PERFORMANCE ANALYSIS OF A STEPPER MOTOR TO USE IN A WAVE ENERGY CONVERTER

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Abstract: One of the main advantages of ocean waves as resources for electrical energy production is its high energy density. Several methods have been proposed for the conversion of ocean wave that is mechanical energy into electrical energy. One such method consist the use of a direct drive generator with a point absorber floating element. The generator is driven by mechanical mechanism system and floating element oscillates due to the sea wave's movement. This paper presents the study of design and steady state of a stepper motor as a generator mode, to use in a wave energy conversion system. A NEMA 23 single-phase stepper motor has been chosen. Based on the dimension of the selected stepper motor, magnetic flux density was solved by using a finite element analysis tool. The effect of the parameter of the stepper motor such as air-gap, thickness of permanent magnet and type of permanent magnet on the performance of stepper motor are analyzed by FEMM software and the results are also discussed.

Keywords: Finite Element Analysis (FEA), Finite element magnetic method (FEMM), Stepper Motor, Wave energy, Wave energy conversion system

I. INTRODUCTION

The estimated available energy in oceans is between 40 000 TWh and 80 000 TWh per year, mostly found in offshore locations. Ocean energy comes in a variety of forms such as marine currents, tidal currents, geothermal vents, and waves, among them wave energy is the most interesting because it has the highest energy density [8]. The energy conversion from the ocean waves into electrical energy has been considered for a long time. The wave energy, its current status and perspectives have carefully been documented in [3,4].

Wave energy converters (WEC) convert the mechanical energy of waves into electrical energy. WECs traditionally use a system which converts the slow linear motion of the wave energy absorber to a high speed rotating motion of generators which require complex mechanical interfaces [9]. Compared with more mature renewable technologies, such as wind and solar energy, wave energy converters (WECs) are not yet commercially competitive. There are several concepts being tested and some of them have already reached full scale. In order to convert wave energy into electricity, WECs must have some kind of Power Take-Off (PTO). Main characteristics of a PTO system should include which ability to create high thrust which induces low velocity movements upon the floating bodies because of sea waves; high efficiency which is related from the economical point of view with the electricity cost; low maintenance requirements due to the obvious WEC inaccessibility during large periods of time [2]. The WEC and its mechanical mechanisms PTO components are illustrated in Fig. 1.The main components is a floating buoy connected to mechanical mechanisms which rotate the generator. Alternatively, in many applications, stepper motor can be used low speed generators. Thus, permanent magnet stepper motor is chosen as the low speed generator. In this paper, after permanent magnet stepper motor (PMSM) is designed by theoretical model, this design is analysed again by finite element analysis (FEA) software.

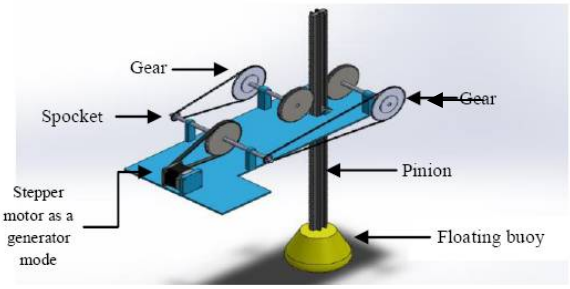

Fig.1. Schematic of Wave Energy Converter

II. WAVE ENERGY GENERATION

Wave energy generation refers to the energy of ocean surface waves and the utilisation of that energy to generate electricity. Wave energy depends on wind speed, time duration of the wind blowing and the distance of open water that the wind has blown over (fetch), and water depth [5].

Wave power could be determined by wave height, wavelength, and water density. The following equation is described mathematically [6]:

$$P = \frac{\rho g^2 H^2 T}{32\pi} \quad (1)$$

where:
P = wave energy flux per unit wave crest length (kW/m)
P = the mass density of the water(kg/m^3),
g = gravitational gravity (m/s^2)
H = Wave height (m)
T =Wave time cycle (s)

For example: for 1.6 m wave height and 10 seconds period, the power produced is approximately 12.8 kW/m.

2.1. Wave Energy Converters

WECs have been developed to extract energy from shoreline out to the deeper waters offshore. These devices are generally categorized by the installation location and the Power Take-Off (PTO) system. Locations are shoreline, near shore and offshore (Fig. 2).

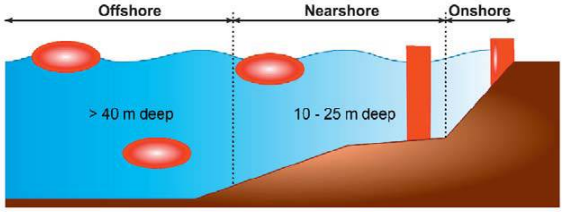

Fig.2. WECs location [1]

In this context, most devices can be characterized as belonging to six types: Attenuator, Point absorber, Oscillating wave surge converter, Oscillating water column, Overtopping device and Submerged pressure differential [1]. This system is based on the point absorber.

2.2.1. Point Absorber

The point absorber is a floating structure that captures energy from the vertical motion of the waves. This up-and-down motion of the device drives generators that create an electric current.

III. STEPPER MOTOR

A stepper motor is an electromechanical device which converts electrical pulses into discrete mechanical movements. The shaft or spindle of a stepper motor rotates in discrete step increments when electrical command pulses are applied to it in the proper sequence. The motors rotation has several direct relationships to these applied input pulses. The sequence of the applied pulses is directly related to the direction of motor shafts rotation.

The speed of the motor shafts rotation is directly related to the frequency of the input pulses and the length of rotation is directly related to the number of input pulses applied. The desired value parameters of stepper motor are shown in Table 1.

Name of Parameters	Rated Value	Unit
Number of phases	single	phase
Number of pole pairs	25	Pole
Air gap distance	0.381	mm

.Table1: Specifications of Stepper Motor

3.1. Types of Stepper Motor

There is a large variety of stepper motors which can be divided into the following three basic categories:

(a)Variable Reluctance
(b)Permanent Magnet
(c)Hybrid

3.1.1. Permanent Magnet Stepper Motor

Fig. 3 shows a cutaway diagram of a typical permanent magnet stepper motor. The rotor for the permanent magnet motor is called a canstack rotor. The canstack rotor shows that the permanent magnet motor can have multiple rotor windings, which means that the shaft for this type of stepper motor will turn fewer degrees as each pulse of current is received at the stator. For example, if the rotor has 50 teeth and the stator has 8 poles with 5 teeth each (total of 40 teeth), the stepper motor is able to move 200 distinct steps to make one complete revolution. This means that shaft of the motor will turn 1.8° per step. The main feature of the permanent magnet motor is that a permanent magnet is used for the rotor, which means that no brushes are required. The drawback of this type of motor is that it has relatively low torque and must be used for low-speed applications.

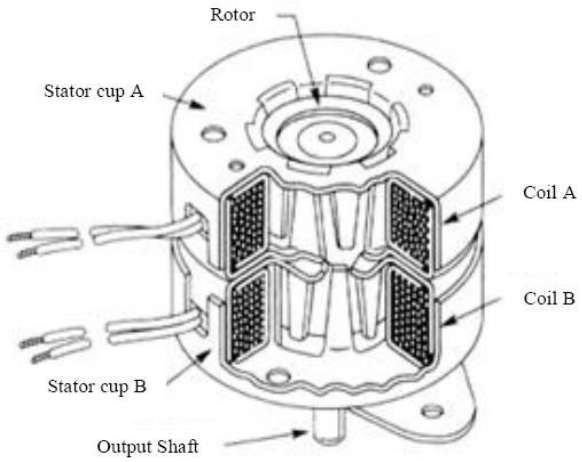

Fig.3. Cutaway diagram of a permanent magnet stepper motor

3.2. Design Equation for Permanent Magnet Stepper Motor

The total rotor inertia of the permanent magnet stepper motor is calculated from equation (2) to equation (5).

The shaft inertia J_{shaft}, oz.in.s^2, is

$$J_{shaft} = 0.0184\left[\frac{D_s}{2}\right]^4 L_{sh} \quad (2)$$

Where D_s is stator diameter and L_{sh} is length of shaft.

The inertia of the hub J_{hub}, oz.in.s^2, is

$$J_{hub} = 0.00636\left[\frac{D_{rm}}{2}\right]^4 L_{hub} \quad (3)$$

Where D_{rm} is diameter of the magnet and L_{hub} is length of hub.

The inertia of the magnet J_{mag}, oz.in.s^2, is

$$J_{mag}=\left[\frac{Dro}{2}\right]^4 \frac{L_{mag}\left(\text{mag density}\right)}{772}-\left[\frac{Drm}{2}\right]^4 \frac{L_{mag}\,(\text{mag density})}{772} \quad (4)$$

Where D_{ro} is outside diameter of the rotor and L_{mag} is length of magnet.

The total rotor inertia J_{rotor} is then:

$$J_{rotor}= J_{shaft} + J_{hub} + J_{mag} \quad (5)$$

3.2.1. Stator Pole Pieces Calculation

The ID of the stator D_{si} is found as follows:

$$D_{si}=D_{so}+2L_g \quad (6)$$

From the required resolution, a number of stator teeth are selected. The step angle, θ_s=1.8 is equal to 360 divided by the total number of stator teeth, N_s.

$$\text{So, } N_s=\frac{360}{\theta_s} \quad (7)$$

Then the number of teeth on one phase set N_{sp} becomes:

$$N_{sp}=\frac{N_s}{2} \quad (8)$$

Each phase set consists of two pole pieces P_{pc} so each pole piece has one-half of the teeth N_{pc},

$$N_{pc}=\frac{N_{sp}}{2} \quad (9)$$

3.2.2. Stator Teeth Calculation

The circumference of the stator inner diameter (ID) C_{si},

$$C_{si}=\pi D_{si} \quad (10)$$

Determine the space available for teeth by dividing C_{si} by the total teeth N_{sp}.

$$L_{space}=C_{si}/N_{sp} \quad (11)$$

3.2.3. Winding and Winding Resistance

The available winding area A_{wnd} is

$$A_{wnd}=\left[\frac{D_{so}-\left(D_{bsi}+2T_{mtl}\right)}{2}\right]\left(w_b-2T_{mtl}\right) \quad (12)$$

$$R_{ph}=\frac{(MTL,in)\left(N_{ph}\rho_\Omega\right)}{(12in/ft)(1000ft)} \quad (13)$$

3.2.4. Estimating the Torque

$$T_{av}= 90P^2F_1\varphi_2 \text{ oz.in} \quad (14)$$

Where;

P =number of pole pairs

F_1 =stator mmf, A.turn

Φ_2 =flux under one rotor pole

3.2.5. Efficiency Calculation

The stator copper losses are given by,

$$P_{cu}=nI^2R \quad (15)$$

where;

n =number of phases

I =current in RMS value (A)

R =winding resistance (ohm)

The total losses at full load is given by,

$$P_{losses}=P_{cu} + \text{no load losses} \quad (16)$$

Output power of the motor can be calculated by,

$$P_{out}=VI \quad (17)$$

Input power of the motor is calculated by the following equation,

$$P_{in}= P_{out}+ P_{losses} \quad (18)$$

Efficiency of the motor can be calculated by,

$$\text{efficiency}=P_{out}/P_{in}x100\% \quad (19)$$

According to the above equations, resistance, torque, power losses and efficiency can be calculated.

3.3. Design Results for Stepper Motor

The mechanical design parameters of the permanent magnet stepper motor are shown in Table 2.

Parameters	Value	Unit
Outer diameter of stator, D_{so}	5.6	cm
Inner diameter of stator, D_{si}	2.8	cm
Average radius of stator winding	2.39	cm
Active length of stator winding	10.6	cm
The number of turn per coil	24	turns
The total number of stator coil	23	
Air gap distance, L_g	0.381	mm
Air gap flux density, B	0.5	T

Table2: The Mechanical Design Parameters for Permanent Magnet Stepper Motor

The output results for permanent magnet stepper motor are shown in Table 3. This table shows stepper motor 24V, 4A. The output power, stator resistance, the developed torque and efficicency of the machine are 54W, 2.5ohm, 9Nm and 56.3%.

Parameters	Value	Unit
rated voltage	24	V
rated current	4	A
The stator resistance	2.5	ohm
The stator inductance	3.0	mH
The copper losses	40	W
The input power	96	W
The output power	54	W
The developed torque of the machine	9	Nm
Efficiency	56.3	%

Table3: Electrical Design Results for Permanent Magnet Stepper Motor

3.4. Finite Element Analysis

Finite element analysis (FEA) can be used to analyse the linear electric or magnetic behaviour of devices. Analyses typically involve the evaluation of magnetic, electric and thermal fields. Further applications include the analysis of shape-memory materials and piezoelectric effects. An analysis can be static, harmonic or transient state in nature. Due to the complexity of the practical applications of the technique, it is not unusual to have magnetic, dielectric and thermal couplings in a single model. Such complex analyses generally make realistic modeling an ardouous task.

3.5. Performance Analysis of Permanent Magnet Stepper Motor

In this analysis, the performance of 96W permanent magnet stepper motor is analyzed with finite element analysis (method). At present, several commercial 2D/3D finite element packages are available and may also be applied also to permanent magnet machine design.

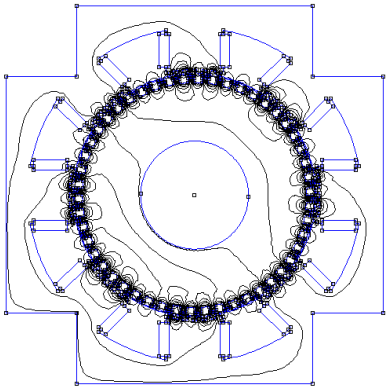

Fig.4. Electromagnetic field distribution of the permanent magnet stepper motor

For the electromagnetic design of electrical machines, the finite element analysis may be considered to be a well-established design method, even though occasionally, certain particular computation procedures are to be updated [7].

To run the FEA software, the first step is to draw the machine geometry with the calculated design parameters on the working plane. And then, material selection for main portion is made. The electromagnetic field distribution of the permanent magnet stepper motor is shown in Fig 4.

Fig. 5 shows the electromagnetic field distribution of the permanent magnet stepper motor by using FEM software. After running, these model display FEM result output, flux density which can be plotted as a colour density plot.

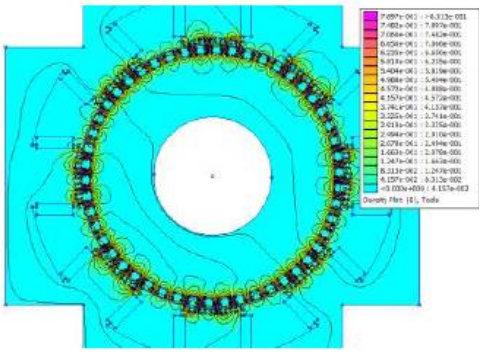

Fig.5. The magnetic flux density for PMSM by using FEM

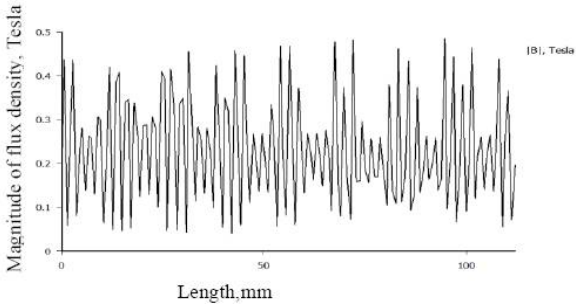

Fig.6. The Magnitude of flux density plot

The result of the magnitude of flux density for PMSM by using the finite-element analysis is shown in Fig. 6. In figure, it can be seen that the highest value of flux density for PMSM is between 50mm and 100mm, and its lowest value is between 0mm and 50mm.

3.6.Results and Properties of Three Magnets

The properties of three magnets depend on its thickness are shown in Table 4 and Table 5.

Name of Magnet	NdFeB	SmCo	Alnico
Normal flux density (tesla)	0.488	0.388	0.08
Average flux density (tesla)	0.3	0.2	0.025
Magnitude of flux density (tesla)	0.48	0.39	0.07

Table4: Comparison of Three Magnets for the Thickness at 0.3mm

Name of Magnet	NdFeB	SmCo	Alnico
Norma flux density (tesla)	0.5	0.49	0.1
Average flux density (tesla)	0.4	0.3	0.05
Magnitude of flux density (tesla)	0.62	0.5	0.125

Table5: Comparison of Three Magnets for the Thickness at 0.6mm

When the types of magnet and its thickness are changed by using FEA software, the magnitudes of flux density in NdFeB and SmCo do not greatly change but that in Alnico changes significantly is

shown in Table 4 and Table 5. According to Table 4 and Table 5, the NdFeB magnets are the most powerful commercially produced magnets because of material magnet density. It can replace SmCo magnets in most cases.

3.7. Comparison of Losses and Efficiency

The comparison of losses and efficiency between theory model and finite element analysis for permanent magnet stepper motor are illustrated in Table 6.

Specifications	Sizing Equation (PMSM)	2D FEA (PMSM)
Air gap flux density, T	0.5	0.488
Inductance, mH	3.0	2.9
Resistance, ohm	2.5	-
Copper losses, W	40	-
Friction and windage losses,W	0.96	-
Total iron losses,W	0.96	
The developed torque of the machine, Nm	9	10
The output power,W	54	60
Efficiency, %	56.3	60

Table6: Comparison of Losses and Efficiency between Theory Model and FEA Software

In this table, air gap flux density, inductance, the output power and the development torque of the machine are 0.5T, 3.0mH, 54W, 9Nm and 56.3% from the theory model design. According to FEA software, air gap flux density, inductance are lower than the theory model design and the output power, the development torque of the machine and efficiency are higher than the theory model design.

CONCLUSIONS

In this paper, the theoretical model is focused on the permanent magnet stepper motor using wave energy convertor. When the design of the physically model is well known, this information is applied for the design and the operating wave energy system. And then, permanent magnet stepper motor is mainly emphasized in this study. Moreover, the finite element analysis was used to evaluate the accurate flux density in the motor components. In this paper, the air gap flux density and resistance are 0.5T and 2.5 from the initial sizing equation. According to the FEA software, the air gap flux density and the resistance are lower than the initial value. When the thickness of permanent magnet of machine is increased from 0.3mm to 0.6mm, the value of the air gap flux density is increased 0.01%. On the other hand, as the thickness of the permanent magnet increases, the cost is high and technical problems will occur. Therefore, the suitable thickness for permanent magnet is required to be selected for this research. Moreover, the air gap plays a very important role in the performance of the permanent magnet stepper motor. The air-gap needs to be as small as possible to have a better power and efficiency.

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REFERENCES

[1] Hosna Titah-Benbouzid, “An Up-to-Date Technologies Review and Evaluation of Wave Energy Converters”, International Review of Electrical Engineering (I.R.E.E.), Vol. 10, N. 1, 2015.

[2] Pedro Beirao, “Design and analysis of buoy geometries for a wave energy converter”, researchgate conference paper,2013.

[3] Leishman JM, Scobie G,”The development of wave power, a techno-economical study”,Glasgow: Economic Assessment Unit National Engineering Laboratory; 1976.

[4] Cruz J, editor. “Ocean wave energy, current status and future perspectives”. Berlin Heidelberg: Springer-Verlag; 2008.

[5] R. G. Dean and R. A. Dalrymple, "Water wavemechanics for engineers and scientists", Advanced Series on Ocean Engineering, World Scientific, Singapore, 1991. ISBN 978-9810204204, PP 64-65.

[6] Goda, Y. "Random Seas and Design of Maritime Structures", World Scientific, 2000.

[7] Caricchi, F., Crescimbini, F., Di Napoli, A., Santini, E., 1992. “Optimum CAD-CAE Design Axial-flux Permanent Magnet Motors. In Proceedings of International Conference on Electrical Machines, ICEM’92, pp.637-641.

[8] Lewis A, Estefen , Huckerby J, Musial W, Pontes T, Torres-Martinez J. Ocean energy. In: Edenhofer O, Pichs-Madruga R, Sokona Y, et al., editors. IPCC special report on renewable energy sources and climate change mitigation. Cambridge: Cambridge University Press; 2011.

[9] Dang The Ba, ‘’ Numerical Simulation and Experimental Analysis for A Linear Trigonal Double-Face Permanent Magnet Generator Used in Direct Driven Wave Energy Conversion”, 2nd Humboldt Kolleg in conjunction with International Conference on Natural Sciences, HK-ICONS 2014.

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