Application of PMSM for Electric Generation from Ocean Waves by EPEW

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Abstract

Nowadays there are different devices for harvesting ocean wave power, but there is not a commercial device to generate electricity from ocean wave. In this paper power take-off system of new device EPEW[1] is surveyed. A 40 HP permanent magnet synchronous machine is coupled with EPEW's crank shaft (PTO), so that wave power is converted to AC electricity. Generated voltage and current wave form for optimum power conversion state of PMSM is simulated in the paper and Torque-Angular velocity figure of PMSM is plotted according to the simulation results, also device efficiency in converting wave power to mechanical and electrical power is surveyed. PMSM efficiency in converting crank shaft motive force to electrical power has been achieved 32%. According to the results EPEW's efficiency in converting wave power to electrical is achieved 5% more than other wave power convertors (OWC).

1. Introduction

Ocean is containing of enormous amount of renewable energy. Ocean energy comes in variety of forms such as geothermal vents, ocean current and waves. The most commercially viable resources are ocean current and waves which have both undergone limited commercial development. There is approximately 1-10 TW of wave energy in the entire ocean [1] and wave energy provides 15-20 times more available energy per square meter than either wind or solar [2]. There are effective methods for converting wind or solar energy to electricity but there is not a commercial apparatus to convert ocean waves to electricity.

The implement for converting wave energy to electrical is called power take-off system (PTO) and mainly three type of power take off system most commonly is used in wave convertor devices.

Air/Water Turbine forms part of an integral system that consists of a capture device, which also includes an electric generator. This PTO system is used in *Oscillating wave columns (OWC)* and *Overtapping devices* [3].

Direct Drive is consisting of a moving part named translator on which linear generators is mounted on it. PTO system of *buoyant moored devices* mostly is from this kind [3].

Hydraulics PTO system is consisting of a hydraulic circuit which transfers absorbed force of wave to a hydraulic motor which drives electrical generator. This kind of PTO is used in Pelamis (*Hinged contour devices*) [4, 5].

In this context PTO of new wave power convertor device, EPEW, is investigated. The EPEW harvests wave power by *absorber plate* WECs and absorbed power is converted to rotating motive force by a crank shaft in PTO [6-8]. So that it is possible with EPEW to drive a rotating generator by ocean waves for electric generation. In this paper, 40 HP permanent magnet synchronous machine is applied for electric generation from EPEW's output torque. Ocean waves are supposed 0.8 *meter* of amplitude and frequency of 1 *rad/sec* monochromatic waves which is applied to absorber plate (EPEW's WEC) and consequently EPEW's converted torque is applied to PMSM. Output voltage and current wave form are simulated also conversion efficiency and Torque-Angular velocity figure is analyzed for PMSM.

All simulation in the paper is simulated with MATLAB® software and linearized wave theory is applied.

2. Generated Torque by EPEW

In EPEW, for smoothing absorbed power from WECs, crank shaft is exploited like as power take-off system. EPEW harnesses wave energy by four different WECs, absorbed force by these WECs is transmitted to crank shaft. Crank shaft converts oscillating motion of absorber plates to rotating motive force, and it mechanically sums the torques in effect of forces from WECs. Incident torque on a single arm of crank shaft is as below;

$$\vec{T}_i = \vec{r}_i \times \vec{F}_i . \cos\beta \tag{1}$$

Where $\vec{r}_i$ is radios vector of i-th arm of crank shaft, $\vec{F}_i$ is transmitted force from i-th WEC to i-th arm of crank shaft.

Converted torque by crank shaft which is sum of four different torques from WECs has been calculated as below;

$$T_C = \sum_{\eta=0}^{3} r_\eta \times \left[\left(-D_P \dot{x}_{P\eta} - M_P \ddot{x}_{P\eta} - \frac{2i\rho\sigma A_I}{k_0} \sinh k_0 h \, e^{-i\left(\sigma t - \frac{\pi}{2}\eta\right)}\right) . Z(t) . \cos\beta\right] \tag{2}$$

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[1] *Engine for Producing Energy from Sea Waves (EPEW) is designed and patented by Ehsan Enferad.*

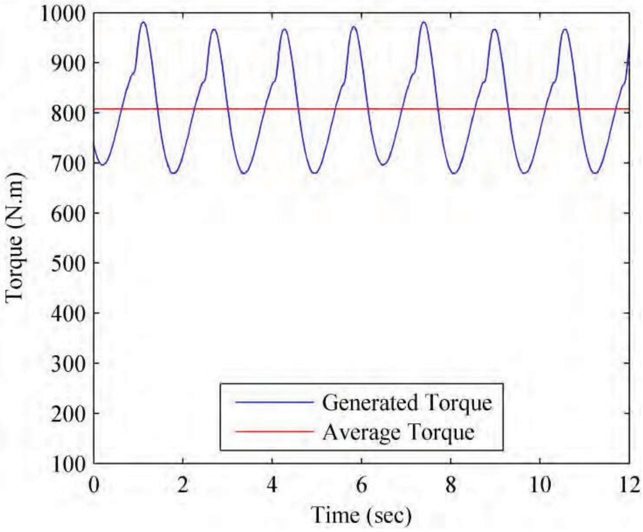

Fig. 1. Converted torque by EPEW's crank shaft while incident sea wave characterize are $A_I = 0.8\, meter$, $\sigma = 1\, rad/sec$.

Where M_P is added mass of absorber plate, D_P is the adding damping of absorber plate, k_0 is the wave number of incident wave, ρ is sea water density and is $1020 kg/m^3$ and x_P is displacement of the absorber plate. Converted crank shaft torque by EPEW is illustrated in Fig. 1. According to this figure, crank shaft converts smooth torque from variable forces of WECs and the mean converted torque have been obtained 808 N.m.

3. EPEW's Crank Shaft Angular Velocity

EPEW's PTO mechanical model is similar to the internal combustion engine's crank shaft. So that, PTO torque and angular velocity for EPEW is solved like as mechanical problem of internal combustion engine's crank shaft with some assumptions which has been mention in the paper. Dynamic equation of crank shaft is obtained as follow [9];

$$J_{crank}(\theta)\ddot{\theta} = T_c(\theta) - T_m(\theta,\dot{\theta},\ddot{\theta}) - T_f(\dot{\theta}) - T_l \qquad (3)$$

In above equation, θ is crank shaft's angle, $T_c(\theta)$ is input torque of crank shaft which is calculated from Eq. (2), $T_f(\dot{\theta})$ models the fraction losses, $T_m(\theta,\dot{\theta},\ddot{\theta})$ is mass torque and for two lumped masses connecting-rod model for N_c-arm crank shaft is computed from below equation [10];

$$T_m(\theta,\dot{\theta},\ddot{\theta}) = \sum_{j=1}^{N_c}\left(J_A(\theta-\theta_j) + m_B r^2\right)\ddot{\theta} + \sum_{j=1}^{N_c}\frac{1}{2}\left(\frac{\partial J_A(\theta-\theta_j)}{\partial\theta}\right)\dot{\theta}^2 \qquad (4)$$

$$J_A = m_A.\left(\frac{ds(\theta)}{d\theta}\right)^2 \qquad (5)$$

In above equations, J_A is variable inertia of oscillating masses relative to one WEC, m_A is sum of all oscillating masses (WEC and oscillating mass of connecting rod), m_B is the rotating mass, θ_j are the phasing angles, r is the crank radius and $s(\theta)$ is the WEC displacement with respect to the crank shaft angle. $s(\theta)$ can be calculated with following equation;

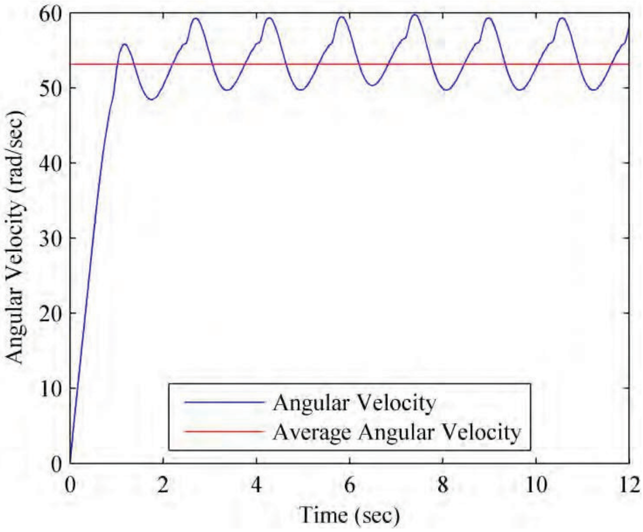

Fig. 2. Angular velocity of crank shaft without load torque.

$$s(\theta) = r(1-\cos(\theta)) + l\left(1-\sqrt{1-\frac{r^2}{l^2}sin^2(\theta)}\right) \qquad (6)$$

Where l is length of connecting-rods.
Also in this paper fraction losses of crank shaft is neglected so that by substituting Eq. (4) in Eq. (3) the dynamic equation of the crank shaft is;

$$J_{total}(\theta)\ddot{\theta} = T_c(\theta) - \acute{T}_m(\theta,\dot{\theta}) - T_l \qquad (7)$$

In this equation $J_{total}(\theta)$ is the total inertia including the crank shaft inertia $J_{crank}(\theta)$, the inertia of all rotating parts $N_c m_B r^2$ of the connecting-rods and the inertia of all oscillating masses (WECs).

$$J_{total}(\theta) = J_{crank} + N_c m_B r^2 + \sum_{j=1}^{Nc} J_A(\theta-\theta_j) \qquad (8)$$

And $\acute{T}_m(\theta,\dot{\theta})$ is the component of the mass torque depending on crank shaft angular velocity;

$$\acute{T}_m(\theta,\dot{\theta}) = \sum_{j=1}^{Nc}\frac{1}{2}\frac{\partial J_A(\theta-\theta_j)}{\partial\theta}\dot{\theta}^2 \qquad (9)$$

By substituting crank shaft parameters (m_A, m_B, …) in dynamic equation and replacing RMS amount of J_A and $\acute{T}_m$ instead of their real amount for simplicity, EPEW's crank shaft angular velocity ω in no-load condition is achieved from Eq. (10) and is illustrated in Fig. 2.

$$\omega = \frac{d\theta}{dt} = \dot{\theta} \qquad (10)$$

4. Speed Regulation with Gearbox

A gearbox is used in EPEW for speed regulation of crank shaft with rotating electrical generator. According to Fig. 3 dynamic equation of rotating generator while its parameter is reflected from gear G to gear C is as follow [11];

$$T_l = (\frac{N_C}{N_G})^2 J_G \ddot{\theta} + (\frac{N_C}{N_G})^2 B_G \dot{\theta} + \frac{N_C}{N_G}(T_e + T_f) \qquad (11)$$

In Eq. (11), T_l is generator torque when it is reflected to crank shaft side, T_e is electro-mechanical torque of generator, T_f is the total friction torque, N_C is the teeth number of gear train which is connected to crank shaft, N_G is the teeth number of gear train which is connected to rotating generator, J_G is generator inertia in $kg.m^2$ and B_G is viscous friction coefficient $N.m.s$.

Angular velocity equation in two sides of gear box is as follow;

$$\frac{\omega_G}{\omega} = \frac{N_C}{N_G} \qquad (12)$$

Where ω_G is generator angular velocity and is equal to $\omega_G = \dot{\theta}_G$ and ω is crank shaft angular velocity.

In EPEW design Eq. (12) has been assumed approximately six ($N_C/N_G \approx 6$). So that crank shaft angular velocity is increased six times while it is transmitted to generator via gearbox.

5. Permanent Magnet Synchronous Machine coupled with EPEW

For mechanical-electrical conversion, a sinusoidal permanent magnet synchronous machine is used like as generator in EPEW. A 40 HP, 500 V, 3000 RPM PMSM generator is coupled with crank shaft via a gearbox. PM machine equations are as follow [12];

$$L_d \frac{d}{dt} i_d = v_d - R_s . i_d + L_q . p . \omega_r i_q \qquad (13)$$

$$L_q \frac{d}{dt} i_q = v_q - R_s . i_q - L_d . p . \omega_r i_d - \lambda . p . \omega_G \qquad (14)$$

Where L_q is q axis inductance, L_d is d axis inductance, i_d and i_q are d and q axis current respectively, ω_G is rotor speed (generator - angular velocity) and λ Amplitude of the flux induced by the permanent magnets of the rotor in the stator phases. The electro-mechanical torque of PMSM generator is calculated from below equation;

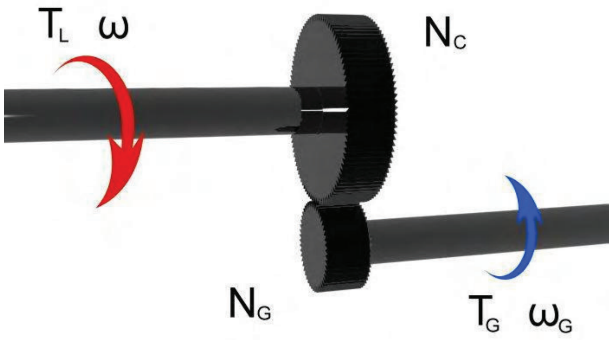

Fig. 3. Figure of gear train, Right side is connected to generator and left side is connected to crank shaft.

$$T_e = \frac{3}{2} p [\lambda . i_q + (L_d - L_q) . i_q . i_d] \qquad (15)$$

In generator the torque and rotor speed are related with the following equation;

$$J_G \ddot{\theta}_G + B_G \dot{\theta}_G + T_f + T_e = T_G \qquad (16)$$

Where T_f is the total coulomb friction torque, T_G is the input mechanical torque which is transmitted via gearbox and $\dot{\theta}_G$ is angular velocity of generator's rotor. In this paper generator parameter for 40HP PMSM generator is supposed according to Table.1.

Table.1. 40HP PMSM generator parameter.

PMSM Generator Parameter	Amount
J_G, Total inertia	0.011 $kg.m^2$
B_G, Viscous friction coefficient	0.001889 $N.m.s$
p, Number of pole pair	4
L_d, d axis inductance	0.000635 H
L_q, q axis inductance	0.000635 H
λ, Amplitude of the flux induced by the permanent magnets	0.192 $V.s$
R_s, Resistance of the stator windings	0.05 Ω

By applying the generator torque achieved from equations (15) and (16) to gearbox equation (Eq. (11)) and converted torque by crank shaft (Eq. (2)), generator T_e- ω_G curve is achieved as Fig. 4. Also output voltage and current with the optimum resistive load (symmetric star load $R_L = 2.3\Omega$) is shown in Figs. 5 & 6.

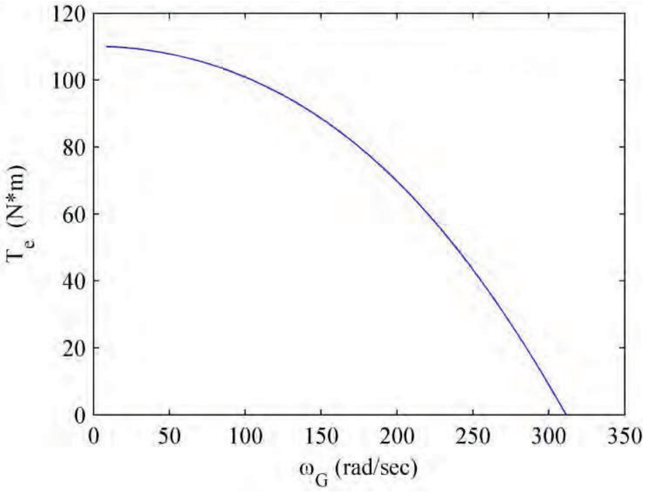

Fig. 4. $T - \omega$ curve of PMSM.

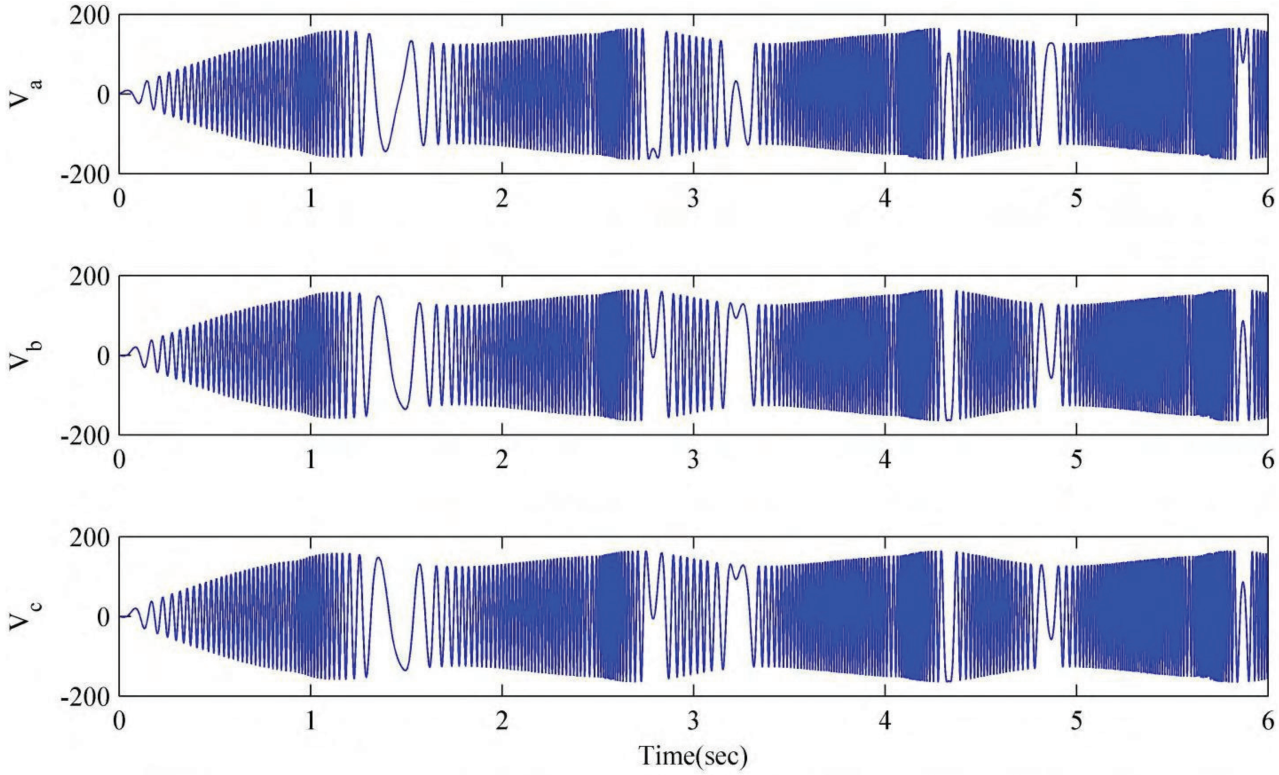

Fig. 5. PMSM output voltage for 2.3 Ω symmetric star load.

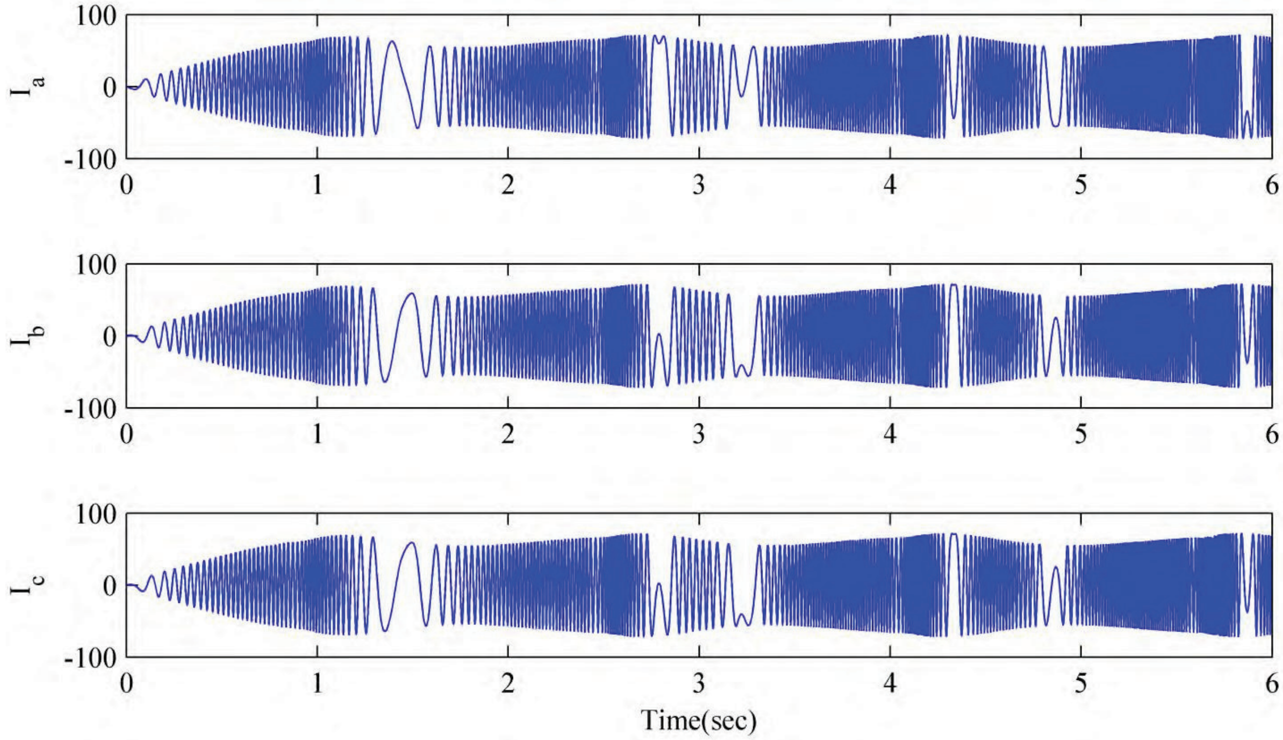

Fig. 6. PMSM output voltage for 2.3 Ω symmetric star load.

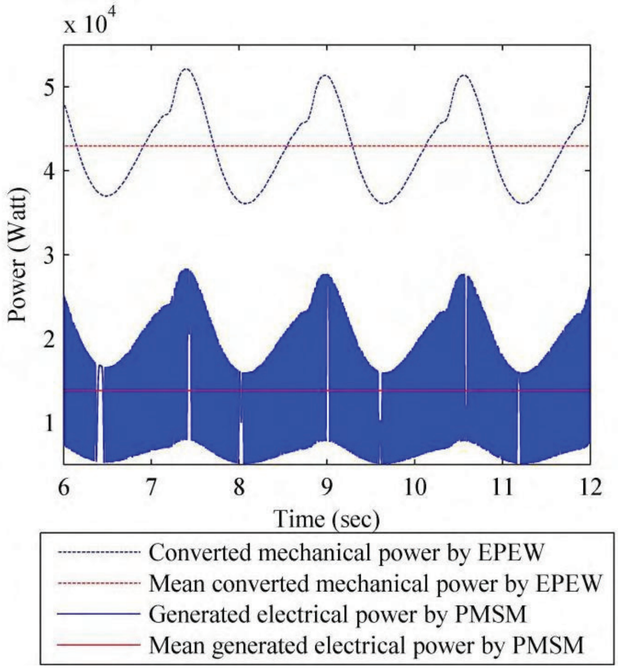

Fig. 7. Converted mechanical and electrical powers.

Converted powers by EPEW from ocean wave is illustrated in Fig. 7.

6. Conclusion

In this paper, a permanent magnet synchronous machine is used with EPEW for electric generation from ocean waves. According to the simulation result for an ocean with wave characteristics $h = 10,\ A_I = 0.8$ and $\sigma = 1$ which has been studied in the paper, 73 kw power is available in four meters of wave front and EPEW extract 44.9 kw of this wave power and mean generated electric power by PMSM is 14.5 kw which refers that PMSM efficiency is 32% in converting mechanical power (power from EPEW) to electrical power. Overall EPEW efficiency in converting wave power to electrical is almost 20% which shows a 5% improve in comparison to the previous wave power convertors devices (OWC) [13].

7. References

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