A Permanent Magnet Generator with PCB Stator for Low Speed Marine Current Applications

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Abstract: This paper introduces the design and development of a novel axial-flux permanent magnet generator (PMG) using a printed circuit board (PCB) stator winding. This design has the mechanical rigidity, high efficiency and zero cogging torque required for a low speed water current turbine. The PCB stator has simplified the design and construction and avoids any slip rings. The flexible PCB winding represents an ultra thin electromagnetic exciting source where coils are wound in a wedge shape. The proposed multi-poles generator can be used for various low speed applications especially in small marine current energy conversion systems.

1. Introduction

The concern for the world's future good is intimately linked with civilization's need for energy. The global energy demand is continuously increasing. Today's global energy production is highly, in fact 83% dependent on fossil fuel resources such as oil, gas and coal. These resources are limited and their use results in global warming due to emission of greenhouse gases like carbon dioxide. Interest in renewable energy such as wind, geothermal, solar and ocean, has depended on the perceived risks of using fossil fuels.

The ocean contains an enormous energy resource that can be exploited contributing in a sustainable manner to meet the increasing global energy demand. The oceans, covering more than 75% of the Earth, have long been appreciated as a vast renewable resource. Several types of ocean energy sources with different origins (thermal energy and kinetic energy) exist – tidal energy, thermal energy, marine current and ocean waves.

The ocean current resources still remain predominantly untapped. However, the physics behind ocean currents is very promising for energy conversion. Kinetic energy from the sea can be harnessed using relatively conventional techniques which are similar in principle to those for extracting energy from the wind. Though energy conversion from marine currents is quite similar to that of wind energy conversion but there are also several differences between them. The underwater placement of a marine current energy converter (MCEC) gives some advantages such as no noise disturbance for the public, low visual exposure and little use of land space but also adds some challenges like the need for water and salt proof technology, difficult and costly maintenance etc. Another characteristic is the difference in density, which results in a higher power density. The energy content of a marine current of only 1m/s is equivalent to a wind speed of 9m/s. A final characteristic to highlight is the relatively high degree of utilization. A high utilization factor is important to achieve an economically viable power production [1].

A present day typical and a new directly driven marine current power plant are designed. The electromechanical system of a hydro power plant usually consists of three main parts: turbine, gearbox and generator. Due to the low current velocities, a marine current turbine will experience low rotational speeds, typically below 100 rpm. In conventional hydro installation, the generator rotational speed is usually 1500 or 1800 rpm. This means that a gearbox is needed between the turbine and the generator. The gearbox adds to the weight, generates noise, and demands regular maintenance and increases losses. The solution is to use of direct driven generator. In such system [2-3] the generator is directly driven by the turbine. The aim of this research project is to design a direct driven generator well suited to the slow moving marine currents energy conversion system.

2. Double sided pmg using pcb stator

Using permanent magnet (PM) generators as low speed energy converters is very common. The low speed generator does not require step-up gearbox in power transmission between the turbine and the generator, which is typically required in conventional drive train. As the generator is directly driven by the turbine, it is commonly known as a direct drive generator. The advantages are low noise, high overall efficiency due to a low cut-in speed, high reliability, reduced weight and diminished need for maintenance. However, the diameter of a low-speed generator may be rather large because a large number of poles are needed in a low-speed machine.

According to the earlier research [4], the axial-flux PMSG type is very suitable for low speed applications. In low speed direct driven systems, PM axial-flux generators have proven to be superior to radial-flux generators in many aspects such as high torque/volume ratio, high efficiency and short length [5]. However the axial-gap design cannot take advantage of small air gap because the effective air gap, i.e. summation of mechanical air gap and the height of coil winding, is much greater than the radial-gap design. The reluctance of air is extremely high compared to other materials. Reducing the magnet-to-stator gap improves the efficiency. In addition, it cannot reduce the air gap length because small air gap increase the attractive magnetic force in axial direction, which is directly transmitted to the bearing increases the bearing friction loss.

For conventional AFPM machine, the stator is slotted type as the slotless axial field machines require more magnet material than the slotted one. The slotless machines require a larger diameter due to the additional turns. So the copper loss in the slotless machine is higher than that of slotted one. Whereas the tooth/slot structure has cogging torque due to the existence of tooth/slot structure. It generally requires a some innovative design to reduce the cogging torque [4].

The conventional axial-gap machine has the iron loss due to the alternating magnetic flux in the stator. Iron loss consumes significant amount of power and it increases with the increase of the rotor speed and alternating magnetic flux density [6].

The ironless axial-gap structure can be a good solution as it has no iron loss and no need to concern about the cogging torque reduction. But still the air gap flux density problem reveals. The effective air gap is n times of the diameter of the stator coil in addition to the mechanical clearance and the thickness of resin (where n = 1+ number of turns).

The axial-gap machine using PCB winding is developed to improve the demerits of the conventional machine. Since PCB is nonmagnetic material, it has no iron loss in the stator. The magnetic field from the permanent magnets of the two rotors rotates synchronously. This structure has zero cogging torque and there is no unbalanced magnetic force acting on the stator. The effective air gap is the summation of the thickness of the PCB and the mechanical clearance between the rotor and the stator. The PCB is very thin (1/16 inch for a 4 layers PCB) and as the PCB is nonmagnetic material, required mechanical clearance is very small result a very small air gap. This design also prevents the axial magnetic force from being transmitted to the bearing, which decreases mechanical friction loss.

3. Prototype design

The generator assembly includes two rotor yoke (Upper and lower) incorporate with permanent magnet pole and a printed circuit board stator. The stator is fixed and the rotor is connected with the rotary shaft using hub and bearing.

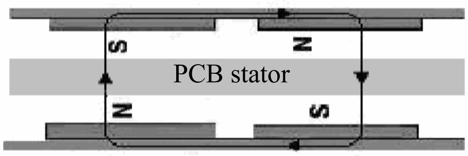

Fig. 1 2D view of the double sided AFPMG with PCB stator

3.1 Rotor

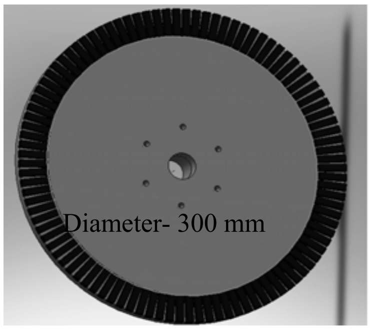

Fig. 2 Rotor disk with magnets

The two rotors are of surface mounted type. The permanent magnets are arranged as shown in fig.1. This generator configuration is termed as TORUS N-S (North-South). The flux direction of this topology is also shown in fig. 1. The two rotors are magnetically and mechanically coupled. The permanent magnets are arranged at equal angular spacing wherein each pair of magnetic pole pairs is equally magnetized so that the north and the south poles thereof are of equal strength. The yoke is made of mild steel (C-1020) of thickness ½ inch. The magnets are of N-42 grade NdFeB. The maximum pull force of the magnet is 22.40 lb. Each rotor section has 100 Poles.

3.2 Stator

The PCB stator winding as used herein refers to a circuit board including a dielectric board (FR-4) with lead wires disposed in different layers of the dielectric board. The PCB stator winding is secured to the fixed structure. The PCB winding are at the outer edge of the rotor. The stator is tapped at the edge and the stepped portion is tightly fitted with the structure.

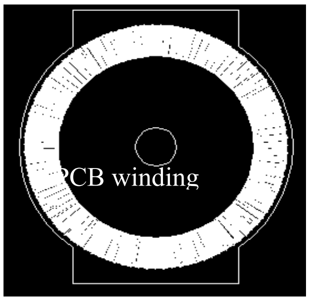

Fig. 3 The PCB stator

3.3 Stator Winding

The PCB is of 4 layers. The windings are wedge shaped which offers more surface area than conventional rectangular shape. In each layer, number of turns is 4 and the number of coil is 100. This is a single phase alternator. In order to increase the voltage of the generator all the coils are connected in series. The choice to increase voltage by connecting all the coils in series is made due to concerns of the current carrying ability of the copper used in the PCB stator. Whereas, to take the advantage of lower resistance, the four stacked stators (4 layers PCB) are wired together in series.

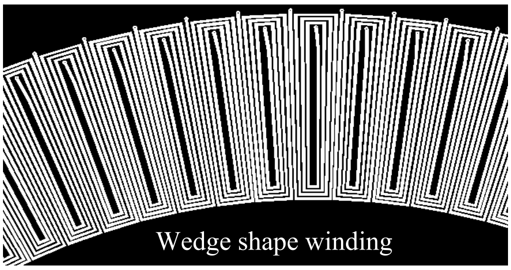

Fig. 4 PCB stator winding

4. Calculated result

Induced voltage is calculated by-

$$E_{rms} = \frac{E_{\max}}{\sqrt{2}} = \frac{2\pi}{\sqrt{2}} \times N \times f \times \varphi_{\max} \times \frac{N_s}{N_{ph}} \quad (1)$$

Where, N is the number of turn per coil, N_s-number of slots, N_{ph}- number of phases, f-electric frequency and Φ_{max}- peak value of the fundamental flux

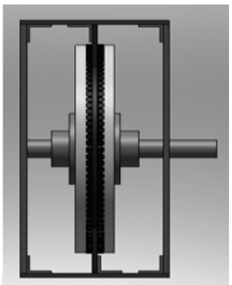

Fig. 5 3D view of the final design

Φ_{max} is calculated from-

$$\varphi_{\max} = A_{magn} \cdot B_{\max} \quad (2)$$

Where, A_{magn}- magnet area and B_{max} - maximum air gap flux density

Air gap flux density is calculated by-

$$B_{\max} = B_r \cdot \frac{l_m}{(l_m + \delta)} \quad (3)$$

Where, Br- remnant flux density of the magnet, lm- magnet length and δ- air gap length between the two rotors

From the equations (1)-(3), the calculated magnet area is 1.6×10^{-4} m^2 and maximum flux from the magnet of 1.1×10^{-4} wb. For this machine, 4 turns will induce about 12 volt. As the trace width of the PCB is 16 mil and the resistance of winding is 34 ohm. High winding resistance is acceptable for micro power generation at sea floor, the intended application of this generator.

5. Test results

5.1 Stress and strain test

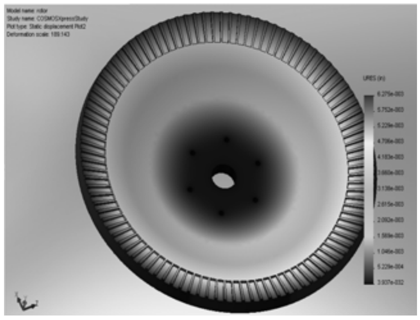

Fig. 6 Static displacement plot of rotor yoke

As the pull force of the magnet is very high, there is a question of using materials and thickness of material for the rotor yoke. The stress and strain of the rotor yoke is tested by FEA using solid works. The maximum stress at the edge is 2e+008 N/m^2 and minimum stress at the center is 5e+005 N/m^2 (see figure 6).

5.2 Test results

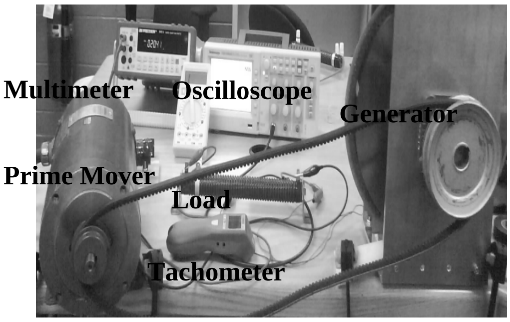

Fig. 7 The testing setup for the generator

The designed generator is tested (fig. 7) and the test result is shown. In fig. 8 the open circuit characteristic is shown. The open circuit voltage at the designed frequency is about 6v which is similar to that of the calculated result.

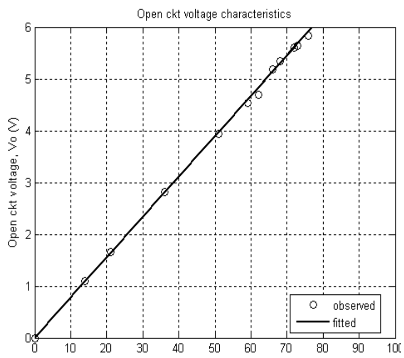

Fig. 8 The open circuit characteristic curve

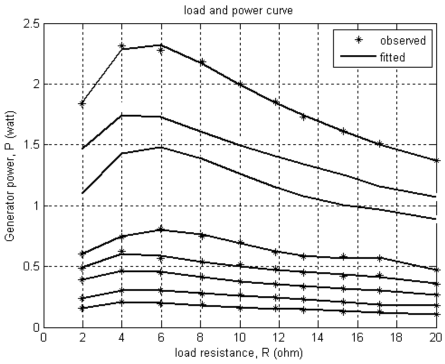

Fig. 9 The power curve

A power resistor is used as a load while testing the generator. In fig. 9 the power curve is presented for different load (0-20 Ohm) and in different frequency (20Hz, 25Hz, 35Hz, 40Hz, 55Hz, 60Hz, 70Hz). The measured resistance of the coil is 4.3ohm. So the maximum power occurs at around 4ohm. The rated power of the generator at 72 rpm is 1.8 watt.

6. Conclusions

The design of a PMG using PCB stator is presented. It is designed to have zero cogging torque and zero iron loss. The PCB stator design simplifies the fabrication and assembly process of building AFPMG. Due to its high efficiency and low loss, it is an excellent choice for small marine current energy conversion system.

Acknowledgement

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