

Review of Maximum Power Point Tracking Algorithm for Tidal Turbine Generator

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Abstract—Tidal energy is a clean and environment-friendly energy source. It has many advantages such as sustainability, low initial cost, abundant and highly predictable due to its regular pattern. The working principle of tidal energy conversion system (TECS) is to use the potential and kinetic energy of the ocean waves caused by the celestial gravitation to drive the turbine that is coupled with a generator to produce electricity.

However, due to the physical structure of the generator, the power output is closely related with water speed, direction, load amount, etc., which show highly non-linear characteristics. The water speed and direction of the tidal stream are closely related to the moon phase, which can be considered as deterministic factor. However, there are non-deterministic factors such as sea habitat migration, seaweed entanglement, bio-fouling, etc. that can make the power output sub-optimal. In order to extract the maximum potential of tidal power in terms of electricity, the maximum power point (MPP) needs to be monitored and tracked in real time.

In this paper, we will review state-of-the-art MPP tracking (MPPT) of TECS such as optimal tip speed ratio (TSR) method, optimum relation based (ORB) method, and perturb and observe (P&O) method. Based on the reviewed methods, we summarize the principles, advantages and limitations of the methods, and show the performance of MPPT based on P&O in TECS with simulated results.

Index Terms—MPPT, Tidal Energy Conversion System, tip speed ratio, optimum relation, perturb and observe

I. INTRODUCTION

In recent years, the demand for renewable energy is drawing more and more attention since the price of conventional fuels are increased and the global temperature becomes higher and higher. There are several kinds of renewable energy, among them tidal energy shows its potential advantages including sustainability, low initial cost, abundant and highly predictable due to its regular pattern.

However, the maximum power is non-linearly related to the water flow speed and load demand, thus it is challenging to harvest the power at its optimal point. A series of algorithms that tracks the maximum power point (MPP) known as MPP tracking (MPPT) is developed in recent years.

Theoretically, recovering power of wind turbine generator is limited to approximately 59.3% (known as Betz limit) of the kinetic energy of the wind [1], which is also applicable to in stream tidal turbine. In practice, a power coefficient C_p takes into consideration frictional losses, rotational speed of the turbine, pitch angle, tip speed ratio (TSR) will not reach the

Betz limit. Since the C_p is a multivariate non-linear function and related to the optimal power output, it is feasible to track the maximum power point although the challenge is to solve non-linear time variant optimization problem. Many studies have been carried out on approaches of MPPT [2].

Generally, MPPT methods can be mainly classified into two categories: sensor based methods and sensorless methods. The sensor based methods are dedicated to develop the MPPT by control of turbine rotating speed at specific tidal current speed, commonly known as TSR (tip speed ratio) [3], [4]. TSR control regulates directly the turbine speed or torque to maintain the TSR at an optimum value by measuring the turbine speed.

The other sensor method of MPPT is optimum relation based method (ORB) [5] and it requires real-time monitoring of tidal stream speed as well as prior knowledge of tidal turbine characteristics. The MPP is tracked with the aid of optimum relation between different system variables such as power vs. shaft speed, power vs. torque etc. However, this method is limited by the dependency on the tidal characteristics.

Sensorless methods [6] rely on monitoring of the power variation. The most well known sensorless method is perturb and observe (P&O) [7] algorithm, because it does not need sensors and without the dependency on the system characteristics. It reduces the cost and improves the reliability.

II. TIDAL ENERGY CONVERSION SYSTEM

The block diagram of the TECS with MPPT algorithm [5] is shown as below in Fig. 1. The tidal turbine is coupled with the permanent magnet synchronous generator (PMSG) through a gear box. Compared with other generators, PMSG has higher power density and does not need excitation current from additional devices. The rectifier is a three phase diode rectifier for converting three phase AC voltage to DC voltage. The buck converter is a DC-DC step-down converter that the voltage input-output ratio is controlled by a pulse width modulation (PWM) signal from the MPPT controller. The controller reads the output voltage and current of the tidal generator to modulate the PWM signal.

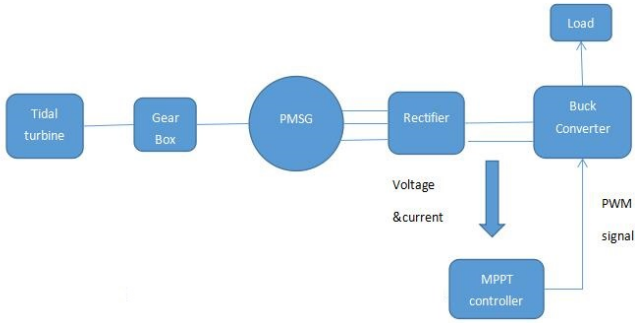


Fig. 1: Block Diagram of a Tidal Energy Conversion System

A. Characteristics of TECS

The mechanical power of the tidal p_{tidal} can be expressed as:

$$p_{tidal} = \frac{1}{2} \rho \pi R^2 v^3 \quad (1)$$

where ρ is the (sea) water density, R is the turbine radius and v is the tidal stream speed.

The power captured by the blades of the tidal turbine [8] is:

$$p_{turbine} = C_p(\lambda, \beta) p_{tidal} \quad (2)$$

where $C_p(\lambda, \beta)$ is the turbine power coefficient which is a function of tip speed ratio λ and pitch angle β , usually we assume the pitch angle is 0 degree. Also, the tip speed ratio can be calculated with :

$$\lambda = \frac{R \omega_{turbine}}{v} \quad (3)$$

where $\omega_{turbine}$ is the rotating angle speed with unit of rad/s. Fig. 2 shows the relationship of $C_p(\lambda, \beta)$ vs. λ with $\beta = 0$.

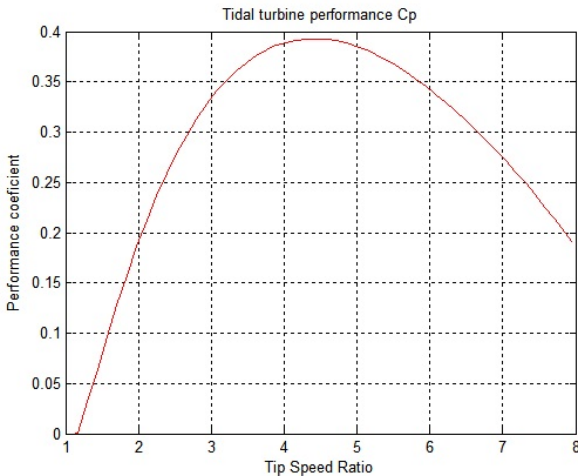


Fig. 2: C_p vs TSR Curve

For the same tidal stream, the bigger $C_p(\lambda, \beta)$ is, the more power tidal turbine can produce (assuming the constant

efficiency of PMSG). The power output curve with respect to the revolution speed under different tidal speeds is shown in Fig. 3.

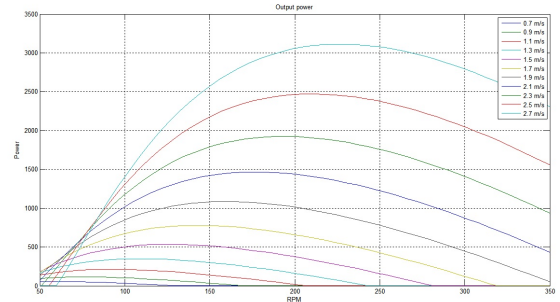


Fig. 3: Power vs Revolution per Minute (RPM) Curve with respect to Different Tidal Current Speed

III. REVIEW OF THE STATE-OF-THE-ART MPPT CONTROL METHODS

In order to extract the optimum power in the TECS (Tidal Energy Conversion System), some MPPT algorithms are reported which have been applied in wind energy system successfully. The accuracy of MPP tracked by the MPPT algorithm reflects the performance of a TECS. The maximum power extraction algorithms can be classified into three main control methods, namely TSR control, ORB control (sensor based) and P&O control (sensorless).

TSR control method is simple [9]. It regulates the rotational speed of the generator in order to maintain the TSR to an optimum value at which the tidal turbine system can produce maximum output power. However, by using this method we need to measure the wind and turbine shaft speeds in real time, which, in fact would reduce the dynamic response and accuracy of the whole system meanwhile increasing the cost by assigning some sensors.

In ORB control method, the MPP is tracked with the aid of optimum relation between different system variables such as power vs. shaft speed [5], power vs. torque [5], [10] and so on. ORB algorithms have good dynamic response and simple implementation. ORB control is mostly used in some wind energy system, it needs the prior knowledge of accurate system parameters that varies from one system to another and also may change due to system aging. This is the main drawback of this method. Therefore such method needs continuous simulations and lab testing to acquire prior knowledge of the system parameters.

The P&O control algorithms [6], [10]–[15] use the optimum relationship of the system to track the MPP by continuously changing the maximizing variable and observing the power captured. Based on the power measurements variation with the perturbation introduced, the next perturbation size and direction may be determined until the algorithm reaches the MPP. Most of the work done for MPPT using P&O has used the power-speed curve of the turbine [10], [11]. But there

is a possibility of using other system parameters as control variables for the MPPT, like the DC-link voltage and duty cycle which will in turn reduce the cost of system and increase reliability by removing the need for shaft speed sensing.

Tidal current speed measurements are not needed for P&O algorithms which reduces the cost as well. Prior knowledge of the system parameters is not a must for the algorithm to work, making this method more reliable and less complex. Also, P&O comprises the fixed-step duty cycle change and the variable-step duty cycle change. However, in order to reduce the impact of the sensor accuracy on the generated power, the fixed-step duty change is chosen as a simulation case study in the following section and the performance is reported.

A summary of reviewed MPPT algorithms is shown in Fig. 4.

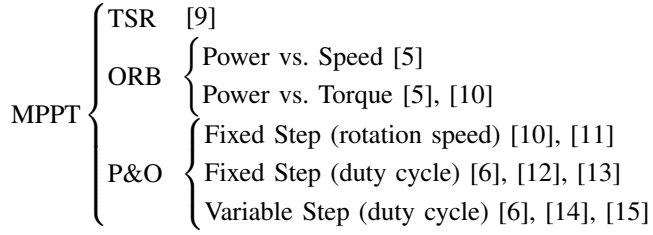


Fig. 4: Categories of MPPT Algorithms

IV. FIXED-STEP DUTY MPPT CONTROL METHOD

In this paper, the fixed step duty change MPPT method is to modify the duty ratio of the Buck converter to get the maximum power output from the generator. This procedure should be done continuously, and because of no need for the turbine characteristic and speed measurements, it is more reliable and less costly. From the analysis, we can see that when the output power reaches maximum for certain tidal current, the rotational speed of generator should satisfy:

$$\frac{dp}{d\omega_g} = 0 \quad (4)$$

where ω_g is the generator's rotational speed. And the curve is shown below in the Fig. 5.

Then we should find the function related the power and the duty ratio, using the chain theory we have:

$$\frac{dp}{d\omega_g} = \frac{dp}{dD} \frac{dD}{dV_{in}} \frac{dV_{in}}{d\omega_g} = 0 \quad (5)$$

In the DC-DC buck converter, the duty ratio D can be expressed as

$$D = \frac{V_{out}}{V_{in}} \quad (6)$$

Here V_{in} is the input voltage for the converter, namely, the output voltage of the rectifier, and V_{out} is the output voltage of the converter. So the duty ratio can be differentiated by the input voltage,

$$\frac{dD}{dV_{in}} = -\frac{V_{out}}{V_{in}^2} \neq 0 \quad (7)$$

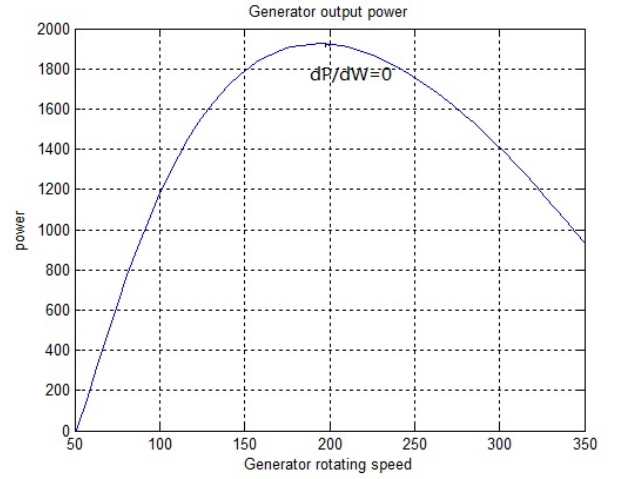


Fig. 5: Power vs Generator Rotation Speed Curve

And the converter input voltage is equal to the rectifier output voltage, that is positive value about the variation of generator speed.

$$\frac{dV_{in}}{d\omega_g} > 0 \quad (8)$$

With the above equations combined, we can get:

$$\frac{dp}{dD} = 0 \quad (9)$$

Based on the above equations, in the same way, we can induce the following rules:

$$\frac{dp}{d\omega_g} > 0, \frac{dD}{dV_{in}} < 0, \frac{dV_{in}}{d\omega_g} > 0 \Rightarrow \frac{dp}{dD} < 0 \quad (10)$$

$$\frac{dp}{d\omega_g} < 0, \frac{dD}{dV_{in}} < 0, \frac{dV_{in}}{d\omega_g} > 0 \Rightarrow \frac{dp}{dD} > 0 \quad (11)$$

Using the relation of (10), the control system can detect the variation of the output power of the generation system and estimate the location of current rotation speed of the generator. Then the duty ratio will be adjusted and the current rotation speed of generator can be reached at the optimal point which is the rotation speed at maximum power point in Fig. 5.

Next, the output power of system will be remeasured and the duty ratio will be readjusted according to (10). This process will be performed continuously, and the MPPT control will be performed on the tidal generation system. There are two kinds of perturbation for the duty ratio, one is the fixed step size and the other is the variable step. However, in order to reduce the impact of the sensor accuracy on the generated power, here we choose the fixed step size one. And the algorithm is as follows:

$$D_m = D_{m-1} + \Delta D_{m-1} \quad (12)$$

$$\Delta D_{m-1} = C_1 \text{sign}(\Delta D_{m-2}) \text{sign}(p_{m-1} - p_{m-2}) \quad (13)$$

where ΔD_{m-1} is the duty cycle change at step $m-1$, p_{m-1} is the output power at the step $m-1$, p_{m-2} is the output power at step $m-2$, C_1 is a constant determining the speed

and accuracy of the convergence to the MPP; and the function $sign(a)$ is defined as:

$$sign(a) = \begin{cases} 1 & \text{if } a \geq 0 \\ -1 & \text{if } a < 0 \end{cases} \quad (14)$$

The performances without MPPT control and with the fixed duty ratio MPPT control are shown in Figs. 6 and 7, respectively.

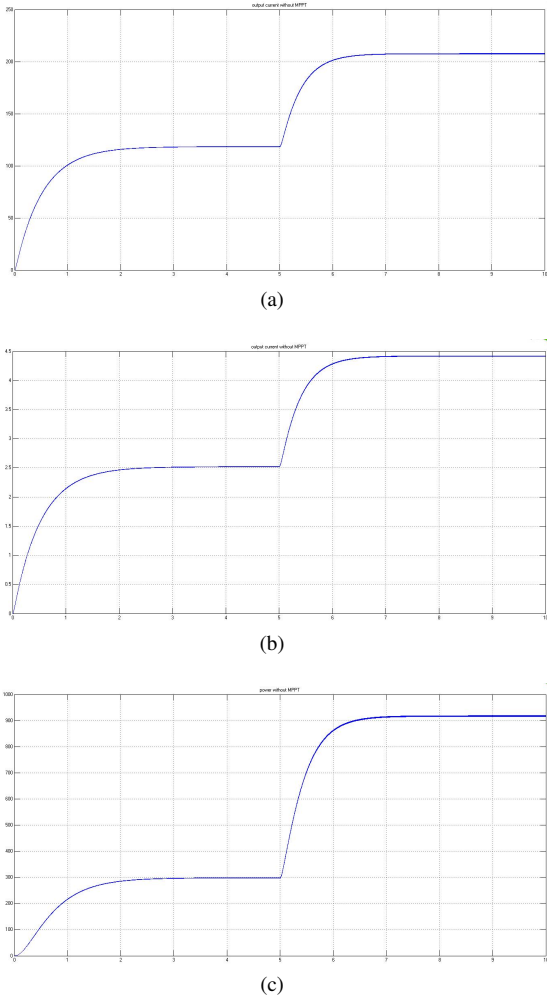


Fig. 6: Output (a) Voltage, (b) Current and (c) Power with respect to time without MPPT Control

The conventional control without MPPT has a constant duty ratio of 0.45. In order to compare the performance of MPPT algorithm against the conventional algorithm, we introduce a step-input with the value of 1.5m/s for the first 5s and 2.0 m/s for the last 5s. Comparing the above figures, we can see that at 4s the output powers are 300w and 400w for controls without and with MPPT, respectively, so the MPPT improves the efficiency by amount of 33.3% under the tidal current speed of 1.5m/s. However, when the input has changed into 2.0m/s, at 9s, the output powers are 920w and 1000w, respectively. Therefore the performance is improved by 8.7%.

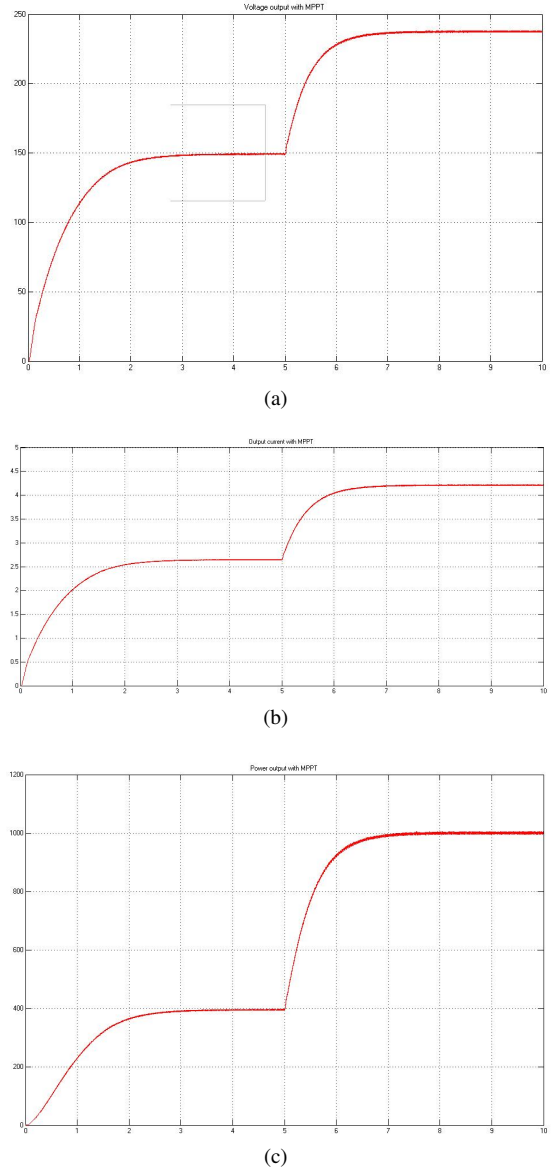


Fig. 7: Output (a) Voltage, (b) Current and (c) Power with respect to time with Fixed Duty Ratio MPPT Control

V. CONCLUSION

The MPPT control methods for tidal energy generation system are reviewed. And this method is based on the duty ratio regulation of buck type DC-DC converter, the MPPT control methods have advantages as follows. First, the tidal generator can be performed actively as changing the tidal speed, therefore the mechanical stress and unbalanced power can be reduced. Second, it is not necessary to need the information about tidal turbine characteristic, so the generation system can be stable under the condition of changing the parameters of system frequently. Finally, measuring errors and additional sensing systems due to measuring the tidal speed and/or tidal turbine speed are not existed, the reliability of system performance is developed and the cost to construct

entire generation system can be saved.

The simulation results show that output power can be increased under the MPPT control compared with the output power without MPPT control. It means that tidal energy can be transformed to electrical energy more efficiently by MPPT control method.

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