Maximum Power Tracking of Ocean Energy Generator Based on Active Disturbance Rejection Control

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Abstract. In order to make the ocean energy generator system realize the maximum power under various conditions, this paper proposes a control strategy based on linear active disturbance rejection control algorithm. The output power is mainly affected by the spin-speed of the generator in a nonlinear manner, and this phenomenon is originated from the tip speed ratio state of the turbine blades. This tip speed ratio associated maximum power can be achieved through a coupled control system that adjusts the spin-speed of generator elaborately. The state equations of ocean power generation system are transformed into a standard form to fit the linear active disturbance rejection control. Finally, the simulation model of the system is established by using Matlab/Simulink platform, with a series of input signals for different working conditions. The results verify that the maximum power under control can be effectively attained by a quick tracking of the target speed.

Keywords: Ocean power generation system; Linear active disturbance rejection control; maximum power output; Optimal tip speed ratio; Matlab/Simulink simulation.

1. Introduction

Among various forms of marine energy, ocean energy stands out because of its strong predictability, high energy density and impact on the marine environment[1]. At present, there are many achievements, such as the LHD modular tidal current generator set, "Haineng III" floating tidal current power station developed in China, SR2000 turbine generator set developed in UK, etc[2]. The power flow generation system mainly has the problem of low efficiency of energy capture and utilization[3]. Its power flow signal is complex due to the interference of external factors, and mathematical modeling of this system is a very difficult task [3]. Therefore, it is necessary to design a maximum power tracking control method which does not depend on the system model and can improve the stability and anti-interference ability of the system.

The influence of blade pitch angle on the dynamic characteristics of the horizontal axis tidal current motor is verified by experiments that the curves correspond to different blade pitch angles and to different maximum power coefficient and optimal tip speed ratio[4][5]. The specific functional relationship between the utilization coefficient of the power flow energy, tip speed ratio and pitch angle is obtained, and the maximum power output of the system can be achieved by controlling the motor speed to make the system run in the optimal tip speed ratio state[6][7]. Jingqing Han proposed a new active disturbance rejection controller (ADRC) which integrates the state observer and anti-jamming technology[8]. The feedback linearization of the system greatly
improves the disturbance and dynamic performance of the controlled object by means of complex parameter settings[9]. Zhiqiang Gao designed a linear active disturbance rejection controller (LADRC) as an improved ADRC - extended state observer(ESO): (1) it reduces the tracking differentiator part; (2) the original feedback mode of nonlinear combination is changed to PD control[10][11][12]. Compared with ADRC, the biggest advantage of LADRC is that it greatly reduces the control process and setting process, as well as easier realization of accurate control[13].

In this paper, based on the maximum power point tracking (MPPT) control method of optimal tip speed ratio, combined with the idea of active disturbance rejection control, a control strategy is designed to realize the motor speed tracking the target speed quickly, so as to achieve the maximum power output of the tidal current power generation system.

2. Turbine Characteristics and Principle of Maximum Ocean Energy Capturing

Ocean power generation system is generally composed of water turbine, permanent magnet synchronous generator, and control module. According to the Bates theory, the power absorbed by the turbine from the tidal current is[14]:

\[ P_\omega = \frac{1}{2} \rho A C_p (\lambda, \theta) v^3 = \frac{1}{2} \rho \pi C_p (\lambda, \theta) R^2 v^3 \]  

(1)

Here, \( \rho \) is the current density; A is the cross flow area through the turbine; \( C_p \) is the utilization coefficient of tidal current energy; \( \lambda \) is the tip speed ratio; \( \theta \) is the blade pitch angle; \( v \) is the velocity of water flow; R is the radius of impeller. Among them, \( C_p \) is the function of \( \lambda \) and \( \theta \). The relation is shown in equation (2)[15]:

\[
\begin{align*}
C_p(\lambda, \theta) &= 0.5176 \left( \frac{1.16}{\alpha} - 4.4\theta - 0.5 \right) e^{-\frac{21}{\alpha}} + 0.0068\lambda \\
\frac{1}{\alpha} &= \frac{1}{\lambda + 0.08\theta - \frac{0.035}{\theta^3+1}}
\end{align*}
\]

(2)

Figure 1 demonstrates the variation of \( C_p \) along with \( \lambda \) at the given \( \theta \). It can be seen that the curve has its corresponding maximum power flow energy utilization coefficient, which is labeled as \( C_{p_{max}} \); When a value has been determined, its corresponding \( C_{p_{max}} \) only corresponds to the special abscissa value, that is, the optimal tip speed ratio \( \lambda_{opt} \).

![Figure 1. Relationship curve of \( C_{p_{max}} \) and \( \lambda_{opt} \).](image)

![Figure 2. The relationship curve of \( C_p, \lambda \) and \( \theta \).](image)

Figure 2 shows that when the angle \( \theta \) ranges from 1 to 5 degrees, the curve of \( C_p \) changes along with \( \lambda \). When \( \theta = 3^\circ \) and \( \lambda = 4 \), the utilization coefficient of tidal current energy can reach the maximum value, about 0.3.

Therefore, when the ocean power generation system needs to use the maximum power tracking control, and get \( \lambda_{opt} = 4 \) consequently. Because the blade tip speed ratio formula is:

\[ \lambda = \frac{2 \pi n R}{v} = \frac{\omega R}{v} \]

(3)
Here, $\omega$ is the angular velocity of the turbine, same as the motor speed. Then, the target speed $\omega^*$ can be determined by the relationship of the blade tip speed ratio $\lambda$ and motor speed $\omega$. Later, the generator speed $\omega$ is controlled to track $\omega^*$ quickly with respect to the state of optimal tip speed ratio. Finally, the maximum power flow energy utilization coefficient $C_{p_{\text{max}}}$ and the maximum power output can be obtained.

3. Model of Power Flow Generator

The voltage, torque and dynamic equations of PMSG in the $d-q$ rotating coordinate system are as follows:

the equation of voltage,

$$
\begin{align*}
\begin{cases}
u_d = R_s i_d + nL\omega i_q + L \frac{di_d}{dt} \\
u_q = R_s i_q + nL\omega i_d + n\omega \psi_f + L \frac{di_q}{dt}
\end{cases}
\end{align*}
$$

(4)

the equation of torque,

$$
T_e = \frac{3}{2} n (\psi_f i_q + (L_d - L_q) i_d i_q)
$$

(5)

the equation of dynamic,

$$
J \frac{d\omega}{dt} = T_m - T_e - B\omega
$$

(6)

Here, $u_d, u_q$ are two voltage components on two axes of the $d-q$ rotating coordinate system; $i_d, i_q$ are two current components on the two axes of the $d-q$ rotating coordinate system; $R_s$ is the resistance of the armature coil; $\psi_f$ is the flux linkage of rotor; $L$ is the armature inductance; $J$ is the moment of inertia of the motor; $T_m$ is the driving torque of hydraulic turbine; $B$ is the viscous friction coefficient.

As a typical and effective method of vector control, field orientation can be used to solve the following problems: (1) the mathematical model is complex and is difficult to operate; (2) the strong coupling motor system cannot be decoupled; (3) the motor torque is unstable and the speed range is small.

Therefore, this paper adopts the method of $i_q^* = 0$. Then the torque equation can be changed into:

$$
T_e = \frac{3}{2} n\psi_f i_q
$$

(7)

4. Design of MPPT Controller

In order to make the rotating speed of motor reach the target speed quickly, a speed closed-loop controller based on LADRC is designed and its work flow is shown in figure 3.

![Flow chart of speed control of Tidal current power generation system.](image)

Figure 3. Flow chart of speed control of Tidal current power generation system.
When the flow velocity is in between the cut in velocity and the rated velocity, the maximum power tracking control is in action. After the flow velocity $v$ is detected, the target speed $\omega^*$ can be obtained. The turbine and generator are driven by the water flushing torque $T_m$. Actual speed of generator $\omega$ is transmitted to the extended state observer (ESO) through the speed feedback link, and the ESO outputs the current state of the generator $z_1, z_2$, which are observation value of $\omega$ and unknown disturbance in the controlled object. Next, the difference between $z_1$ and target signal $\omega^*$ is imported into the closed-loop system and is adjusted by the proportion link $\omega(t)$; $z_2$ is fed back to $u_q(t)$ in advance to form the control input $u_q$ of the controlled system.

$i_d, i_q$ are two current components on the two axes of the $d-q$ rotating coordinate system. Then they are converted into the component $i_\alpha, i_\beta$ of stationary coordinate system in the PARK inverse transformation. Then $i_\alpha$ and $i_\beta$ are converted into the current components $i_a, i_b, i_c$ in the abc three-phase static coordinate system in the CLARK inverse transformation, and finally reaches the PMSG. Therefore, the whole workflow forms a complete closed-loop control.

The following expression is the conversion process of PARK and CLARK inverse transformation:\[16]:

$$
\begin{align*}
    i_\alpha &= i_d \cos \phi - i_q \sin \phi \\
    i_\beta &= i_d \sin \phi + i_q \cos \phi \\
    i_a &= \frac{\sqrt{2}}{2} i_\alpha \\
    i_b &= -\frac{\sqrt{3}}{2} i_\alpha + \frac{\sqrt{2}}{2} i_\beta \\
    i_c &= \frac{\sqrt{3}}{2} i_\alpha - \frac{\sqrt{2}}{2} i_\beta
\end{align*}
$$

(8)

(9)

It can be seen from that in the control strategy design of linear active disturbance rejection method, the expression form of the controlled object should be designed as follows (taking the first-order system as an example):

$$
\dot{y} = ay + w + bu = ay + w + (b - b_0)u + b_0
$$

(10)

Among them, $y$ and $u$ are the input signal and output signal, $a$ is the coefficient of $y$, $w$ is the external disturbance, $b$ is the coefficient of the output signal, and $b_0$ is the estimated value of $b$, which needs to be adjusted during simulation.

From the PMSG dynamic equation (6), the speed control loop equation of the motor is:

$$
\dot{\omega} = \frac{1}{J}(T_m - B\omega) - \frac{n_\psi}{J} i_q
$$

(11)

It can be seen that this system is a first-order system, and $\omega$ is the input $y$; $i_q$ is the output $u$; $-\frac{n_\psi}{J}$ is the coefficient $b$ of the output $u$. Then the standard form required by LADRC written in the form of formula (10) is:

$$
\dot{\omega} = \frac{1}{J}(T_m - B\omega) + (b - b_0)i_q + b_0 i_q
$$

(12)

The ESO model can be designed as follows:

$$
\begin{align*}
    \dot{z}_1 &= z_2 - \frac{n_\psi}{J} i_q + \beta_1(\omega - z_1) \\
    \dot{z}_2 &= \beta_2(\omega - z_1)
\end{align*}
$$

(13)

Here, $\frac{1}{J}(T_m - B\omega) = z_2$, it represents the unknown disturbance of the system. Then the governing equation of the system can be designed as:

$$
\begin{align*}
    u_0(t) &= k_p(\omega^* - z_1) \\
    i_q &= u_q(t) - \frac{z_2}{b_0}
\end{align*}
$$

(14)
β₁ can be taken as 2ω₀, β₂ can be taken as ω₀², of which ω₀ is the bandwidth of ESO. kₚ is the function of ωₑ, which is the proportional coefficient of closed-loop control and also the parameter to be set, and ω₀ is proportional to 3 to 5 times of ωₑ [10][17][18]. To sum up, only two parameters need to be set in the simulation, that are b₀ and ωₑ.

5. Simulation and Verification of the System
In order to verify the effectiveness of the control strategy, the system modeling and simulation verification are conducted through the MATLAB / Simulink simulation platform. The simulation parameters are set as follows: impeller radius R = 0.5 m; optimal tip speed ratio λₜ = 4; moment of inertia J = 0.001 kg·m²; viscous friction coefficient B = 0.06 kg·m²/s; Polar logarithm n = 2; flux linkage ψf = 0.2 Wb; maximum power flow energy utilization factor Cₚₘₐₓ = 0.3.

5.1. Simulation of Velocity Change with Step Input Signal
As the square wave signal has the characteristics of repeated and rapid changes, it can more comprehensively reflect the dynamic response ability of the power flow power generation system when the flow rate changes sharply. Therefore, this paper firstly selects the square wave as the input signal to investigate the dynamic control ability of the controller to the power generation system. The characteristics of the square wave signal are given as follows: the amplitude equals to 4, the frequency is 0.5 Hz, and the verification period is 5 s. The target speed cycles the sudden reciprocate rotation in 2 seconds with the maximum speed at 4 r/s. Parameters b₀ and ω₀ are tuned to −1000 and 4ωₑ respectively. ωₑ takes 30, 40, and 50 respectively.
Figure 6. Motor speed change curve when $\omega_c$ is 50.

Figure 4, 5, and 6 illustrate that, as $\omega_c$ gradually increases, the time required for the generator speed to track the target speed becomes shorter. That is, the response speed becomes much faster. But when $\omega_c = 50$, the generator speed has a certain overshoot relative to the target speed, which does not meet the requirements. By comparison, when $b_0 = -1000$, $\omega_c = 40$, $\omega_0 = 4\omega_c$, the generator speed tracking the target speed can achieve the best effect from the perspective of response speed and overshoot. The ocean power generation system has a strong dynamic performance, which can achieve maximum power tracking.

5.2. Simulate Flow Rate Changes with Sinusoidal Input Signal

However, the ocean power generation performs in a very gentle fashion rather than sudden changes in reality. For this reason, in the simulation, a sine wave signal is employed to simulate the flow rate fluctuation of the actual power generation. The sine wave signal has the following characteristics: the amplitude is selected as 4, the frequency is selected as 0.25 Hz, and the verification period is 5 s. The sine-shaped target speed has the maximum value of 4 r/s in 1 s (the 1st quadrant) for its cycle. Parameters $b_0$ and $\omega_0$ are tuned to $-1000$ and $4\omega_c$ respectively. $\omega_c$ takes 20, 50, and 100 respectively. The simulation results are shown in Figures 7, 8, and 9.

Figure 7. Motor speed change curve when $\omega_c$ is 20.
Figure 8. Motor speed change curve when $\omega_c$ is 50.

Figure 9. Motor speed change curve when $\omega_c$ is 100.

It can be seen from Fig. 7, 8, and 9, that as $\omega_c$ gradually increases, the tracking time to the target speed becomes shorter without overshoot. When $b_0 = -1000$, $\omega_c = 40$, and $\omega_0 = 4\omega_c$, the tracking speed achieves the best effect regardless to the response speed or the overshoot angle. This conclusion verifies that the ocean power generation system can achieve the maximum power tracking for output.

6. Conclusion
This paper proposes a maximum power tracking control strategy based on the linear auto-disturbance rejection control, which serves the problem of low energy capture efficiency of ocean power generation systems. First of all, in order to simulate extreme rapid flow changes rate conditions, and to verify the dynamic response capability of the system, a square wave signal is used as the input signal. After setting appropriate parameters, the generator speed reaches and maintains the target speed quickly after a short delay without overshoot. Then a sinusoidal signal was employed for smoothly changing flow rate in reality rather than the square wave and the final generator speed has a good agreement with the target speed quickly without overshoot, as well. In summary, the maximum power tracking method is effective for ocean energy power output control.

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