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Comparative Study Between MPPT Algorithms Applied to Wind Energy Conversion System

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Abstract— **This paper provides a review of MPPT controllers used for extracting maximum power from the wind energy systems using permanent magnet synchronous generators. These MPPT controllers can be classified in to three main control algorithm, namely optimal torque control (OTC), power signal feedback (PSF) and hill-climb search (HCS). Most control schemes use the HCS technique, because it's simple and easy to implement, but it's less efficient and present wrong directionality under rapid variation in wind speed. To solve these problems, Hybrid HCS method (HHCS) is proposed; it combines OTC and HCS control. A comparison has been made between the performance of the different MPPT algorithms on the basis of speed responses and ability to achieve the maximum energy. The performance of the proposed control is validated through simulation results.**

Keywords- **Wind Energy, Maximum Power Point Tracking, PMSG, Hybrid HCS.**

I. INTRODUCTION

Wind energy source is becoming more and more used as a renewable source since it offers several advantages such as incurring no fuel, not being polluting and inexhaustible source. The output power of wind energy system varies continually as wind speed changes. To operate in variable-speed conditions, a wind energy system needs a power electronic converter. Several work have considered the different possible configurations of electrical generators and power converters for variable-speed wind turbine systems [1-4].

The permanent magnet synchronous generator (PMSG) is chosen due to its high efficiency, reliability, power density, gearless construction [16–20]. Controlling the PMSG to attain the maximum power point (MPP) can be done using a power electronic interface circuit.

In this paper, the PMSG load interfacing is made through a PWM rectifier. The rectifier is controlled and the MPPT is used in determining the optimum rotor speed for each wind speed to obtain maximum power. The maximum power extraction algorithms researched can be classified into three main control methods, namely Optimal Torque Control (OTC), power signal feedback (PSF) control and hill-climb search (HCS) control.

In the first algorithm, the OTC algorithm adjusts the generator torque to its optimal value at different wind speeds. This method requires the wind turbine characteristics (C_{pmax} and λ_{opt}) [4]. In the second method, the reference power trajectory can be mathematically written as a function of power and rotational speed or it can be stored as a look-up table. The main drawback of this method is that the maximum power curve should be obtained by simulations or experimental test. Thus it is complex to implement [2]. The last method is an interesting method to achieve MPPT in wind turbines; it is called Perturbation and Observation algorithm (P&O) or Hill Climbing Searching [5]. This technique has been extensively used in power processing of photovoltaic panels [6,7]. HCS algorithm is a simple method; it does not require prior knowledge about turbine, generator and wind characteristics [2,4].

In the context of variable speed wind energy system, this algorithm brings the operating point toward C_{pmax} by increasing or decreasing then perturbing the rotational speed by a perturbation step. Also, choosing an appropriate step size is not an easy task: though larger step-size means a faster response and more oscillations around the peak point, and hence, less efficiency, a smaller step-size improves efficiency but reduces the convergence speed [2,8]. Two serious problems associated with HCS control which can significantly deteriorate its performances: speed efficiency trade off and wrong directionality under rapid wind change

To solve this problem, hybrid methods namely Hybrid HCS (HHCS) is described in this paper where the OTC control is combined to the conventional HCS algorithm,. It merges the advantages of two MPPT processes to solve the problem of the classical HCS algorithm. We make an application on a wind turbine system using the different MPPT strategies (OTC, PSF and HHCS) and a comparison has been achieved under different wind speed conditions. The performances of the studied system are verified by simulation analyses carried by using MATLAB®-SIMULINK® software.

II. SYSTEM DESCRIPTION

The block diagram of the variable speed wind energy system studied is shown in Fig. 1. It consists of a horizontal wind turbine connected to a permanent magnet synchronous generator (PMSG), PWM rectifier, batteries and load.

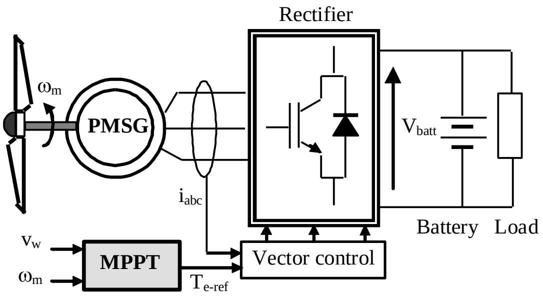

Fig.1 Wind energy conversion system

A. Wind turbine model

Wind turbine mechanical power, P_m, is given by the following equation:

$$P_m = \frac{1}{2} C_p(\lambda).\rho.A.v_w^3 \qquad (1)$$

Where P_m is the extracted power from the wind, ρ is the air density [kg/m^3], A is the area swept by the rotor blades, v_w is the wind speed [m/s] and C_p is called the power coefficient.

C_p depends on a factor λ known as the tip speed ratio (TSR). TSR is defined as the ratio of the turbine's blade-tip speed to the wind velocity, and can be expressed by Eq. (2):

$$\lambda = \frac{\omega_m . R}{v_w} \qquad (2)$$

Where ω_m is the turbine angular speed and R the turbine radius.

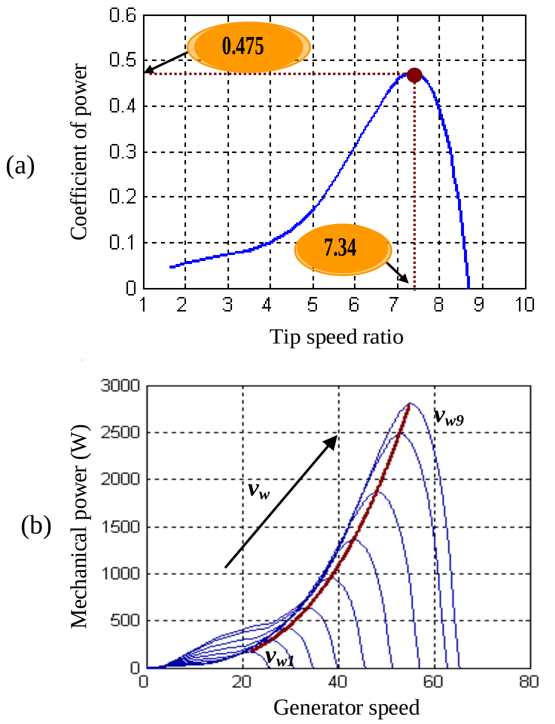

Fig.2 Characteristic curves of wind turbine
(a) Power conversion coefficient versus tip speed ratio. (b) Turbine power versus rotational speed

The C_p versus tip speed ratio (TSR) curve is shown in Fig.2.a by assuming that the blade pitch angle β is constant. [9]: the value of C_p is a function of λ and it is maximal at the particular λ_{opt}. The variation of power captured by the wind turbine versus the rotational speed for different values of wind speed is shown in fig.2.b.

The mechanical system is represented by the following equation:

$$J \frac{d\omega_m}{dt} = T_m - T_e - f\omega_m \qquad (3)$$

Where: J is the total inertia in (kg m²), T_m is the mechanical torque developed by the turbine in (N.m), T_e is the electromagnetic torque in (N.m), and f is the viscous friction coefficient in (N.m.s rad^{-1}).

B. Permanent magnet synchronous generators model

The electrical equations that describe the behaviour of PMSG in the rotor (dq) reference frame are given by:

$$\begin{aligned} V_d &= R_s i_d - \omega_e \psi_q + \frac{d\psi_d}{dt} \\ V_q &= R_s i_q + \omega_e \psi_d + \frac{d\psi_q}{dt} \end{aligned} \qquad (4)$$

Where i_d, i_q, V_d, V_q, are the currents and voltages in the dq reference frame, L_d and L_d are the equivalent stator inductances in the dq synchronous reference frame, and R_s stator resistance, ω_e is the electric frequency that is related to the mechanical speed via $\omega_e = p\omega_m$

$$\psi_d = L_d i_d + \psi_f \qquad (5)$$

$$\psi_q = L_q i_q \qquad (6)$$

Where Ψ_f is the permanent magnetic flux produced by the rotor magnets, and P is the pair pole number of the machine. The magnetic flux Ψ_f is a constant that depends on the material used for the realization of the magnets.

The electrical torque applied to the PMSG rotor can be expressed by Eq. (7), by considering a PMSG without rotor saliency (L_d=L_q). As a consequence, the generator torque may be controlled simply by regulating the current I_q.

$$T_e = \frac{3}{2}.p.\psi_f.i_q \qquad (7)$$

III. MPPT TECHNIQUES

A. Optimal Torque Control (OTC)

Optimal Torque control adjusts the generator torque to its optimal at different wind speeds. However it requires the knowledge of turbine characteristics (C_{pmax} and λ_{opt}). If the conditions are optimal, based on equation (.2), the optimum speed of the rotor can be estimated as:

$$\omega_{m,opt} = \frac{V_w . \lambda_{opt}}{R} \quad (8)$$

Combining equations (.1) and (.2), the maximum power output by wind turbine is given by:

$$P_{m,opt} = \frac{C_{p\max} . \rho . \pi . R^5}{2 . \lambda_{opt}^3} . \omega_{m,opt}^3 = K_{opt} . \omega_{m,opt}^3 \quad (9)$$

and then the maximum torque is:

$$T_{m,opt} = \frac{C_{p\max} . \rho . \pi . R^5}{2 . \lambda_{opt}^3} . \omega_{m,opt}^2 = K_{opt} . \omega_{m,opt}^2 \quad (10)$$

Where K_{opt} is a constant determined by the wind turbine characteristics.

B. Power Signal Feedback (PSF)

Power Signal Feedback control generates a reference power signal to maximize the output power. However it requires the knowledge of the wind turbine's maximum power curve which can be obtained from the experimental results or simulations. Then, the data points for maximum turbine power and the corresponding wind turbine speed must be recorded in a lookup table [4,8]. The PSF control method regulates the turbine power to maintain it to an optimal value, so that the power coefficient C_p is always at its maximum value corresponding to the optimum tip speed ratio.

C. HCS control

Hill climb Searching is widely used in wind energy systems to determine the optimal operating point that will maximize the extracted power. This control is base on perturbing a control variable with a step and observing the resulting, the power previously delivered is compares with the one after disturbance. Choosing an appropriate step size is not an easy task: larger step-size means a faster response and much oscillation around the peak point, and hence, deteriorates the efficiency. A smaller step-size improves the efficiency but the controller will become very slow, as shown in Fig. 3. There is a Trade off between the tracking speed and the control efficiency.

The magnitude of the step-size is the main factor determining the amplitude of oscillations and hence the convergence rate to the final response. To overcome this trade-off, the step-size of varying amplitude can be applied. The step-size amplitude can be determined according to power variations based on the previously applied disturbance. Therefore, larger step-size amplitude is selected when power is far from MPP due to the larger magnitude of $P_m(\omega_m)$ slope and small amplitude is selected when power is close to MPP. The step-size is continually decreased until it approaches zero in the aim to drive the operating point to settle down at the MPP

A disadvantage of HCS method, described by fig.4 [8], appears (in bleu color) in the case of a sudden increase of wind speed, where the algorithm responds as if the increase occurred as a result of the previous perturbation of the operating speed.

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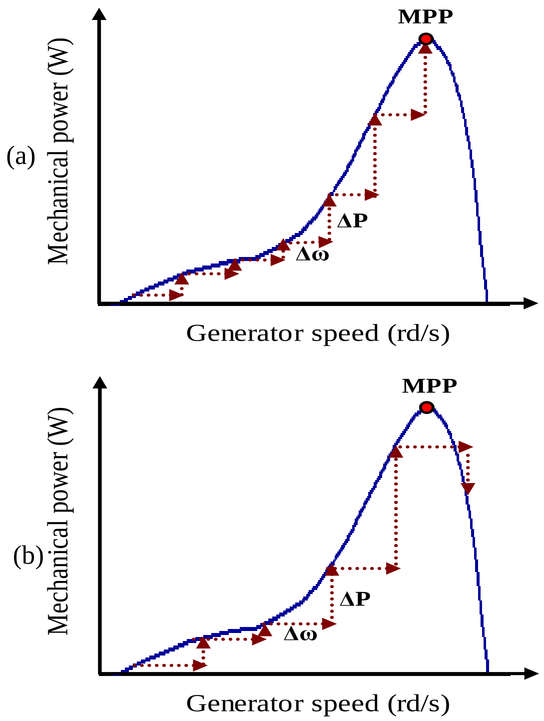


Fig. 3. HCS control (a) smaller perturbation, (b) larger perturbation.

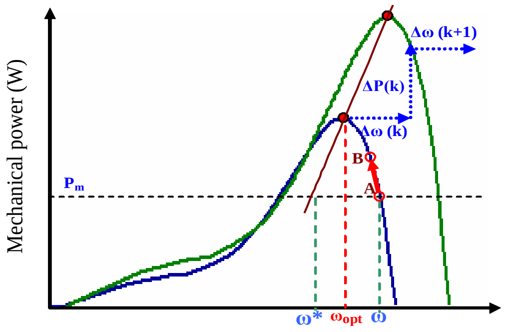


Fig. 4. Deviation from the MPP with the HCS algorithm under rapidly changing wind conditions and operating in Mode2 [Kasmi]

This wrong decision leads to the failure in keeping track of MPP. The use of variable step size amplitude overcomes the trade-off between the response speed and the steady state oscillations that occur in the conventional P&O method, but if the system operating point changes quickly (rapid wind change), the algorithm will be prone to errors [4,8]

In this paper, hybrid HCS algorithm (HHCS) is presented to track the maximum power point, MPP, where the OTC method is merged with HCS to solve the two problems associated with conventional HCS: speed efficiency trade-off and wrong directionality under rapid wind change.

During the normal hill climbing, if we happen to attain the maximum, then we can extract the k_{opt} from there by measuring the mechanical power and the rotational speed. Once the k_{opt} is known, then it can serve as an accurate reference ω_m^* for both the size and the direction of the next perturbation when the variation of wind speed is detected. The speed step can be calculated following eq.11. The perturbation size will automatically approach towards zero thus eliminating the speed-efficiency concession of a normal HCS. This idea is proposed by Kazmi [8] where this method is presented and applied to adjusting the dc-dc converter duty cycle of a dc-dc buck boost converter.

$$\Delta\omega_m(k+1)=\alpha.(\omega_m-\omega_m^*) \tag{12}$$

Where ω_m^* is the abscissa of the optimal curve corresponding to the mechanical power. Fig. (4) provides an example of HHCS control working during the Mode 2. The direction in which the operating point travels is the direction of $(\omega_m-\omega_m^*)$, (point A to B). Mode 2 keeps in operation until the operating point reaches sufficiently closer to the curve characterized by k_{opt}. The Flowchart of the hybrid HCS MPPT control is shown in fig.5

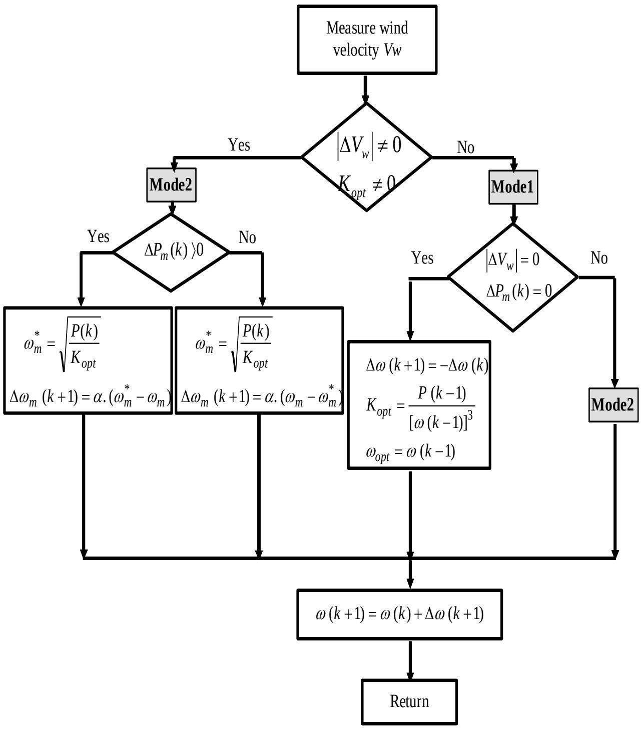


Fig. 5. Flowchart of the hybrid HCS MPPT control.

IV. NUMERICAL SIMULATION

The performances of different MPPT controls are presented. The simulated system diagram is shown in Fig. 1. The simulations are carried out using Matlab/Simulink mathematical analysis software package. The system component parameters are described in [9]. A battery voltage of 800V is considered and its value is constant whatever wind speed variation. A vector control strategy is used, whose principle is to adjust PMSG rotational speeds according to an optimal reference speed obtained from an MPPT controller. In this control, the d-axis reference current is set at zero in order to decrease the copper losses in the stator windings. The q-axis reference current is proportional to the torque reference that is generated from an MPPT controller and varies under wind speed variations. Hysteresis-band current control technique is used [10].

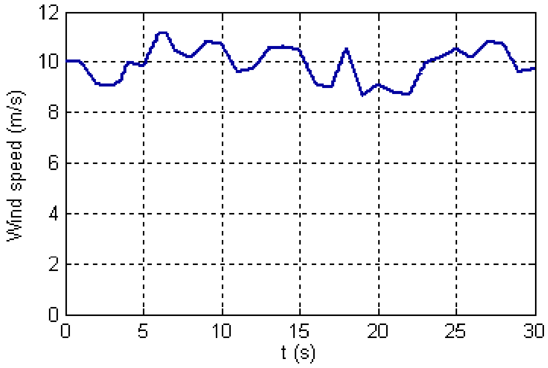
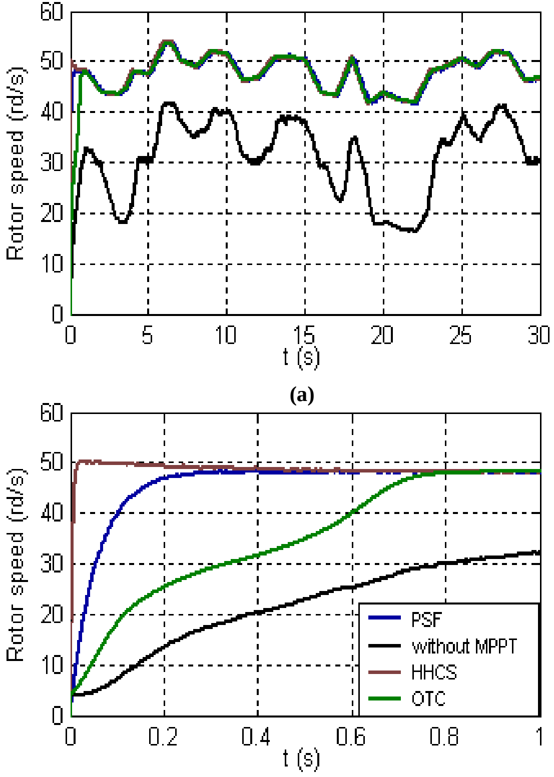


Fig.6 Wind speed profile

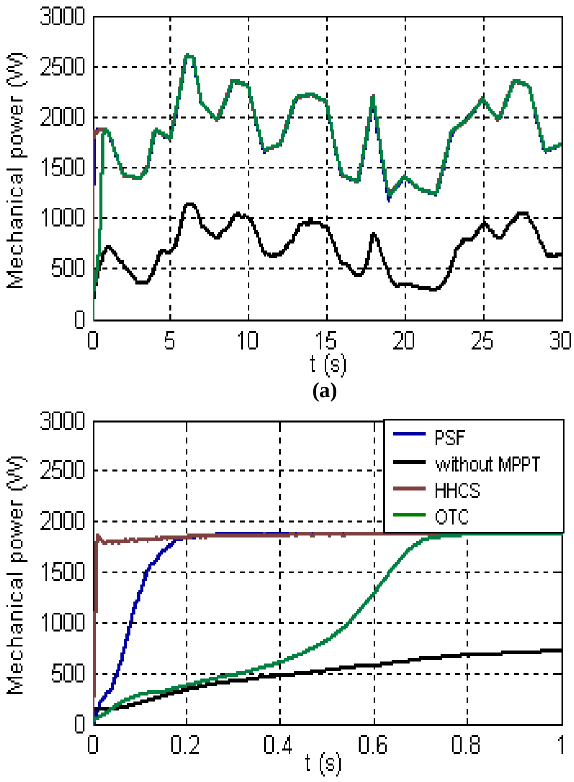


(a)

(b)

Fig.7 (a). Waveform of rotor speed, (b). Zoom of the transitional state.

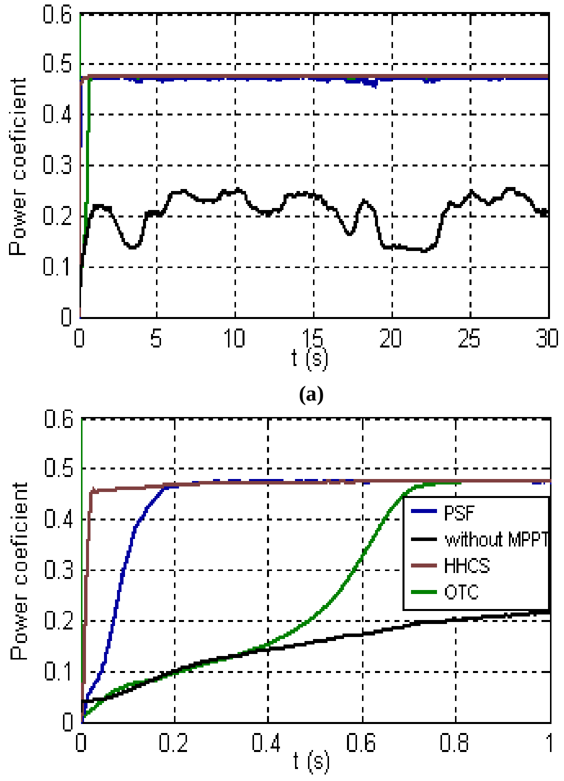
The studied MPPT methods are OTC, PSF and hybrid HCS. Fig. 6 shows the wind speed profile. The mechanical power, rotor speed, power coefficient and tip speed ratio, with a zoom are shown in figs.(7-10). Good tracking capability was observed. Without MPPT strategy, the maximum power obtained is 1060W. The maximum value of C_p of the turbine considered is 0.475, and it was found that without MPPT strategy, this value does not exceeds 0.25. The hybrid HHCS controller seems to be the fastest in achieving the steady-state (0.01s compared to 0.72 for OTC and 0.19 for PSF).



(a)

(b)

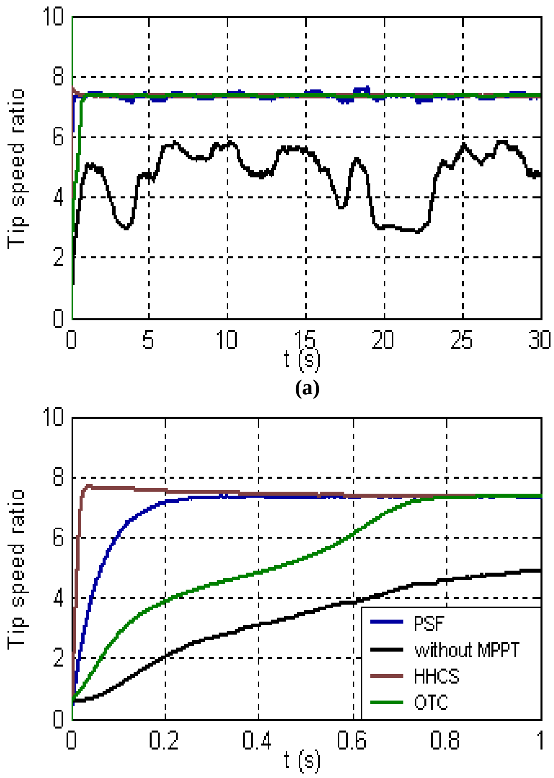
Fig.8 (a). Waveform of mechanical power, (b). Zoom of the transitional state.



(a)

(b)

Fig.9 (a). Waveform of power coeficient, (b). Zoom of the transitional state.



(a)

(b)

Fig.10 (a). Waveform of mechanical power, (b). Zoom of the transitional state.

The optimal value of power coefficient is reached and this value is maintained even after the change in wind speed. It can therefore be concluded from the results of simulation that the proposed control algorithm has good capability of tracking peak power points.

V. CONCLUSION

This paper proposes a novel MPPT algorithm for a permanent magnet direct drive wind energy conversion system. This control is used to overcome the trade-off between the response speed and the steady state oscillations and also makes sure that the variation in wind speed should lead the HHCS in the correct direction.

For verifying the effectiveness of the proposed MPPT method, simulation models are built. The proposed HHCS control is compared with the traditional OTC and PSF methods and the results show the advantage of the hybrid HHCS strategy in terms of response speed and the efficiency under quickly changing in wind speed. This method also has good application potential in other types of wind energy conversion systems.

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