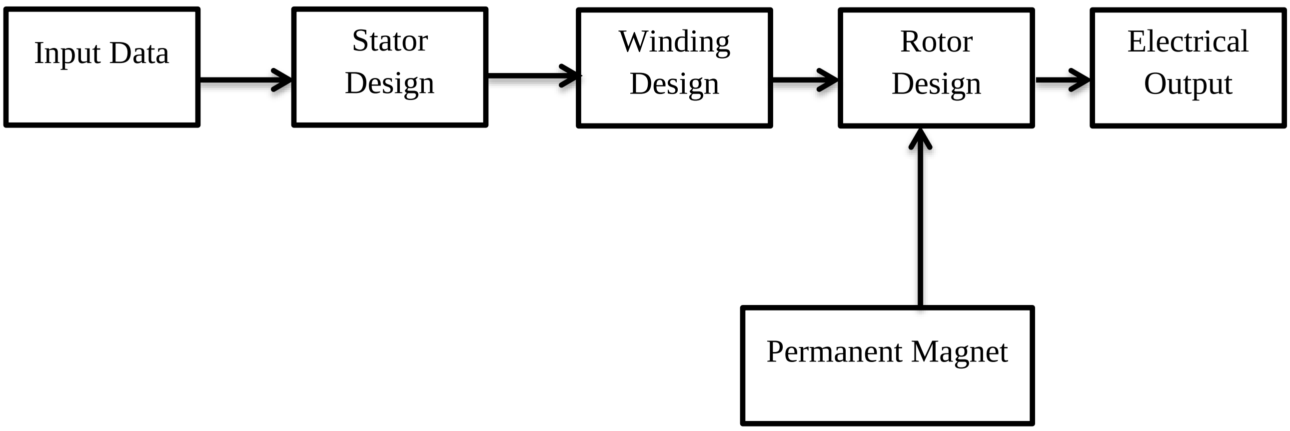


Figure1: Design Sequence for Permanent Magnet Generator

And the rated phase current was found to be 4.17A from equation 2

$I_{ph} = \frac{Q}{mV_{ph}}$ = 4.17A (2)

3.1 Stator Design

Determining the details of core geometry for an electrical machine toward satisfying the requirements of a given design specification constitutes a challenge. The task is complex because of numerous choices available in terms of design parameters such as dimensions, shape and slot number. The task is also onerous, since the wrong choices can perilously affect the performance, ultimately rendering the machine useless. This may explain the reason why many manufacturers prefer to utilize existing lamination designs since they feel safe on account of these already being "tested" before, even though such may leave much to be desired when it comes to optimality. Consider the output equation of equation (3)

$P = \frac{\pi}{2} D_{sb}{}^2 l_c B_g Q_{sel} \omega_r$ (3)

where B_g and Q_{sel} are the initial estimates of the effective air gap flux density and the specific electrical loading respectively. ω_r is the specified prime mover angular velocity. The choice of the value Q_{sel} depends on the cooling method adopted, temperature rise limit. Current density value varies between 8000 to 24000 A/m for permanent magnet machines.

B_g = 10,000 Gauss = 1 Tesla and Q_{sel} is assumed as 11800 A/m

$\omega_r = \frac{2\pi N}{60}$ (4)

By appropriate substitution of the parameters into equation (4), the specified prime mover angular velocity was determined to be 52.37 rad/sec.

Evidently, P is the active power output, which the generator is being designed to deliver. By definition, P is

$P = Q \cos \varphi = m V_{ph} I_{ph} \cos \varphi = 1000\text{W}$ (5)

The term $D_{sb}{}^2 l_c$, which evidently is indicative of the stator bore volume, can now be found as

$D_{sb}{}^2 l_c = \frac{2P}{\pi B_g Q_{sel} \omega_r}$ (6)

Equation (6) is the stator bore diameter and is the core length. The prime mover speed largely determines what the stator bore diameter will be, on the basis of which the core length can be established.

$D_{sb}{}^2 l_c = 0.00103\, m^3$

Existing relationship between D_{sb} and l_c

Pole pitch = $\tau_p = \frac{\pi D_{sb}}{p} = \frac{3.142 \times D_{sb}}{12} = 0.26\, D_{sb}$

Core length / pole pitch = $\frac{l_c}{0.26\, D_{sb}}$ = 1

$l_c = 0.26\, D_{sb}$

$D_{sb}{}^2\, 0.26\, D_{sb} = 0.00103\, m^3$

$D_{sb}{}^3 0.26 = 0.00103\, m^3$

$D_{sb}{}^3 = 0.0039\, m^3 = 0.16 m$

Therefore, $l_c = 0.042\, m$

Stator bore diameter D_{sb} = 0.16 m

Core length = 0.042m

Factors taken into consideration for the design of stator slots are the number, shape and dimensions. Number of slots should be selected in such a way that a balanced winding can be housed. Also, the number of slots should be estimated by considering the advantages and disadvantages of a high number of slots. Several other factors need to be carefully considered. For instance, a large number of slots lead to a reduction of hot spots within windings as well as reducing tooth harmonics. However, this needs to be counterbalanced by the higher cost of lamination, increased leakage reactance, possible saturation in the teeth and reduced mechanical strength. The determination of the number of slots is the next critical design decision, since it has profound effect on the performance of the generator.

Number of slots: Assuming no. of stator slots /pole/phase is 3,

$N_s = 3 \times 12 \times 1 = 36$

Number of slots N_s= 36 slots

3.2 Winding Design

Winding design was carried out in the same manner as for conventional generators. The design of the individual coils was based on the stator pole pitch, which is

$\tau_p = \frac{\pi D_{sb}}{p}$ = 0.04 (7)

where D_{sb} and p represent the stator bore diameter and number of poles respectively. Of course, it is possible to design a winding with coils having a full pitch equal to the pole pitch. As there are many coils as there are slots, which need to be placed as coil groups in slots. The number of slots per pole per phase, q, plays an important role in the winding layout. Number of slot/pole q was obtained as

$q = \frac{N_S}{mp}$ (8)

q = 3slot/pole

Number of coil groups = $\mathrm{p} \times \mathrm{m} = 12 \times 1 = 12$ coil groups

The angular distance between two adjacent slots in electrical degrees can be found from;

$$\xi = \frac{180}{3} = 60^0$$

In order to obtain the generated EMF (E_{ph}) the winding factor K_w, needs to be defined. For this design, the winding factor K_w is 1. To complete the winding design, the number of turns per phase needs to be known. The per phase emf was obtained using equation 9;

$$E_{ph} = 4.44 f \emptyset T_{ph} K_w \qquad (9)$$

The flux per pole across the air gap was found as in equation 10

$$\phi = \frac{B_g \, D_{sb}{}^2 \, l_c}{p} \qquad (10)$$

$$\phi = 0.0056 \, wb$$

Stator turns per phase T_{ph}

$$T_{ph} = \frac{E_{ph}}{4.44 f \emptyset K_w} \qquad (11)$$

$$T_{ph} = 193$$

conductor per phase, T_{cph}

$$T_{cph} = 2T_{ph} \qquad (12)$$

$$T_{cph} = 386$$

It is now possible to update the initial estimate for the specific current loading, Q_{sel} as

$$Q_{sel} = \frac{mT_{cph}}{\pi \, D_{sb}} \, . I_{ph} \qquad (13)$$

$$Q_{sel} = 3200 \, A/m$$

The winding diagram was constructed in accordance with the calculations made above and it is as shown in figure 3

3.3 Rotor Design

Designing an excitation circuit on the basis of permanent magnets is the next challenge. It is common practice to house the magnets on an internal rotor, although some applications may require variations such as an external rotor, or even axial topologies. The following deliberations apply to an external rotor. Evidently, the methodology can be adopted for any other type of rotor. To adequately design an excitation circuit for a permanent magnet generator, details of all flux paths throughout the machine space need to be accounted for. The main object in rotor core design is to ensure that the permanent magnets selected are adequate to provide the flux required under all specified working (operating) conditions of the generator. For this project, the type of rotor employed is a surface mounted rotor which is made up of rotor disc, permanent magnets, shaft and cooling fan. For the poles, 12 rare earth magnets of equal area are placed in a radial form around the stator core. An air gap clearance of 0.42 mm is given between the permanent magnet and the stator teeth. The rotor has a core diameter of 0.28 m and shaft diameter of 0.020 m. Figure 4 and 5 shows the design of the rotor and complete design of the SPSMPMSG.

3.4 Voltage Regulation

The output of the generator was controlled using a micro controllable motorized auto-transformer.

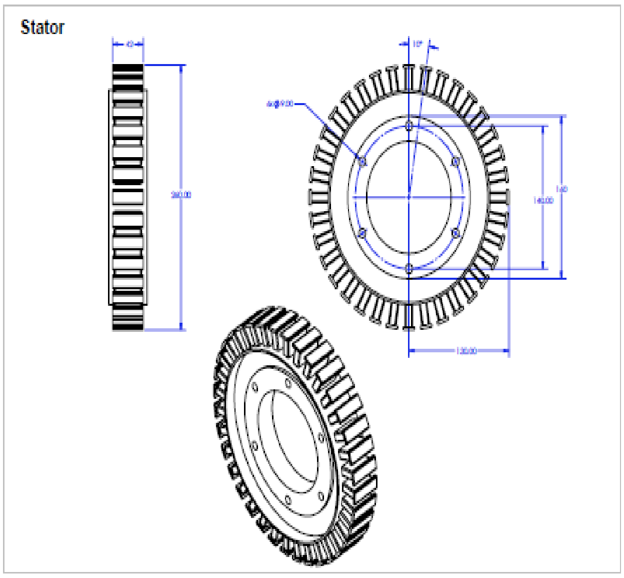


Figure 2: Design of the Stator

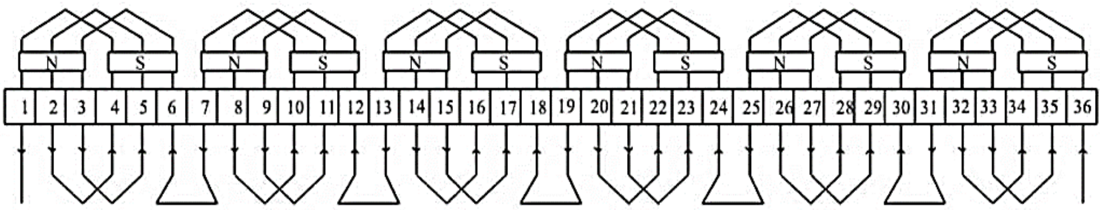


Figure 3: SPSMPMSG Winding Diagram

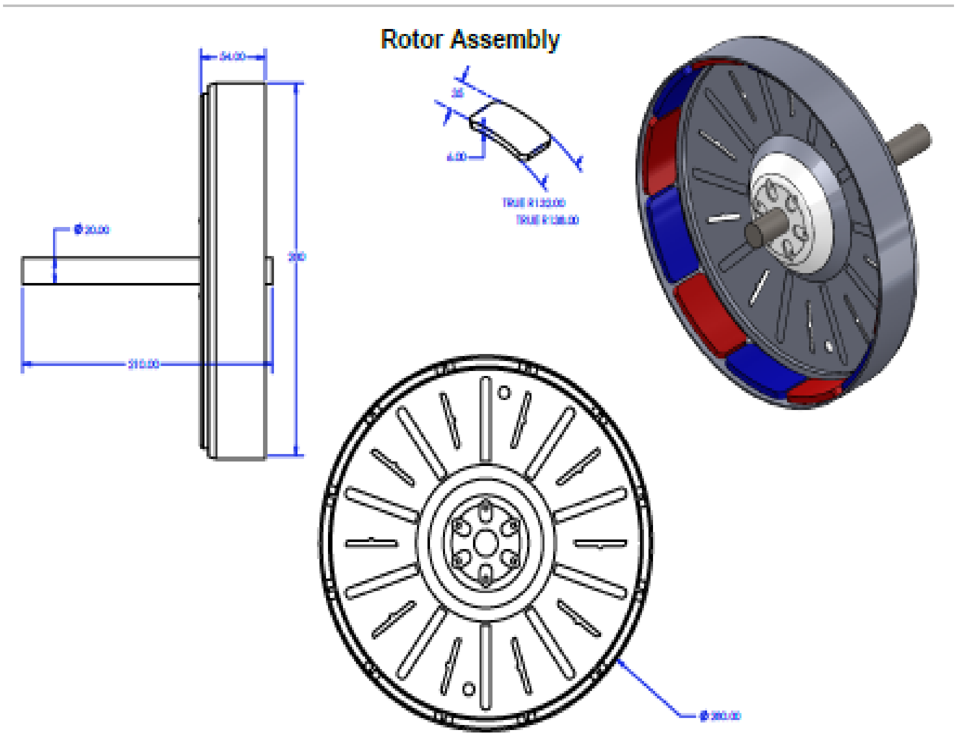
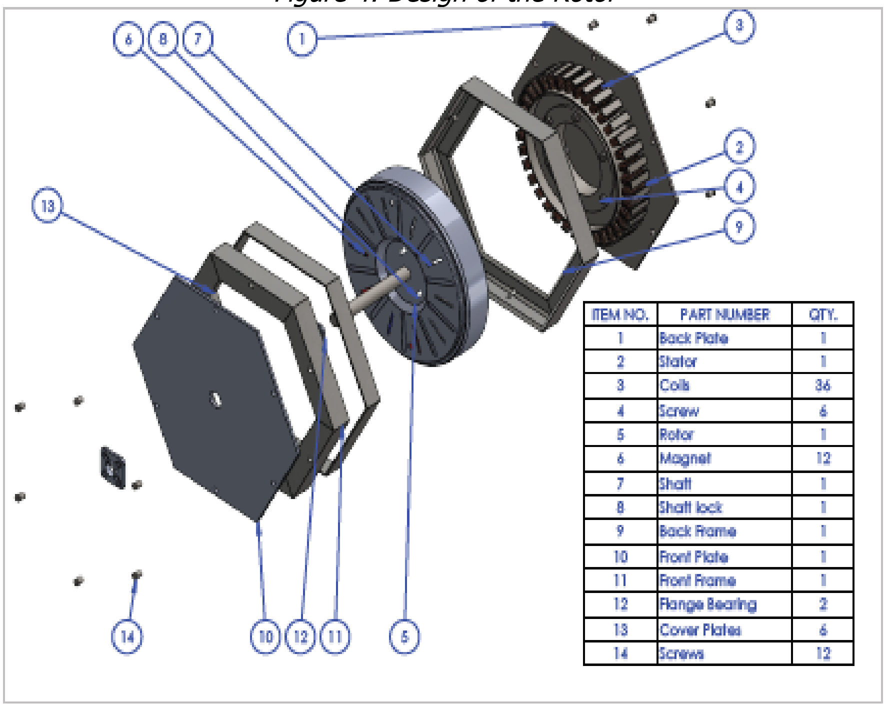


Figure 4: Design of the Rotor



ITEM NO.	PART NUMBER	QTY.
1	Back Plate	1
2	Stator	1
3	Coils	36
4	Screw	6
5	Rotor	1
6	Magnet	12
7	Shaft	1
8	Shaft lock	1
9	Back Frame	1
10	Front Plate	1
11	Front Frame	1
12	Flange Bearing	2
13	Cover Plates	6
14	Screws	12

Figure 5; Complete Assemblage of the SPSMPMSG

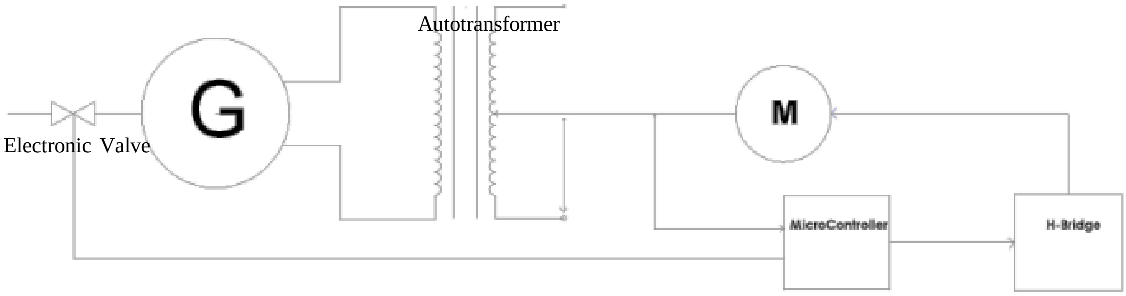


Figure 6: Voltage regulator for the Generator

The micro controllable motorized auto-transformer was chosen in order to get better output even at low speed. The microcontroller was also programmed to regulate the speed of the turbine. The output of the generator is fed into the input of the auto-transformer; the output to be maintained was programmed into the microcontroller. The microcontroller in turn control the generation of pulses in the H-bridge so as to energize the motor. The circuit is as shown in figure 6;

4. RESULTS AND DISCUSSION

The design of the generator was done using CAD, then, the machine was developed and tested. The following diagrams show the developed machine stage by stage. The machine was tested at different speed. The results of the generated voltage output from the generator was tabulated as shown in table 1

Transient analysis of the developed generator was also carried out using ANSYS Maxwell simulation software. The waveform of the generator was satisfactorily sinusoidal. The waveform of the output voltage from the generator is shown in figure 7

5. CONCLUSION

The single-phase surface-mounted permanent magnet synchronous generator has been developed; the design was made with a low turbine speed of 500rpm. Simulated results indicated good performance at low speed and agreed with practical results obtained. The output of the generator was controlled automatically with a motorized auto-transformer. The regulator can regulate as low as 110V to the nominal voltage of 220V. The control of the output of the generator was also achieved by controlling the electric valve of the solar pneumatic source (mechanical energy).

Table 1: Table showing the result of the test carried out on the generator

Speed N/m	Output Voltage V
100	90
200	120
300	160
400	190
500	210

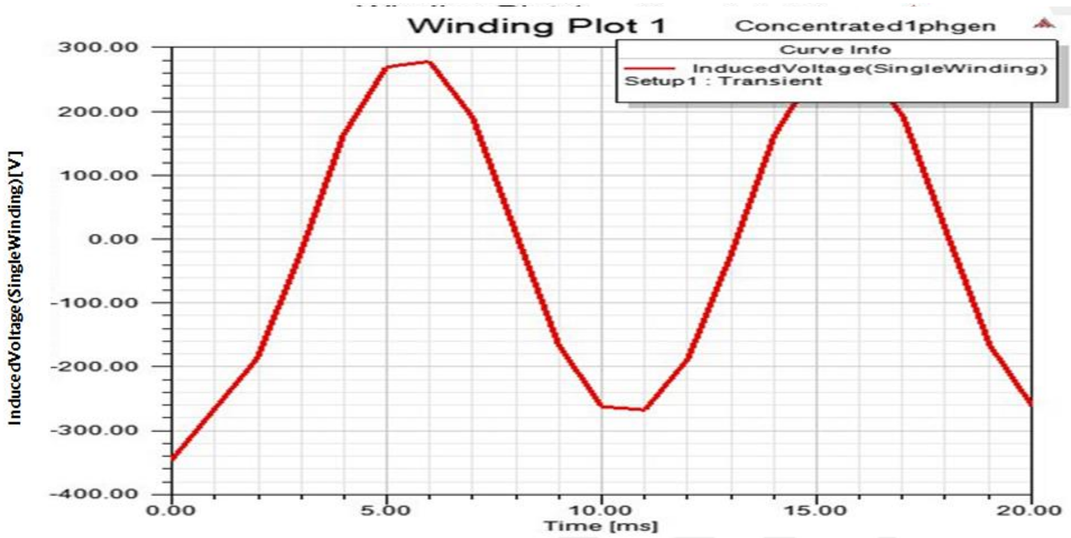


Figure 7: Output Voltage Waveform of the Generator

Figure 8: Developed Stator and Rotor Compartments

Figure 9: Complete Assemblage of the developed Generator.

The output waveform is satisfactorily sinusoidal. The paper reveals that the controllable single-phase surface-mounted permanent magnet synchronous generator which was developed towards solar-pneumatic generation is capable of utilizing renewable energy (compressed air) to generate electricity.

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