Axial Flux Permanent Magnet Generator with Low Cogging Torque for Maintenance Free under Water Power Generating System

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Abstract- The purpose of this study is to develop an all in one and maintenance free power-generating facility for river, ocean or tidal flow. A rotating shaft with turbine, power generator, and auxiliary systems are installed in the same axial line and under water level. This architecture can reduce the mechanical loss and increase the efficiency of electric power generation. The facility can be easily lifted up on water level for its maintenance. To realize the all in one architecture, an excellent shaft seal is required. The shaft seal can prevent ingress of water into the facility. The frictional torque of the shaft seal should also be minimized to increase the efficiency of electric power generation. A diameter of the power generator, installed into the facility, should be minimized hydrodynamic resistance from its architecture. Barnacles and algae growth onto the surface of facility reduce the generating efficiency and increase the hydrodynamic resistance. A new technology is adopted from a coating of hydrated material.

Keywords- Renewable energy; ocean energy; shaft seal; axial flux generator; tidal current; antifouling.

1. Introduction

Nowadays, ocean energy is one of the most important sources of natural energy sources for energy production [1-5]. We know that river, ocean or tidal power is one of the applicable renewable energy resources for obtaining long-term energy product system. This configuration generally used ocean energy producing, however, axial flux permanent magnet generator have some critical issues [6-9]. The axial flux permanent magnet with low cogging torque generator and auxiliary equipment, to ensure a watertight structure to be mounted above sea level [10-15]. It is not easy to predict that more sun and a daily energy production of wind energy generation, because river or ocean currents, is one of the applicable renewable energy sources. Many engineers know this using a turbine energy in river recovery potential is much higher with ocean or tidal stream water wheel [6-9]. However, some issues remain to be resolved. In this embodiment, several bearings and the shaft rotates for a long support and rotation gear change is necessary, therefore, mechanical loss is inevitable so power generation efficiency decreased. For more electrical energy, swivel mile, turbine, alternator and auxiliary systems have to be designed for optimum power generation system mounted in an axial line below sea level in figure 1.

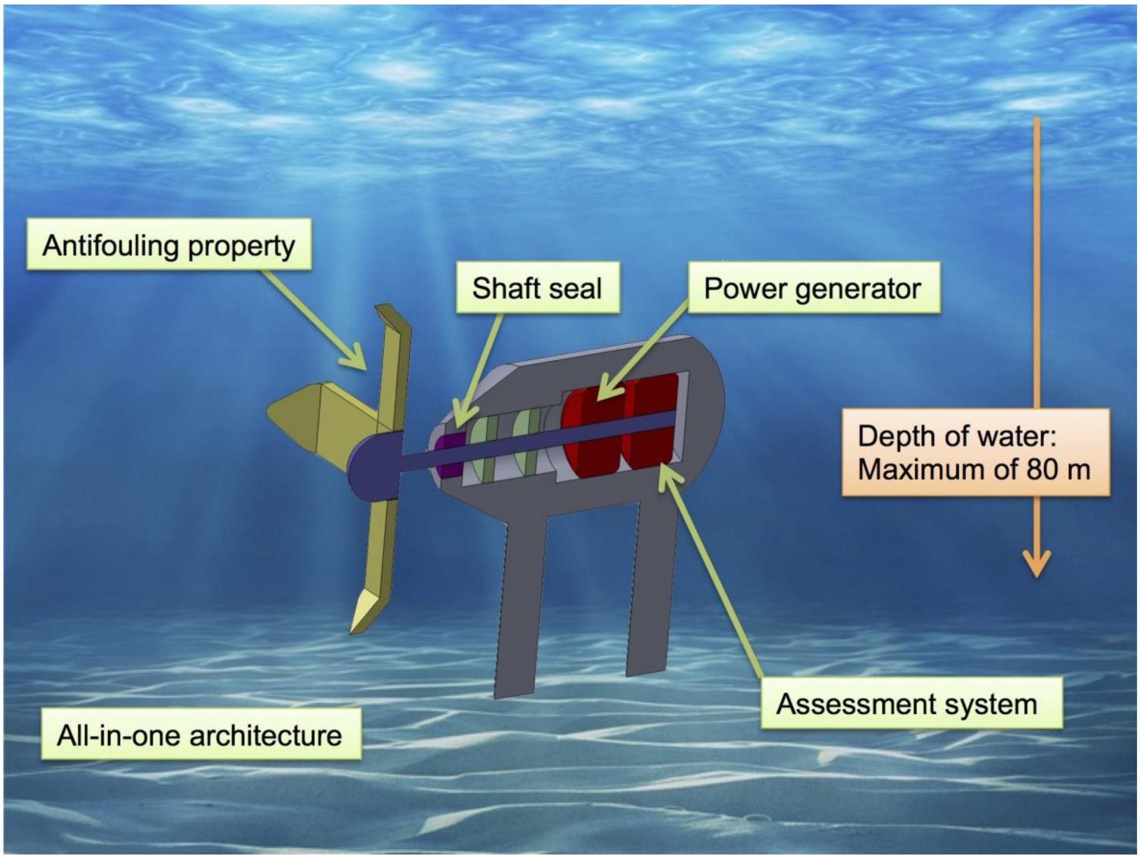

Figure 1. Schematic illustration of all in one and maintenance free power-generating facility.

2. All in One Architecture

A rotating shaft with turbine, power generator, and auxiliary systems are installed in the same axial line and under water level. Figure 2(a) display a widespread design of ocean power generator [33]. Axial flux permanent magnet machine and auxiliary systems must be installed above the sea level to secure waterproof construction. In this embodiment, a long shaft and bearing to support the many ways to change gears, shafts require returning. River or tidal current power structure due to improper alignment, the deviation of the mechanical elements is the reduction of production yield significant energy [5]. In order to generate more electricity, can be reduced the number of these mechanical parts. Figure 2(b) display an optimum power producing system, in which turbine, generator and auxiliary systems with swivel mile are installed under the same axial line and water levels. In this energy producing system, furthermore, perfect shaft seal with low frictional torque that can prevent ingress of seawater is required. Although the shaft seal that can separate between oil and gas had been developed, the shaft seal that can separate between water and air with low frictional torque have not been developed in the past.

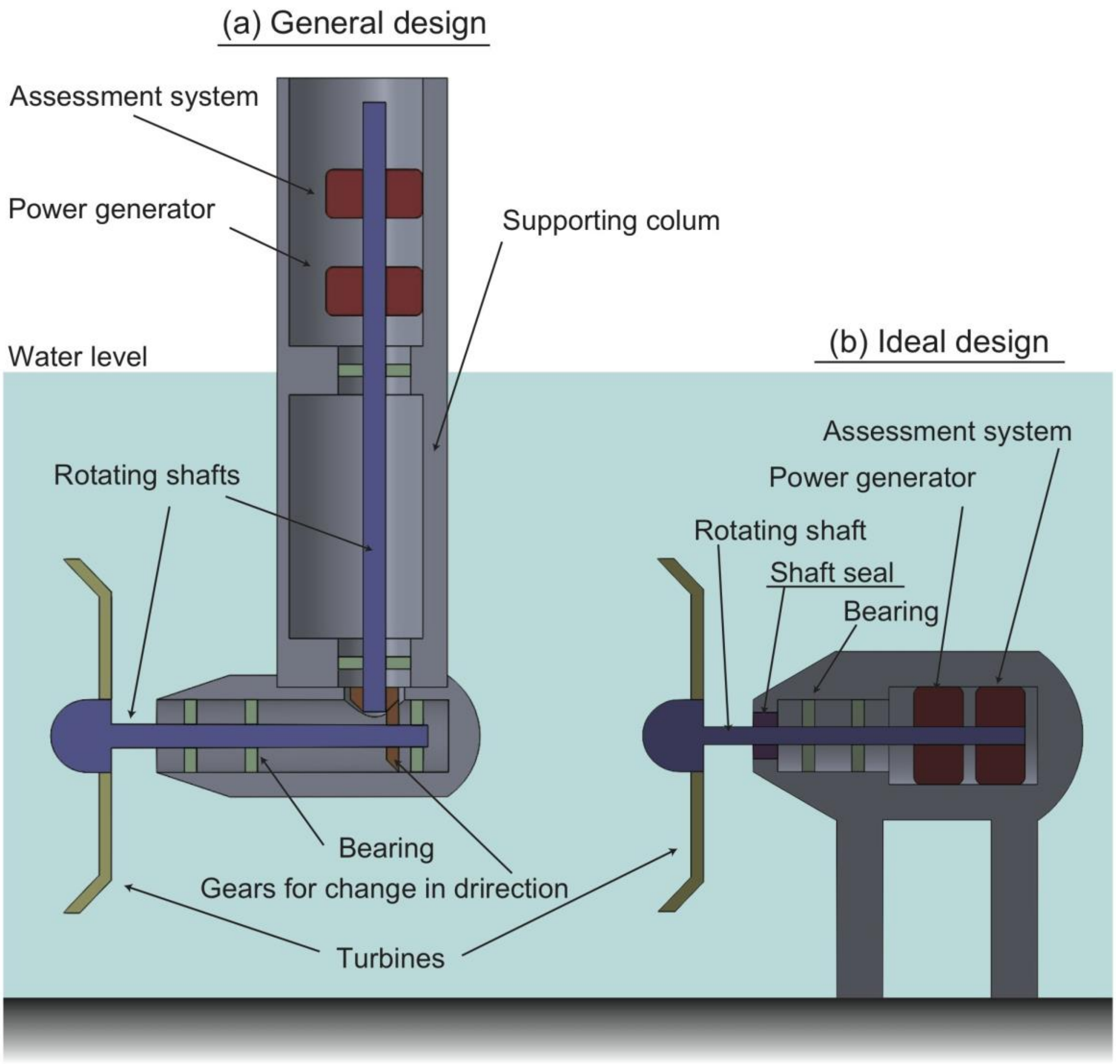

Figure 2. (a) General view of ocean power generator. (b) Optimum design of ocean power producing system.

Figure 3 represents two types of representative shaft seals (a mechanical cover and an oil seal) that have been used as commercial parts. A mechanical seal consists of two main parts: the first ring rotating with the mile and a stationary mating ring with a mechanical body as part of a constant. The first ring is axially pressed against the mating ring. Two ring or dynamic seal surfaces to select a combination of materials for a variety of liquid or gas seal [9]. However, leakage increases the frictional torque as possible is the best way to do that with the minimum rate of a seal by pressing two rings. An oil seal has an elastic polymeric seal lip sliding against the shaft. Seal contact pressure between the fixed and dynamic sealing surfaces by mechanical body is adjusted by a ring spring. It used to differentiate between the main oil seal oils and gases, because the separation between water and air with oil seal is not guaranteed.

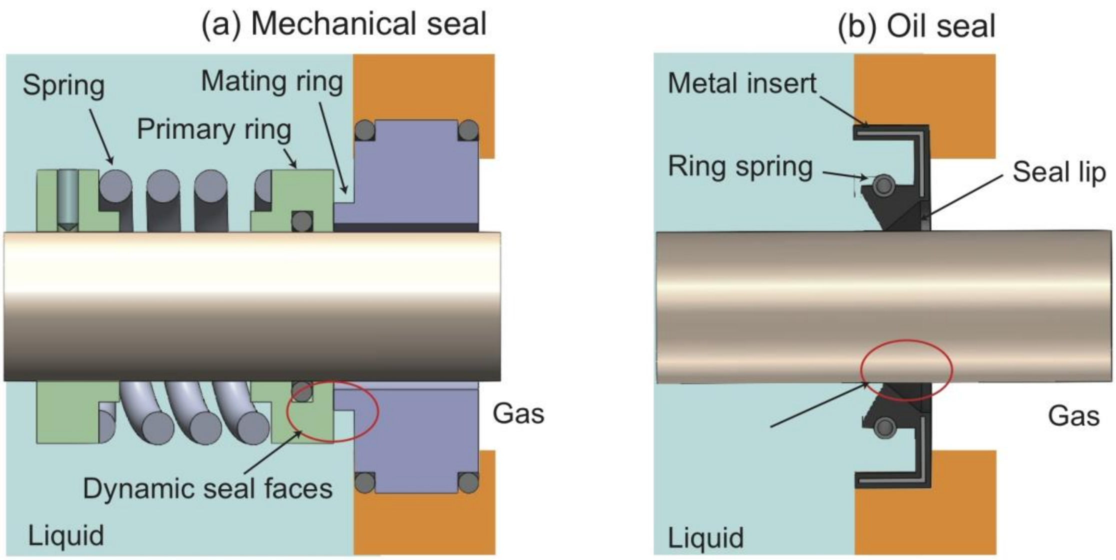

Figure 3. (a) General view of mechanical seal. (b) General view of oil seal.

2.1. Shaft seal

An all-new shaft seal with huge low water leakage and low frictional torque has been developed in order to realize an all-in-one and maintenance-free power-generating facility [25]. Figure 4 represents the structure of the sealing system. The seal lip, made of polyvinyl formal (PVF), was attached to the swivel mile. Suitable pore diameter, density and water holding PVF material has been clarified to have low friction and wear properties [1]. The PVF was composed by a chemical cross-linking reaction of polyvinyl alcohol (PVA) with formaldehyde (HCHO), together with an acid catalyst (H_2SO_4), and has a continuously porous structure. A fiber-reinforced PVF is also adopted in order to match the requirement of high rotational speed of a shaft.

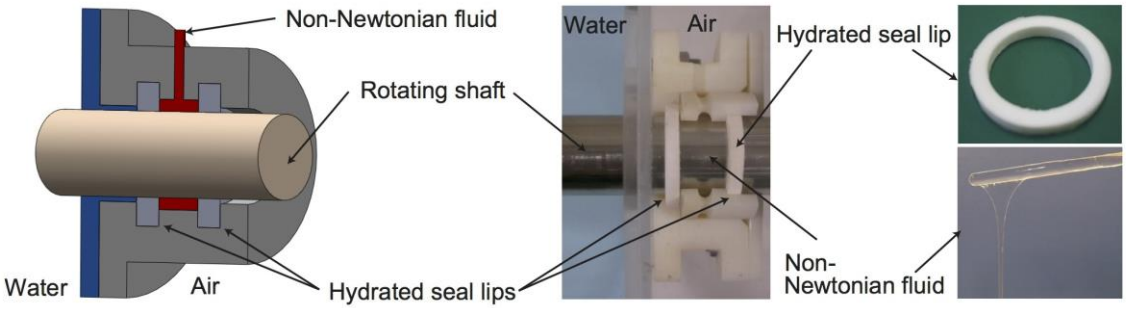

Figure 4. Newly developed shaft seal.

PVF of the seal lip, PVF and dynamic seal between the face despite the expected lubricating viscosity water to maintain hydration while using a lubricating film between the dynamic seal face are very low. To support the lubrication film, an aqueous solution of 3.0wt percentage polyethylene glycol (PEG) was used as a lubricating liquid. The lubricating liquid exhibited non-Newtonian characteristic, where the viscosity reduced with rise in the shear rate.

2.2. Antifouling property

Barnacles do not adsorb onto the surface of soft and hydrated material. We focus on the characteristic. The surface modification, in which a hydrophilic macromolecule or a hydrophilic polymer-gel is grafted, will be proposed. To obtain the tight binding between a base material and a hydrated layer, the ultraprecision machining by using a micro slurry-jet erosion technique or a microelectromechanical (MEMS) technique will be adopted in order to increase the superficial area at microscopic level.

3. Power Generator and Assessment System

A permanent magnet axial flux generator is appropriate for installation in the all-in-one architecture with a long cylinder of machine and electrical room. To increase the power generation amount in the generator, the pole shifting technique is proposed for reducing the cogging torque. The effectiveness of the pole shifting technique on the cogging torque reduction of the axial flux generator has been confirmed in previous studies, in which the axial flux generator was employed in micro wind turbine. In order to evaluate the performance of both the generator and the power-generating facility, an appropriate assessment system will be proposed, based on the previous studies. This generator power will be 550W and it will be useful under low speed conditions. Generator will has axial flux type with permanent magnets. In addition, generator design includes minimum cogging torque and maximum flux density. To provide a maximum flux density NdFeB permanent magnets have been used in the design. Fig 5. shows the 3D model of proposed generator.

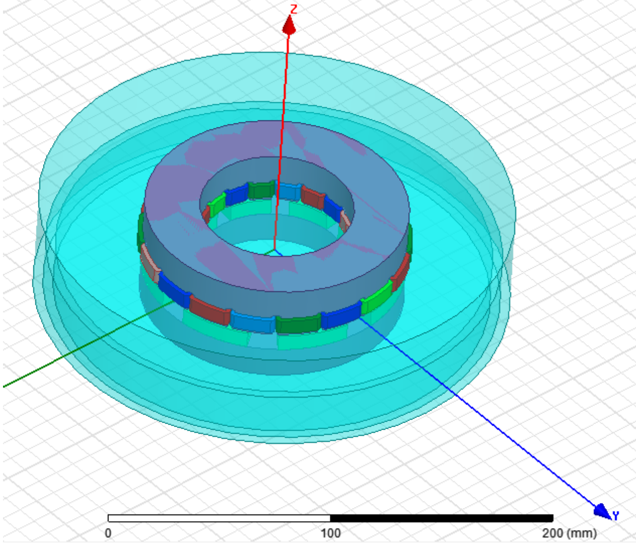

Fig. 5. Developed 550W axial flux generator

Figure six shows NdFeB N42 grade B-H curve under room temperature that used in axial flux generator. The permanent magnet materials are better, particularly after the neodymium-iron-boron (NdFeB) magnets were discovered [16-24]. Also, table one. Shows axial flux permanent magnet generator dimension parameters.

Table 1. Axial Flux Permanent Magnet Generator Parameters

Rated power	**550 W**
Rated speed	750 RPM
Air gap length	1 mm
Number of Poles	8
Connection type	Star-Delta
Phase voltage	220 V
Frequency	50 Hz
Outer Diameter	128 mm
Inner Diameter	73 mm
Length	27 mm

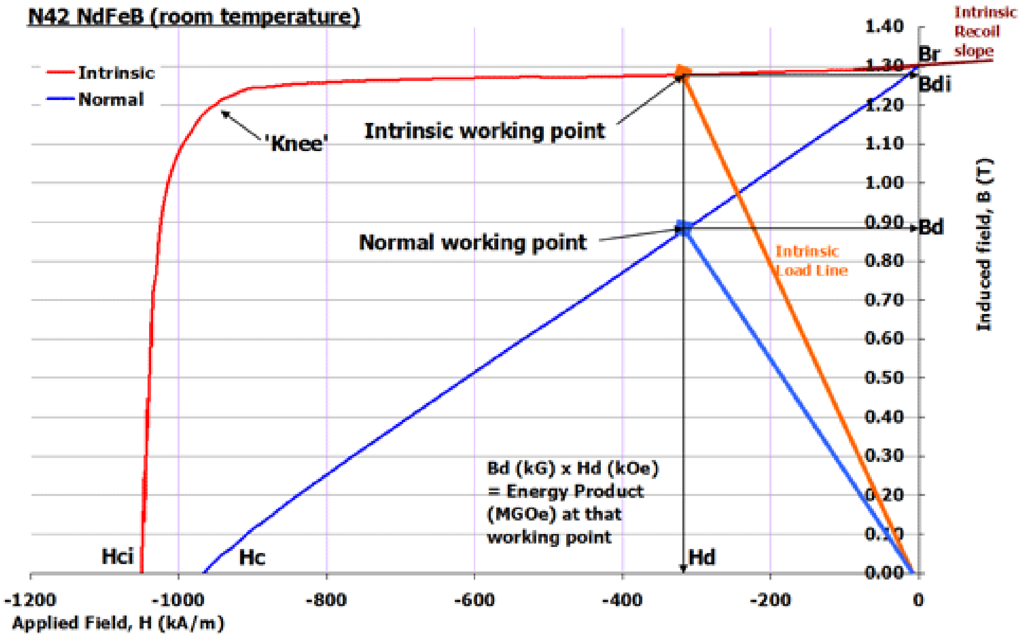

Fig. 6. NdFeB N42 grade B-H curve under room temperature

4. Analysis Results

Simulation results obtained axial flux permanent magnet configuration and permanent magnet (NdFeB-42). Phase current, phase voltage, line voltage, and efficiency characteristics have been investigated under load.

$$T_{cog}(\theta_r) = -\frac{1}{2}\phi_g^2 \frac{dR}{d\theta_r} \quad (1)$$

$$T_\alpha = -\frac{\partial W(\alpha)}{\partial \alpha} = \frac{L_s}{2\mu_0}\left(R_2^2 - R_1^2\right)\pi \cdot \sum_{n=0}^{\infty} G_{nNL} B_{nNL} \sin\left(nNL\alpha + \frac{1}{2}nNL\alpha_s\right)\frac{1}{\alpha_s}\sin\left(\frac{1}{2}nNL\alpha_s\right) \quad (2)$$

The cogging torque can be written as Eq. 1 and 2. Where, R is the air gap reluctance and ϕ_g is air gap flux [26-30].

$$\frac{1}{\alpha_s}\sin\left(\frac{1}{2}nNL\alpha_s\right) = 0 \quad (3)$$

$$\alpha_s = \frac{2m\pi}{NL} \ (m = 1,2,3....N_p / N_l - 1)$$

Eq. 2 is additional method of calculated cogging torque. It called energy method of calculate cogging torque [31-32]. Where T, W(α), α , L_s , α_s are the cogging torque, energy in the air-gap, angle of rotor, stack length, skew angle (Eq. 4), respectively.

Eq. 5 can determine the induced voltage of a concentrated winding per phase.

$$E_f = 4.44 k_w N_p \phi_g (N_r / 60) \quad (5)$$

The equations above mentioned are used in analysis to determine effect of underwater application. Results of this analysis presented in between Fig.7 and Fig. 12

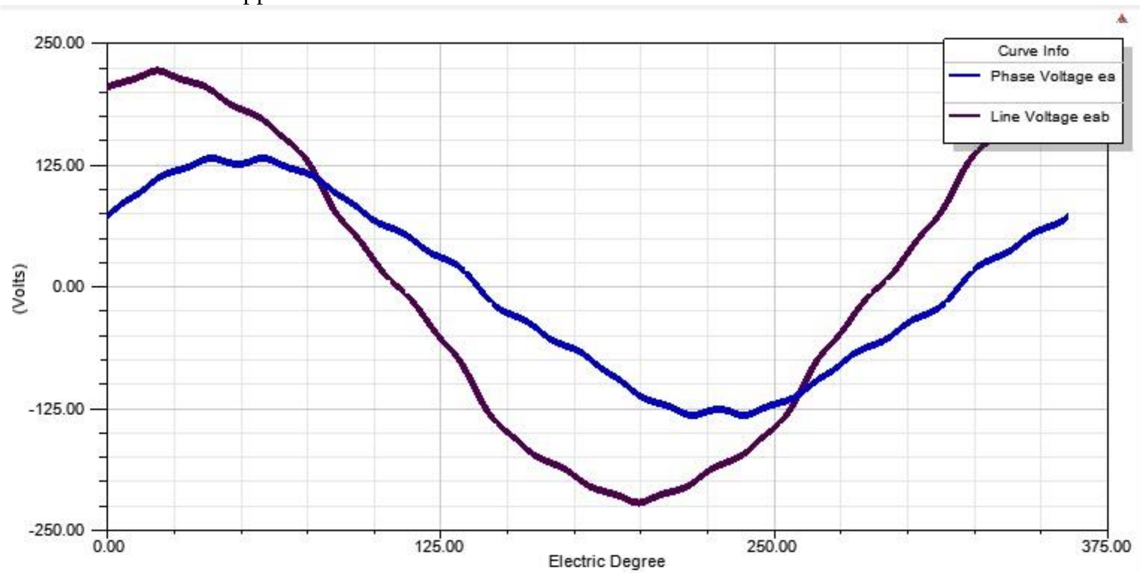

Fig. 7. Induced phase and line voltages at rated speed @750 rpm

Figure 7 and Figure 8 shows that induced phase and line voltages at rated speed and efficiency of axial flux permanent magnet generator respectively. Output line voltage is achieved desired voltage value. In addition, efficiency value is about 80 % for axial flux generator.

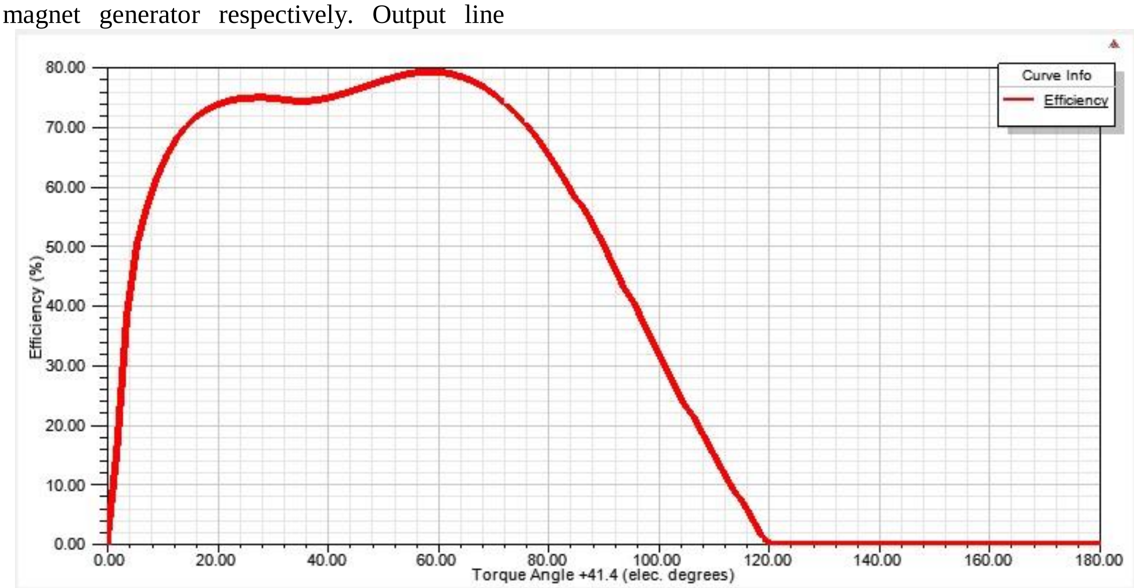

Fig. 8. Efficiency of axial flux permanent magnet generator

$$\eta = \frac{P_{elec}}{P_{mech}} \times 100 \qquad (6)$$

Turbine provides input mechanical energy into system, therefore generated output electrical energy depends on directly input mechanical energy. Eq. 6 shows that how efficiency changed. In addition, this kind of machine effected from tidal current or river speed as input mechanical power. This tidal current or river speed variation always occur so efficiency of machine suddenly changed in this case.

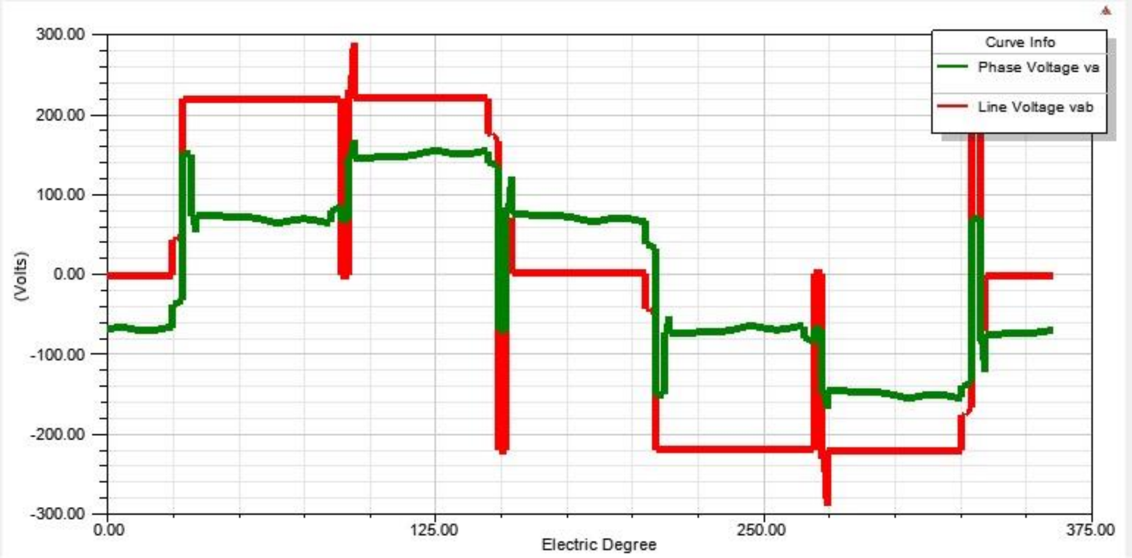

Fig. 9. Phase and line voltages under load

When the electrical load have been taken on the circuit, phase voltages and phase currents (i_a, i_b, i_c) seen in Figure 9 and Figure 10 respectively. Voltage sag occurred in circuit when the electrical load is active. In order to reduce cogging torque, permanent magnets of generator are skewed. Therefore, the induced voltage and current in the windings under the magnet, are also depends on the shift angle. The way to avoid this, to use sinusoidal pressed type magnet with a special design. The generator is designed to provide 220 V at 750 rpm, therefore, the results obtained from simulation prove that the designed generator can provide desired output line voltage value.

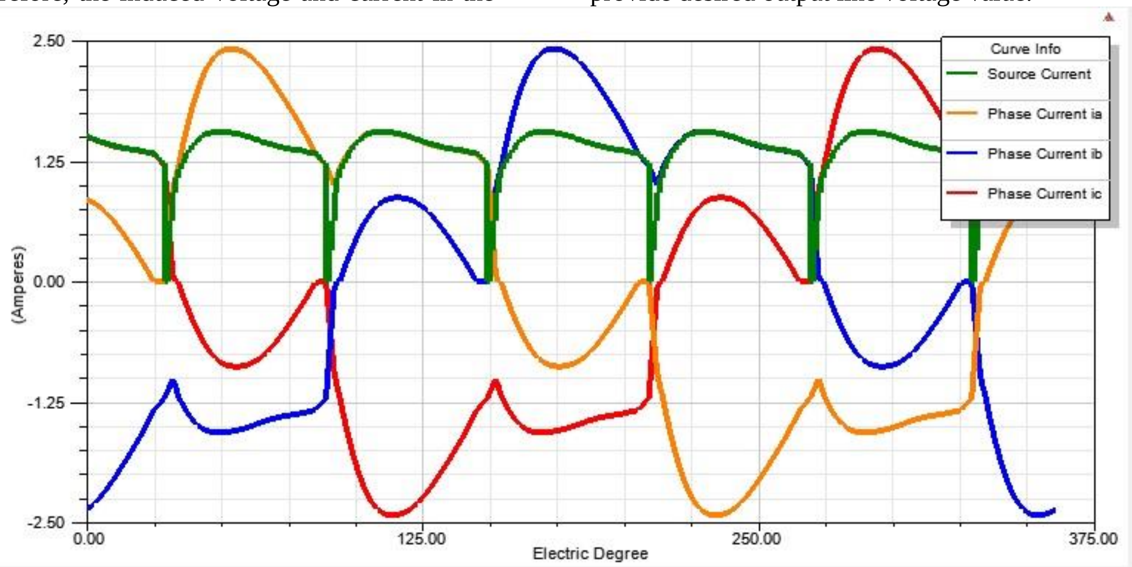

Fig 10. Phase currents (i_a, i_b, i_c) under load

Figure 11 shows three dimensional transient analysis stator currents results. Both analytic and 3D simulations give similar results. These results verified the obtained numerical vales are correct.

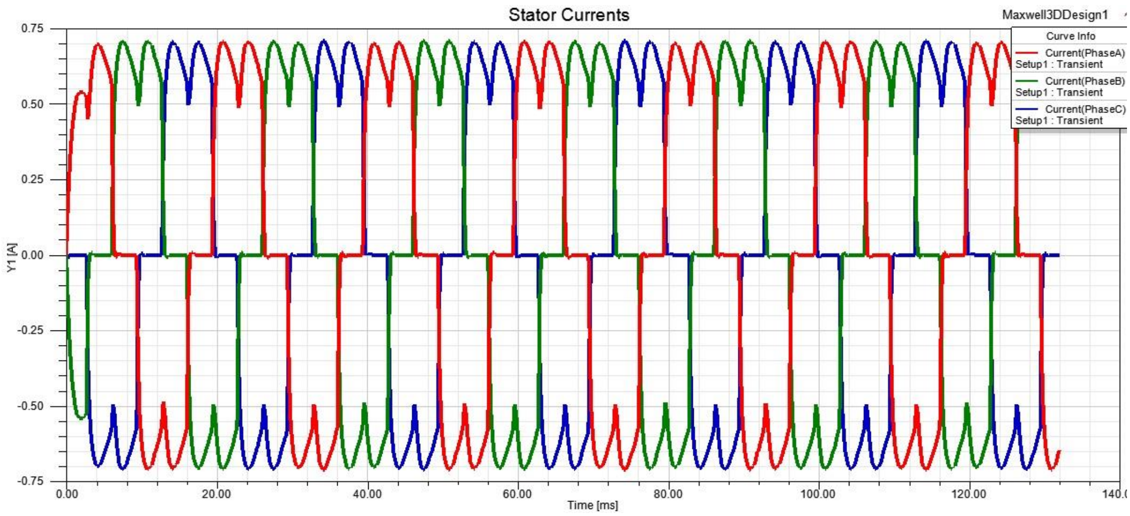

Fig. 11. 3 D Transient simulation stator currents results under 0.1 s

Three-dimensional transient analysis of axial flux permanent generator was carried out. Stator and rotor magnetic flux density is about 1 T at time: 0.2 s, speed: 750 rpm and 182.5 electrical degree. Figure 12 shows that this situation.

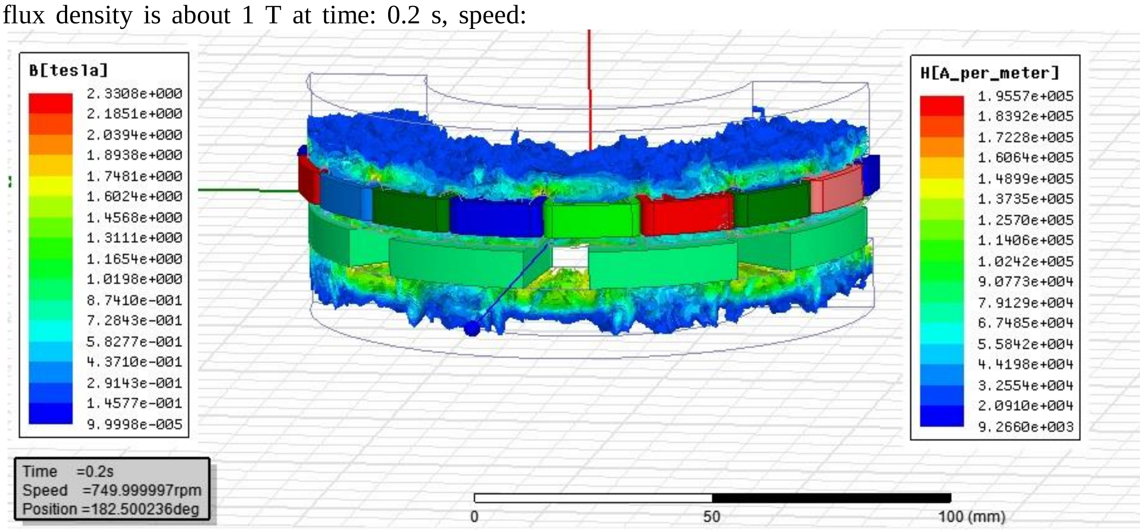

Fig. 12. 3 D Transient simulation stator and rotor magnetic flux density at time speed and position respectively

$$\nabla^2\Psi = \nabla \bullet M \qquad (7)$$

$$H = -\nabla\Psi \qquad (8)$$

Where, H is the field intensity and M is magnetizing vector. Permanent magnets field describes by Eq. 7 and Eq. 8.

5. Conclusion

Axial flux permanent magnet generator designed for under water power generating system. In addition, all in one architecture of system is investigated in the study. NdFeB42 grade permanent magnet used in generator to obtain better efficiency in small volume. So axial flux permanent magnet generator using pole shifting obtained better cogging torque. Both analytic and 3D simulations have been realized in study and results shows that analytic and three-dimensional results similar for axial flux generator. A newly developed shaft seal for all in one architecture is presented in the study. As a result, a new all in one concept under waterpower generating system using axial flux permanent magnet generator with low cogging torque presented.

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