Idea of Extracting Power from a Wave Energy Harvester with a New MPPT Algorithm

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Abstract— The study reveals power production at MPP from a new design of a harvester device which can be a cost effective solution for many offshore marine industries. It is a safe close type structure which can produce electricity internally without taking the water or air from the atmosphere inside this using a wind turbine as power take off device. For achieving maximum power a new, simpler, faster and adaptive MPPT algorithm proposed here that can be applied to wave energy harvesters that use wind turbine for power take off. It is a modified P&O algorithm which uses the ratio of power change to rotor speed change to adapt the converter duty cycle ratio for next perturbation step and needs no prior idea about turbine but can track MPP faster. Comparing to most of the current MPPT algorithms that assume some complex logic, this algorithm is suitable for application in small wave energy converter powering offshore sensor networks that are distant from land.

Keyword- Wave energy converter, OWC, ocean energy harvester, renewable energy.

I. Introduction

There are many offshore marine industries or distant rural places from city where grid based electricity is not reachable. Industries in these areas use sensor network through which they are controlled from distant places remotely. Either for automated control or for monitoring purposes, sensor nodes are used extensively worldwide for various reasons. Lack of grid connection forces them to use expensive batteries. So the most available unlimited natural resource like wave and wind energy harvesting can be the most cost effective source for providing power to these sensor networks which needs small but steady type electricity. Because of their need of tiny power the harvester should be small, cost effective and efficient. A renewable energy harvester can never be efficient without MPP tracking. With a view to make a simple cost effective MPPT system the paper proposes an algorithm that uses least measuring and monitoring devices than others but provides adaptive step size capability. The adaptive step size calculation takes into account the change in power to change in rotor speed ratio and makes a proportionality factor to perturb the next step of the converter duty cycle. And thus it can track MPP faster and easier than traditional P&O algorithm. Though this paper considers the use of this algorithm for wave energy harvesting application but this can be used for small wind energy harvester too.

II. Background

Harvesting wave energy has got huge attention from all over the world. Study is going on for making cost effective, simple and easy to implement harvester system. According to Dorrell, Hsieh and Lin [1], among various wave energy harvesters traditional OWC is the simplest one with two basic components; the chamber and the turbine. Multi chamber or segmented OWC has been studied briefly in [1]. Performance of the turbines like savonious or wells and effect of guided vanes on wells turbine used in OWC, have also been matter of research for Hsieh and Dorrell [2] and Govardhan and Dhanasekaran [3]. A study (before 2010) showed that there were over 1000 patented ideas for wave energy conversion. But most of these are for larger power generation which are complex and of bigger sized with high costing. Another lacking is, they cannot afford their maximum efficiency in rough weather condition. Our new idea for closed type OWC has been designed specially keeping in mind that it can withstand bad sea weather and obviously be cost effective and require less maintenance. The invention is an off shore energy harvesting device for electric power generation. Vehicles like boats and ships on the sea and many other on sea floating projects like floating fish farm can produce the amount of necessary electricity from this device.

III. Device Structure

Without violating the working principle of the OWC, invented device has made a change or modification only to its structure and power take off system. The device shown in fig.1, makes use of the motion of the ocean wave instead of water entering into it. It works with fixed amount of water that remains inside the device to a level that is half of its height. The device has a partition inside, which makes it partly double chambered OWC. In the upper side of the partition, there is a window and there is an aperture at the partition's down side. The down aperture makes fluid movement possible between the two chambers and the upper window carries a horizontal axis, bi-directional wind turbine to allow the wind to flow through it in opposite direction to the water movement. The movement of the turbine rotor is carried out from the box through a gear system and the turbine motion that is the mechanical power is converted to electrical power using an electric generator placed within an enclosure, outside the OWC device.

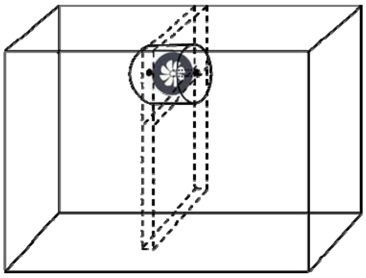

Fig.1 Closed OWC and turbine inside

IV. WORKING PROCEDURE

A half circular floater carrying the big rectangular box is mounted on a rectangular frame which is fixed to the sea bed at its bottom. The device will be moored parallel to the incoming wave front like salter duck installation. As shown in fig. 2, through the center of the floater a metal rod will pass horizontally which will act as central axis about which the device will rotate. The metal rod acting as central axis will be fixed to the frame attached to sea bed. The setup or floater can revolve in a semicircular path (vertical direction) which is limited by two moorings anchored to sea bed. Two moorings will be hooked at the middle point of the floater on both right and left end. The frame prohibits the device to have front, back or any type of motion other than up and down motion. As the wave comes, the device gets tilted and continues to move up and down. The upward and downward movement of the body is limited by the end moorings. This movement will cause the water inside the device to move from one chamber to the other. Since the device is closed and the water level is changing in each chamber due to device movement, so to place the extra water in each chamber or to fill the vacant space of the chamber left by the water, the air trapped above the water must have to move and obviously the movement will be in the opposite direction to the water movement. That is the air leaves the chamber where water enters and enters to the chamber from where water leaves, and the process continues. Due to the movement of the air through the upper ventilator, the turbine placed there, moves. Since the turbine is bi-directional, it moves in the same direction for wind coming from either chamber.

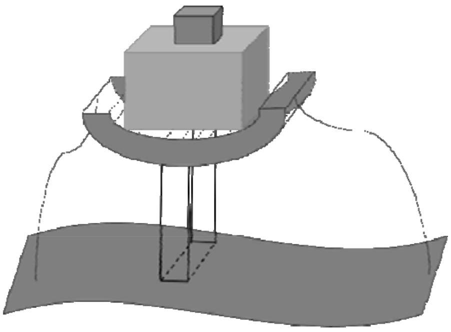

Fig.2 Complete device implementation in sea bed with mooring

The device structure as well as the size of the turbine is related to the power requirement. Efficient conversion of incident wave power will also dependent on some environmental and device sizing factors which is analyzed in detail in this study. A MATLAB program was written to study the device characteristics. The study and the results are explained elaborately in the rest of the paper.

V. RESULTS

The numerical analysis was done in [4]. This study completely follows the method described there but with a small difference in a single device parameter that is turbine radius and here it is 0.1 m which has been kept fixed through all the experiments.

For a device of length 4m, the length of a single chamber is, a=2m and for chamber height d=1m we get the draft height, b=0.5m that is the water will be filled up to height of 0.5m inside the box.

Regarding these factors the results came out, are given bellow in table 1.

TABLE I. Variation of wind velocity and wind power with wave height and wave period

Wave period, T_s sec	**Wave height, H_m m**	**Wind velocity, V_2 m/s**	**Wind power, P_w W**
1.6	0.2	3.99	1.22
	0.25	4.98	2.38
	0.3	5.98	4.11
	0.35	6.98	6.53
1.7	0.2	3.32	0.71
	0.25	4.15	1.38
	0.3	4.98	2.38
	0.35	5.82	3.78
1.8	0.2	2.80	0.42
	0.25	3.50	0.82
	0.3	4.20	1.42
	0.35	4.90	2.26

The result shows the effect of wave period and wave height on wind velocity at turbine as well as available power output from wind. The study considered wave period of the application area ranging from 1.6 s to 1.8 s and wave height ranging from 0.2 m to 0.35 m with 0.1s and 0.05 m increment respectively, in each case.

A. Modeling a suitable wind turbine and calculating mechanical power available from the turbine

From table 1, wave height of 0.35 m results very high velocity wind at the turbine and thus the calculated wind power also becomes high. For our case, the turbine we are considering here is of very small radius of 0.1 m only. So neglecting the wave height ranging upper than 0.3m and taking the rest of the three wave height values for three wave period conditions. Taking average of wind speed values for wave heights ranging from 0.2 to 0.3 m for each of the three cases of wave periods (1.6s, 1.7s, 1.8s) we can consider three approximate wind speed condition for simulating the mechanical power obtainable from the turbine. The approximate wind speed conditions are 3m/s, 5 m/s, and 7 m/s for wave period w.r.t. 1.8s, 1.7s and 1.6s.

For getting mechanical power output from a wind turbine the very first thing to do is to model the turbine, its performance curve and check for the best TSR values. According to Betz law, the power coefficient C_p has a maximum theoretical value equal of 0.593. The rotor power coefficient is usually given as a function of two parameters: the tip speed ratio λ and the blade pitch angle β (in degrees). TSR (λ) was calculated by using simple formulae:

$$\lambda = {}^{\omega r}/_{v_w} \tag{1}$$

Where ω=rotor speed; r = rotor radius and V_ω =wind speed.

Based on previous studies, the power curve can be found by the following equation:

$$C_p(\lambda, \beta) = c_1\left(c_2.\frac{1}{\gamma} - c_3.\beta - c_4.\beta^x - c_5\right)e^{-c_6\frac{1}{\gamma}} \tag{2}$$

γ is defined as,

$$\frac{1}{\gamma} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{3}$$

Here C_1 to C_6 are turbine coefficients which can be assumed from any standard turbine model or previous studies. In this case, we have considered these parameters of the wind turbine as described in “Modelling and Control of Wind Turbines”, thesis by Jasmin Martinez [5]. Using those parameter as: $c1$= 0.5; $c2$=116; $c3$=0.4; $c4$=0; $c5$=5; $c6$=21 we can have performance curve w.r.t tip speed ratio. Here another important parameter is pitch angle β. According to Lubosny [6] coefficient of performance is maximum at pitch angel β=0° degree. So considering fixed pitch wind turbine we can take β value as 0°. For the considered wind speed range and for a rotor of 0.1m radius the speed of rotor should be high. Considering a high range of rotor speed at three different wind speed conditions we got a performance curve ‘C_p Vs TSR’.

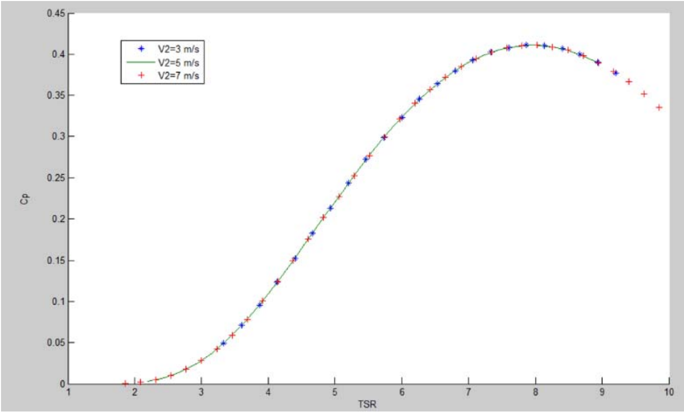

Fig.3 Performance coefficient curve w.r.t. tip speed ratio

The curve in fig.3 was obtained in other device parameter conditions as stated before. As long as β is constant all the C_p curves will follow the same track and since we are considering fixed pitch wind turbine (β=0˚) the three curves follow the same track and reach the peak point of 0.42(approx.). The value of TSR at which max C_p hence maximum power from turbine was found is called the optimum tip speed ratio. For this case optimum tip speed ratio was found at 7.8 (approx.).

B. Available mechanical Power from wind power

Using the C_p curve, available mechanical power from the wind power can be obtained for three different wind speed conditions.

Wind power available at the turbine:

$$P_w = {}^1/_2\, \rho A_2 v_2{}^3 \qquad (4)$$

Using above equation (4), fig. 4 shows the MATLAB simulated power curve for the corresponding C_p values for a range of tip speed ratio values.

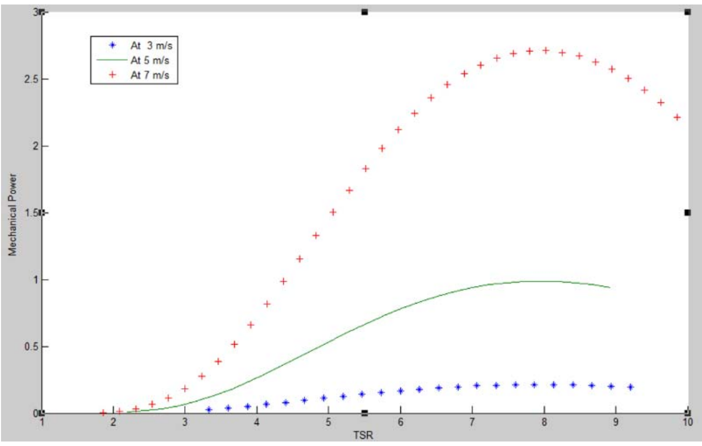

Fig.4 Power available for a range of tip speed ratio

The graph says that, power curve due to minimum wind speed 3m/s, reach optimum TSR value and so the power output reaches its largest value at that wind speed for that particular ratio of rotor speed and wind speed. On the other hand power at both 5 and 7 m/s reaches maximum efficiency. With 7 m/s wind speed, a highest power of 2.71 W can be obtained and for 5 m/s, the power reaches a maximum level of 0.99 W. But the respective rotor speed levels at different wind speed conditions was assumed keeping in mind the standard tip speed ratio and optimum tip speed ratios for wind turbines in general. For doing that the rotor speed due to 7 m/s got very high. Since the turbine radius is very small it might not cope-up with the speed.

Again the wave period condition behind wind speed of 7 m/s (1.6s) was very optimistic which could be irregular for oceans in general. So considering these facts we can say the best solution is to take the middle curve at 5 m/s. So wind speed up to 5 m/s can be assumed as an optimum level for this system design. The respective maximum rotor speed for this case was 450 rad/s. But we can see the maximum C_p is obtained at earlier values of TSR and after a certain point it gets lower for further increase in TSR which happens if rotor speed increases beyond a certain level. So we can assume the rotor speed at 5 m/s should have a value lower than 450 rad/s for extraction of maximum power. For extraction of maximum power at any wind speed condition is called Maximum Power Point Tracking. As we can see this maximum power depends on optimum tip speed ratio and from the equations it is clear that tip speed ratio varies with wind speed and rotor speed condition. To maintain the operating point at the optimum tip speed ratio value for any wind speed and rotor speed condition, is the task performed by MPPT controller.

VI. MPPT METHOD

Efficiency of a renewable energy harvester is ensured by MPP tracking system. In OWC technology, wind flow is bidirectional due to the rise and fall of the inner OWC chamber water column and to utilize wind flow from both direction, bi directional wind turbine is used as power take off device. And for more efficient use of wave energy MPPT system should be used must.

From fig. 3 it is clear that there is a specific TSR value at which the turbine works at MPP. But when wind speed varies, the rotor speed also varies. According to Hui [7] the turbine rotor speed is dependent not only upon the wind speed but also on the load condition, versatile output power is available for the different combined situation of rotor speed, wind speed and generator loading. MPPT system for a wind generator controls the load factor by controlling the converter duty cycle such that the rotor rotates at optimum speed at any wind speed condition. That is, the converter controls the rotor speed by changing the duty cycle during changing wind speed condition so that the turbine can operate at its optimum tip speed ratio.

Among many MPPT algorithms, P&O or HCS method is the most common algorithm [8] which does not require any prior knowledge of the wind turbine's characteristic curve. The only thing done here is by varying the converter duty cycle making the load factor to vary and thus to set an optimum duty ratio for any wind speed condition such that the system runs at maximum power point condition. The MPPT controller application needs a lot of backup devices for measurement and tracking purposes which makes the system complex and expensive too. But there are many applications which need small amount of power and cannot adapt existing complex MPPT algorithms with lots of supporting instruments and costing.

So here is an idea of a new, cost effective, simpler, faster MPPT algorithm that can be applied to any system irrespective of its capacity and size. The new idea proposes an improved and adaptive P&O algorithm that uses least measuring and monitoring devices than others but provides adaptive step size capability. The adaptive step size calculation takes into account the change in power, to change in rotor speed ratio and makes a proportionality factor to perturb the next step of the converter duty cycle. And thus it can track MPP faster and easier than traditional P&O algorithm. It can ensure MPPT for variable wind speed condition too.

The exception with which the proposed algorithm tracks MPP faster than other is that the duty cycle modifying factor k in each step has a proportionality relation with the slope of the turbine power and rotor speed curve. As assumed from general wind turbine characteristic curves (fig.5), that the more the distance from MPP, the larger the value k will have and vice versa. So the step size will be larger when the operating point is far from MPP, applicable for both negative and positive side of the MPP. And the perturbation steps will become smaller as it will approach MPP.

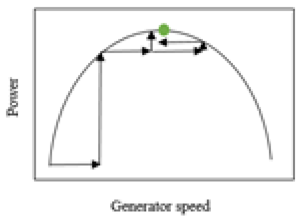

Fig.5 Traditional HCS or P&O algorithm (Modified from [9])

The proposed algorithm can solve the problem of step size and oscillations around the MPP. In the proposed algorithm, changes in duty cycle d is done according to the change in power by a proportionality factor defined as k. k is the ratio of change in power to change in rotor speed. In the beginning of the algorithm an initial value was assigned for duty cycle as D_p.

After primary power check, duty cycle was increased by a pre fixed value d_p. This perturbation effects on output power and hence on rotor speed. Now power and rotor speed is checked for finding the difference ΔP and $\Delta\omega$. Taking the ratio of these values k was found which later used as proportionality factor for multiplication with the pre fixed value d_p and then to subtract from present duty ratio. Final arithmetic program will depend actually on the sign of k. If k is negative then finally addition will be performed and if k is positive the subtraction will be done and new d value will be larger or smaller respectively than the present one.

Which will be clear from the algorithm flow chart given in fig. 6.

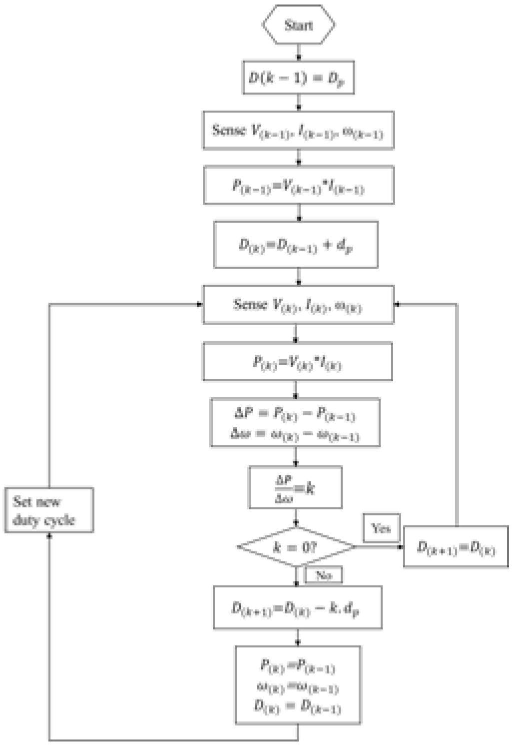

Fig.6 Proposed new, adaptive MPPT algorithm

After modification, the new duty cycle is set for next step and the present values of power, rotor speed and duty cycle are set as previous values for next step. Continuation of search in this way will ensure MPP when the slope or value of *k* becomes 0 and at that point no change is made to duty cycle. Duty cycle is kept at that fixed value as long as the slope check shows value "zero". When any change in wind speed occurs, though a bit late but surely it will make some change in rotor speed and then the algorithm will run again and will set the system at its MPP for that wind speed.

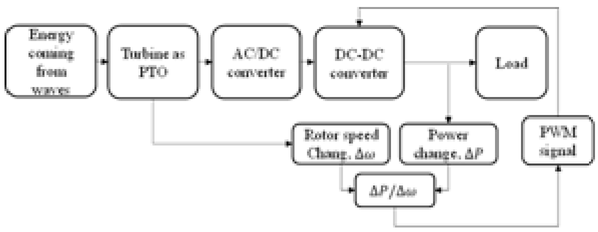

Fig.7 Block diagram showing electric system with algorithm application

Figure 7 shows complete block diagram of the harvester, applying the algorithm to MPPT control system.

VII. DISCUSSION

The proposed new structure has some beneficial characteristics then previous versions of OWC. Firstly, as per system design, there will be no effect of outside atmospheric pressure on inside power calculation. So device installation will be quite easy. Secondly, unlike other inventions which are highly dependent on the direction of the incoming waves, this device can use the waves coming not only from one direction but also from the reverse direction. Thirdly, prior invented power generating systems with complex mechanism needs significant amount of additional costs at the time of manufacturing and installation to ensure the sustainability of the system in case of stormy ocean condition. But our system is of simple structure which is easy to manufacture, install and also needs less security, costing and maintenance effort. Finally, the closed box type structure of the device ensuring better longevity for this energy converter than other WECs.

The study represents the new better idea for wave energy conversion, MPPT algorithm and predicted performance on the basis of numerical analysis and MATLAB based simulated power calculation. Application of these ideas need higher simulation study and before application, lab based small scale wave tank testing.

VIII. CONCLUSION

Our study represents a system design that can avoid performance disruption due to natural calamity. Many offshore wave energy harvesting system need to stop working in rough ocean weather for security reasons. But our system is simple and doesn't involve any hardware that need to be shut down during ocean storm or other harsh wave condition. It's a great facility over other wave energy harvesters. The two unique features that, it produces electric power without any interaction with outside ocean water or atmospheric pressure and a simple, closed structure that can be build using the lower vessel type part of any old ship or boat, add two plus points to our system that it needs less maintenance and it is comparatively cheap and easy to manufacture. And with a view to solve the problem of perturbation step size and oscillations around the MPP a new, simple but faster and adaptive step size MPPT algorithm has been proposed in this paper. The exception with which this algorithm tracks MPP faster than other MPPT algorithms is that the duty cycle modifying factor *d* in each step is multiplied by a factor k where k has a proportionality relation with the ratio of change in power to change in rotor speed.

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