Abstract—Making full use of wind power is one of the main purposes of the wind turbine generator control. Conventional hill climbing search (HCS) method can realize the maximum power point tracking (MPPT). However, the step size of HCS method is constant so that it cannot consider both steady-state response and dynamic response. A fuzzy logical control (FLC) algorithm is proposed to solve this problem in this paper, which can track the maximum power point (MPP) quickly and smoothly. To evaluate MPPT algorithms, four performance indices are also proposed in this paper. They are the energy captured by wind turbine, the maximum power-point tracking time when wind speed changes slowly, the fluctuation magnitude of real power during steady state, and the energy captured by wind turbine when wind speed changes fast. Three cases are designed and simulated in MATLAB/Simulink respectively. The comparison of the three MPPT strategies concludes that the proposed fuzzy logical control algorithm is more superior to the conventional HCS algorithms.

Index Terms—Fuzzy logical control, hill climbing search, maximum power point tracking, permanent magnet synchronous generator, wind generation system.

1. Introduction

Wind turbine is an essential portion in wind generation systems. The amount of mechanical energy that can be extracted from wind is not only depending on wind speed, but also depending on the wind turbine rotational speed.

The wind turbine rotational speed can be adjusted as the wind speed changes to tracking the maximum power point. Currently, researchers have developed many maximum power point tracking (MPPT) strategies. There are three common MPPT algorithms[1],[2]: a) hill climbing search (HCS) or perturbation and observation (P&O)[3],[4], b) wind speed measurement (WSM)[5], c) power signal feedback (PSK). There are also other MPPT algorithms introduced in [6]–[11].

In comparison, the HCS algorithm is popular[12] due to its simplicity and independence of system characteristics and it can avoid using wind speed. However, the step size of HCS algorithm is constant[13]. Choosing an appropriate step size is not an easy task, where large step size means faster response and less steady-state efficiency while small step size improves steady-state efficiency but slows down the convergence speed [8]. The conventional HCS algorithm cannot combine rapidity and efficiency, which means the algorithm cannot adapt well both in the situation that wind speed changes quickly and in the situation that wind speed is constant.

In this paper, a fuzzy-logical-controller based MPPT strategy for wind generation system is proposed, which can realize variable step-size control. The strategy is independent of the turbine’s characteristics. Compared with conventional HCS algorithms with a big step size and a small step size respectively, the proposed algorithm is validated superiorly in MATLAB/Simulink environment. The simulation results indicate the proposed MPPT algorithm has three advantages: a) tracking MPP fast, b) the fluctuation magnitude of real power is small during steady state, and c) the wind energy captured is the most among the three MPPT algorithms.

This paper is organized as follows: Section 2 gives a brief introduction to the wind turbine characteristics and to the wind generation system. Section 3 presents an introduction to the conventional HCS algorithm. In Section 4, we discuss the proposed fuzzy logical control (FLC) strategy and its advantages compared with conventional HCS strategy. Case studies are presented in detail in Section 5. Conclusions are finally made in Section 6.

2. System Overview

2.1 Wind Turbine Characteristics

Depending on the aerodynamic characteristics, the wind
power captured by the wind turbine can be expressed as

\[ P = \frac{1}{2} C_p(\lambda, \beta) \rho \pi R^2 V^3 \]  

(1)

where \( C_p(\lambda, \beta) \) is the wind turbine power coefficient which is a function of \( \lambda \) and \( \beta \), \( \rho \) is the air density, \( R \) is the radius of wind turbine blade, \( V \) is the wind speed, \( \beta \) is the blade pitch angle, and \( \lambda \) is the tip speed ratio:

\[ \lambda = \frac{wR}{V} \]  

(2)

where \( w \) is the wind turbine rotational speed. There exits an optimal tip speed ratio \( \lambda_{\text{opt}} \) that can maximize \( C_p \) and \( P \). Then, the maximum wind power \( P_{\text{max}} \) captured by wind turbine can be described as

\[ P_{\text{max}} = \frac{1}{2} \rho \pi R^2 \frac{C_p}{\lambda_{\text{opt}}} w^3. \]  

(3)

The output mechanical power versus rotational speed characteristic of wind turbine for different wind speeds is shown in Fig. 1, in which the dotted line shows the maximum power points for different wind turbine rotational speed \( w \) and different wind speed \( V \). Each \( P-w \) curve is characterized by a unique turbine speed corresponding to the maximum power point for that wind velocity\(^{[14]} \). The peak power points in the \( P-w \) curves correspond to \( dP/dw = 0^{[15]} \).

A direct driven permanent magnet synchronous generator (PMSG) connected to a utility grid is selected in this paper. The specifications of the simulated PMSG generation system are listed in Table 1.

2.2 Wind Generation System

Direct driven PMSG wind generator can connect a utility grid through various converter topologies\(^{[16]} \), where double PWM converters are a common topology for PMSG wind generation systems. The double PWM converters own a flexible structure for different control methods and can be used to adjust the motor speed and control the power injected into a utility grid. In this paper, the configuration of the imitation platform for the PMSG wind generation system is shown in Fig. 2.

In the operation control process, two PWM converters play different roles. The grid-side converter uses vector control technology based on decoupling control of active power and reactive power, which can smooth the output active power and provide reactive power support for the utility grid. Another task of the grid-side converter is to maintain the stability of the DC bus voltage. The turbine-side converter controls PMSG using vector control technology based on rotor flux oriented control. Then, the rotational speed can be adjusted to maintain the best tip speed ratio and to achieve the maximum wind power tracking when wind speed changes. The simulation model diagram of turbine-side converter control is shown in Fig. 3. From Fig. 3, we can see that the turbine is operated in the rotational speed control mode. The reference rotational speed is dynamically modified as the wind speed changes.

2.3 Issues with MPPT

To maintain the best tip speed ratio and to achieve MPPT control, the rotational speed needs to be adjusted as the wind speed changes in practical operation. The issue with MPPT is how to determine the optimal rotational speed for different wind speed.

Many MPPT algorithms have already been proposed. Among them, the HCS method is popularly applied for the method is simple, fast and it can operate independently from predefined wind turbine characteristic.

![Fig. 1. Wind turbine P–w characteristics and maximum power curve.](image)

![Fig. 2. PMSG wind generation system with double PWM converters.](image)

![Fig. 3. Turbine-side converter control model for simulation.](image)
Then operating-point will jump to point C from point B instantly. FLC algorithm is described in detail in Section 4. The proposed FLC algorithm, which can realize variable step-size control as wind speed changes. As shown in Fig. 4, the input variables of fuzzy logical control algorithm are rotational speed \( w \) and mechanical power \( P \). The reference rotational speed \( \omega_{ref} \) can be calculated through fuzzy logic rules. The proposed FLC algorithm is described in detail in Section 4.

### 3. Basic Principle of HCS Algorithm

The process of the conventional hill climbing searching algorithm used for the maximum power point tracking can be explained using Fig. 5. The basic principle of the HCS algorithm is: if the previous increment of rotational speed \( \Delta w \) results in an increase of mechanical power \( \Delta P \), the search of \( \Delta w \) continues in the same direction; otherwise, the search reverses its direction. The algorithm is described in detail as follows.

Assume that the wind turbine is operating at point A in the characteristic curve shown in Fig. 5. The wind turbine rotational speed is increased and the corresponding mechanical power is detected. If the power is increased compared with that in the earlier step, the search process is in the correct direction, and the wind turbine rotational speed is increased again. If the power is decreased compared with that in the earlier step, the search will be in the opposite direction. This process is continued until the powers slope becomes zero, indicating that the HCS algorithm succeeds to reach the maximum power point, which corresponds to point B.

If the wind speed changes from \( v_3 \) to \( v_1 \), the turbine operating-point will jump to point C from point B instantly. Then \( P \rightarrow w \) slope is positive and the turbine rotational speed is increased. The slope is observed until it becomes zero. Then the wind turbine can track the maximum power point, i.e., it will operate at point D. Now if there is a decrease in wind speed from \( v_1 \) to \( v_2 \), the operating-point could eventually shift from point D to point F, depending on the same principle.

The flow chart of conventional HCS algorithm is illustrated in Fig. 6.

### 4. Introduction to FLC Algorithm

The conventional HCS algorithm implementation is simple and is independent of turbine characteristics\([12]\), but there still exist issues like the selection of step size. A big step size can track the MPP fast but at the same time it can result in severe oscillations around the maximum power point. Reducing the perturbation step size can minimize the oscillations around MPP. However, a small step size can slow down the MPPT process especially when wind speed varies fast. To give a solution to this conflicting situation, a fuzzy logical control algorithm which has a variable perturbation step size is proposed in this paper. The FLC algorithm can effectively track the MPP fast and smoothly.

In the part of setting reference wind turbine rotational speed, the conventional HCS algorithm is replaced by the proposed FLC algorithm, which can realize variable step-size control. Through fuzzy control, the step size can be large when the operating point is far away from the MPP while the step size can become small when the operating point comes close to the MPP. Therefore, the FLC algorithm can dynamically change its step size, depending on the turbine operation condition.

The set of the fuzzy logical controller is described as follows: the input variables are \( \Delta P(k) \) and \( \Delta w(k) \), while the output variable is \( \Delta \omega_{ref}(k) \). \( \Delta P(k) \) and \( \Delta w(k) \) can be obtained by
\[
\Delta P(k) = P(k) - P(k - 1) \quad (4)
\]
\[
\Delta w(k) = w(k) - w(k - 1) . \quad (5)
\]

The member function of input variables of fuzzy logical controller with MATLAB is defined as follows: there are seven member functions of input variable \( \Delta P(k) \): PB (positive big), PM (positive medium), PS (positive small), ZE (zero), NS (negative small), NM (negative medium), and NB (negative big), respectively, as shown in Fig. 7; the member functions of input variable \( \Delta w(k) \) are P (positive), Z (zero), and N (negative), respectively.
depending on the turbine rotational speed can be expressed in (6) to (8) respectively. The detail information can be viewed from Fig. 8.

The member functions of output variable \( \Delta w_{ref}(k) \), which are similar to \( \Delta P(k) \), are PB, PM, PS, ZE, NS, NM, NB, respectively. The detail information can be viewed from Fig. 8.

The relationship between turbine mechanical power and turbine rotational speed can be expressed in (6) to (8) depending on the \( P-w \) curve.

\[
\begin{align*}
\frac{dP}{dw} &> 0, \quad (w < w_{\text{app}}) \quad (6) \\
\frac{dP}{dw} &= 0, \quad (w = w_{\text{app}}) \quad (7) \\
\frac{dP}{dw} &< 0, \quad (w > w_{\text{app}}) \quad (8)
\end{align*}
\]

where \( w_{\text{app}} \) denotes the turbine rotational speed corresponding to the MPP.

The fuzzy logical control rules are based on the properties of wind turbine, as shown in Table 2. Then the newly setting reference rotational speed can be updated by

\[
w_{ref}(k) = w_{ref}(k-1) + \Delta w_{ref}(k). \quad (9)
\]

### 5. Case Studies

Case studies on the proposed MPPT control strategy and two conventional HCS algorithms with different size steps have been conducted to validate the proposed MPPT strategy.

Four performance indices for MPPT in a grid-connected wind generation system are also proposed in this paper. They are the wind energy captured by wind turbine, the maximum power point tracking time when the wind speed changes slowly, the fluctuation magnitude of real power during steady-state, and the wind energy captured by wind turbine when the wind speed changes fast.

<table>
<thead>
<tr>
<th>MPPT strategy</th>
<th>( T_1 ) (s)</th>
<th>( T_2 ) (s)</th>
<th>( \Delta P ) (W)</th>
<th>( W ) (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCS (step size: 0.08 r/min)</td>
<td>0.095</td>
<td>0.086</td>
<td>0.6</td>
<td>6918</td>
</tr>
<tr>
<td>HCS (step size: 0.04 r/min)</td>
<td>0.124</td>
<td>0.169</td>
<td>0.2</td>
<td>6970.5</td>
</tr>
<tr>
<td>FLC (variable step-size)</td>
<td>0.029</td>
<td>0.055</td>
<td>0.25</td>
<td>7010</td>
</tr>
</tbody>
</table>

Table 4: Results of case 2

<table>
<thead>
<tr>
<th>MPPT Strategy</th>
<th>( T_1 ) (s)</th>
<th>( T_2 ) (s)</th>
<th>( \Delta P ) (W)</th>
<th>( W ) (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCS (step size: 0.08 r/min)</td>
<td>0.115</td>
<td>0.088</td>
<td>0.5</td>
<td>6852</td>
</tr>
<tr>
<td>HCS (step size: 0.04 r/min)</td>
<td>0.224</td>
<td>0.173</td>
<td>0.15</td>
<td>6788.5</td>
</tr>
<tr>
<td>FLC (variable step size)</td>
<td>0.073</td>
<td>0.057</td>
<td>0.25</td>
<td>6879</td>
</tr>
</tbody>
</table>

Three cases are designed, and three MPPT control strategies are simulated in the environment of MATLAB/ Simulink respectively. The three MPPT control strategies are: a) HCS algorithm with a big perturbation step size, b) HCS algorithm with a small perturbation step size, and c) FLC algorithm with variable perturbation step size.

Initial conditions of the three cases are the same: the wind speed is 7 m/s, and the wind turbine operates at the optimal point, i.e. MPP.

#### 5.1 Case 1

Case 1: Wind speed rises to 11 m/s linearly from 0.9 s to 1.0 s. The time used for tracking the MPP is \( T_1 \) after the first change of wind speed. From 1.9 s to 2.0 s, wind speed drops to 8 m/s linearly. The time used for tracking the MPP is \( T_2 \) after the second change of wind speed. The symbol \( \Delta P \) denotes the fluctuation magnitude of real power during steady state, while the symbol \( W \) denotes the wind energy captured by the wind turbine from 0.9 s to 3.0 s. The result of case 1 is shown in Table 3.

#### 5.2 Case 2

Case 2: The wind speed is up to 11 m/s in step change at time 1.0 s while down to 8 m/s in step change at time 2.0 s. The result of Case 2 is shown in Table 4. The symbols \( T_1 \), \( T_2 \), and \( \Delta P \) of Table 4 have the same meaning as defined in Case 1. Here \( W \) denotes the wind energy captured by the wind turbine from 1.0 s to 3.0 s.

The output mechanical power curves (1.0 s to 1.5 s) of three different MPPT strategies after the first change of wind speed are given in Fig. 9 in order to compare the performance of the three MPPT strategies more easily. Fig. 10 shows variable perturbation step size of the proposed FLC algorithm. Through Fig. 10, it can be concluded that the step size controlled by the FLC algorithm can be changed suitably depending on the system operation condition. At time 1.073 s, the step size becomes small which can indicate the system operating point is very close to MPP or it is the MPP itself.
Fig. 9. Output power curves of three MPPT strategies: (a) HCS algorithm (step size: 0.08 r/min), (b) HCS algorithm (step size: 0.04 r/min), and (c) FLC algorithm (variable step size).

Fig. 10. Variable step size of FLC algorithm.

Fig. 11. Curve of wind speed.

5.3 Case 3

Case 3: The wind speed changes fast and irregularly from 1.0s to 4.0s. The curve of wind speed is shown in Fig. 11. The wind energies captured by turbines from 1.0 s to 4.0 s through three different MPPT algorithms are listed in Table 5.

Through the above three cases, we can see that the system can always operate at its optimal points for a certain wind speed by using any of the three MPPT strategies. But the emphasis is when the wind speed changes, the FLC algorithm shows good performances than the conventional HCS algorithms no matter its step size is large or small. FLC algorithm can track the MPP much faster than the other two methods. At the same time, the fluctuation magnitude of real power of FLC algorithm is small during steady state. Case studies also show that the wind energy captured by FLC algorithm is the most among the three MPPT strategies both in the situation of wind speed changing slowly and in the situation of wind speed changing fiercely. All these results can validate that the proposed MPPT algorithm is highly efficient than the conventional HCS algorithms.

Generally speaking, compared with the conventional HCS control approaches, the proposed algorithm reflects significant advantages no matter in the aspect of tracking speed or in the aspect of the fluctuation magnitude of real power.

6. Conclusions

This paper proposes a fuzzy-logical-controller based MPPT strategy with variable step size, which can consider both tracking speed and steady-state efficiency. The proposed algorithm can change its perturbation step size dynamically depending on the change of wind speed, which enables the turbine to track the MPP quickly and smoothly.

Three MPPT algorithms and three cases were developed in this paper. The effectiveness of the proposed algorithm is verified in MATLAB/Simulink environment with SimPowerSystems and Fuzzy Logical Toolbox. The simulation results indicate that the proposed fuzzy-logical-controller based MPPT algorithm shows good performance. The wind turbine could track the optimum operating point swiftly using the proposed algorithm and the steady-state power would not fluctuate fiercely. In general, the proposed FLC MPPT algorithm can enhance the efficiency of wind turbine operation compared with the conventional HCS strategy.

Table 5: Results of case 3

<table>
<thead>
<tr>
<th>MPPT Strategy</th>
<th>Case3: $W$ (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCS (step size: 0.08/r/min)</td>
<td>7137.0</td>
</tr>
<tr>
<td>HCS (step size: 0.04/r/min)</td>
<td>6867.5</td>
</tr>
<tr>
<td>FLC (variable step size)</td>
<td>7404.0</td>
</tr>
</tbody>
</table>

References


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