Overview of Maximum Power Point Tracking Control Method for Wind Power Generation System

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Abstract. The maximum power point tracking (MPPT) is one of the most important control issues in the wind power, which aims to maintain the maximum power output as the wind speed is lower than the rated one and thus improve the utilization efficiency of the wind energy. The principle of the MPPT is firstly introduced based on the characteristics of the wind turbine. Next, several MPPT control methods are reviewed. Then, the advantages and disadvantages as well as their respective improvements for each method are analysed. Finally, the development trend and research prospect of MPPT have been pointed out.

1. Introduction

With the rapid development of the modern industry, the energy problem has attracted more and more attention from the world. The wind power has been developed rapidly in all kinds of new energy generations, and the proportion of wind power generation in the total global power generation is becoming higher and higher[1]. The wind energy is renewable, clean and widely distributed. China is one of the world's richest countries with the wind energy. Actively developing wind energy meets the direction of energy reform in China. It can reduce the consumption of the fossil energy while satisfying the energy needs of the people, and then create an environmentally friendly society.

The basic principle of wind power generation is to capture and convert the wind energy into the mechanical energy by using the wind turbine blades first, and then to convert the mechanical energy into the electrical energy by using the wind turbine generator (WTG). The output power of the WTG is directly connected to the power grid or directly supplied the electricity to the consumers.

The WTG is mainly divided into two types: constant speed constant frequency (CSCF) and variable speed constant frequency (VSCF). The speed and frequency of the CSCF are kept constant, and the structure is simple, but the efficiency of the wind energy utilization is particularly low. The speed of the VSCF can be changed with the wind speed by the control strategy to guarantee the maximum coefficient of the wind energy utilization, so the conversion rate of the wind energy is greatly improved. In recent years, with the improvement of the power generation efficiency and the fully-controlled power electronic devices, the VSCF has gradually replaced the CSCF and become the main modern WTG[2]. At present, there are two main types of large WTG including the doubly fed induction generator (DFIG) and the direct drive permanent magnet synchronous generator (PMSG).

The control problems in the WTG primarily include the maximum power point tracking (MPPT), the voltage ride through and the grid-connected control etc[3]. The MPPT control method is the focus of this article. The MPPT is one of the key problems of the VSCF system control. Its function is, under

the rated wind speed, to design control strategy to change the rotating speed of the WTG as the wind speed changes so as to keep the tip speed ratio (TSR) always at the best value, then the output power of the WTG is guaranteed to be maximum. The MPPT methods mainly include the optimal TSR method, the power signal feedback (PSF) method and the hill climbing search (HCS) method, etc. The rest of this paper is as follows: A review of the basic principle of the MPPT is given in Section 2. In Section 3 several MPPT control methods are discussed. Then, the advantages and the disadvantages as well as their respective improvements for each method are analysed. The development trend and the research prospects of the MPPT are presented in Section 4.

2. The characteristics of the WTG and the MPPT
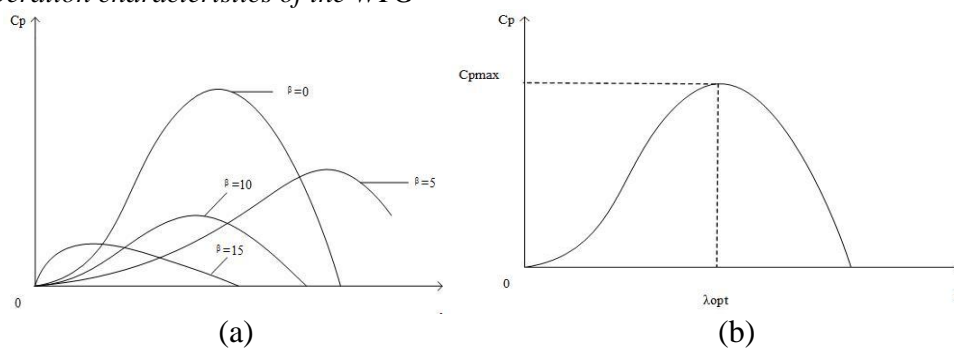
2.1 The operation characteristics of the WTG

<center>(a)   (b)</center>

Figure 1. Relationship between C_p, β and λ

The mechanical power captured by the blades of the WTG can be expressed as:

$$P_m = \frac{1}{2} \rho \pi R^2 C_p (\lambda, \beta) v^3 \tag{1}$$

$$\lambda = \frac{R\omega}{v} \tag{2}$$

Where ρ is the air density, R is the blade radius, C_p is the wind energy utilization coefficient relating to a nonlinear function affected by the blade pitch angle β and the tip-speed ratio λ, v is the wind speed, ω is the wind turbine rotor rotating speed.

According to the Betz' law, no turbine can capture more than 16/27 (59.3%) of the kinetic energy in wind. The object of the MPPT is to find this ideal working point to maintain the highest energy conversion efficiency when the wind speed changes.

The output power regulation scheme of the WTG can be described as: when the actual wind speed is larger than the rated one, the WTG reduces the output power by increasing β and thus maintains its output power at the rated power; otherwise, the WTG keeps β fixed and finds the optimal TSR by adjusting the rotating speed, as shown in figure 1 and thus obtains the maximum power output at the current wind speed.

2.2 The MPPT principle

As can be seen from section 2.1, when the actual wind speed is lower than the rated wind one, the essence of the MPPT is to find the maximum C_p at the current wind speed to maintain the maximum output power. Because the C_p is non-linear with the pitch angle β and the tip-speed ratio λ, for the sake of simplicity, β is fixed and the task is simplified to find the optimal λ to obtain the maximum C_p in practice. It can be seen from equation (2) that λ is linear with the rotating speed ω because of the known wind speed v. The maximum power-rotating speed curve (hereinafter

referred to as the optimal power curve) can be obtained by connecting the maximum power points at different wind speeds, as shown in figure. 2. Therefore, the essence of the MPPT is to regulate the rotating speed of the WTG according to the optimal power curve to maintain the maximum output power[4].
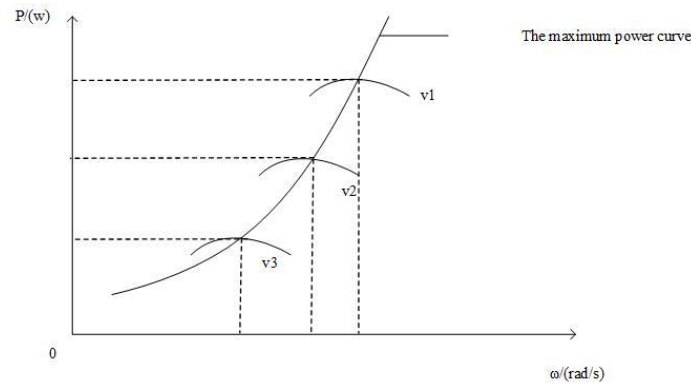

Figure 2. output power of wind turbine under different wind speed and rotating speed

3. Analysis of the MPPT control methods

The MPPT control methods include the PSF method, the optimal torque control (OTC) method, the HCS method, the optimal TSR method, and the extremum search control (ESC) method, as well as some nonlinear control methods. In this section, the above control methods are introduced, and their advantages and disadvantages as well as some relevant improvement strategies are extended.

3.1 The PSF method and its improvements

3.1.1 The method principle. The core of the PSF method is the optimal power curve. The expectation of the control system is the optimal power corresponding to the current wind speed on the optimal power curve. Then the error is obtained by detecting the actual output power of the WTG. Therefore the MPPT is realized by regulating the rotating speed of the WT based on the power signal feedback[5]. This method is stable in operation and suitable for the large wind turbines, but it is necessary to obtain the optimal power curve in advance. Furthermore, the environmental factors will change the actual track of the curve, and thus the precision of the curve will be reduced. Therefore, the efficient wind energy capture ability cannot be guaranteed.

3.1.2 Improvements. In the wind power system, the bandwidth refers to the frequency of the wind speed that the WTG can respond to. In order to increase the tracking bandwidth, an error feed-forward signal of the aerodynamic power and the output power of the WTG is added to the control system[6]. The result is that the tracking speed of the WT becomes obviously quicker.

Since the constant bandwidth control method will increase the machine load, which affects the operating life of the machine[7]. To solve this problem, the response surface analysis method is firstly applied to fit the statistical relationship between the optimal bandwidth and the turbulence wind speed characteristic index (average wind speed, turbulence frequency, turbulence standard deviation), and then the optimal bandwidth is set on line according to the wind speed characteristics[8]. This method realizes the comprehensive optimization of the wind energy capture and the load. However, the load loss coefficient in practical application needs further confirmation.

There exists a beginning speed determination in the control strategy of the WTG. When the rotating speed of the WTG is bigger than the beginning speed, the system regulates the output power according to the optimal power curve. In this method, the optimal compensation coefficient is obtained by the neural network to update the beginning speed, and then the output power of the generator is adjusted according to the optimal power curve, so as to achieve MPPT[9]. This strategy accelerates the tracking process of the WTG to the gradual gust, and provides with great applicability for the different wind regimes and the turbines.

3.2 The OTC method and its improvements

3.2.1 The method principle. Due to the fact that the torque of the WTG is the quadratic function of its rotating speed, the OTC method firstly detects the rotating speed and calculates the corresponding torque as the reference value of control (the optimal torque). Then, it forms the feedback control system with the electromagnetic torque as feedback. That is to say, the WTG regulates the electromagnetic torque to change the rotating speed as the wind speed changes, so that the speed of the WT and the wind speed are satisfied with the optimal TSR of the blade, thus the WT can be operated at the maximum power point. This method does not need the real-time wind speed information. In addition, the power output fluctuation of the WTG is small. However, it is only suitable for the small and the medium turbines[10]. For the large turbines, the rotating speed changes too slow, which results in a longer response time and lower efficiency.

3.2.2 Improvements. Liu designs the optimal torque compensator by the gradient estimation to compensate the optimal given torque value[11]. It reduces the influence of the rotating inertia on the speed regulation. This method can increase the acceleration of the rotating speed of the WT and make system move faster to a new steady working point. The compensator only acts in transient process, which enables the system to go through the transient process faster and effectively speeds up the response speed.

Chen employs the sliding mode variable structure control idea to design a variable structure controller[12]. When the state of the system reaches the sliding surface, the sliding mode motion will be carried out and the equilibrium point is asymptotically stable. It takes into account the dynamics of the WT and makes system reach sliding mode stability point within a limited time, which is equivalent to increasing the unbalanced torque. The average wind energy capture efficiency is raised compared with the traditional method.

3.3 The HCS method and its improvements

3.3.1 The method principle. The power- rotating speed curve of the WTG is the convex function. The HCS method is also called the perturbation observation (P&O) method, which means to observe the change of the output power by continuously applying the rotating speed disturbance to the WTG. If the output power increases, the direction of the disturbance is kept constant, otherwise the direction will be reversed so as to achieve MPPT[13]. The advantage of the HCS is that the accurate parameters of the WT and the wind speed are not required. But the determination of the disturbance step length is a difficult point in the algorithm. If the fixed speed disturbance is selected, the maximum output power will be always in the fluctuating state.

3.3.2 Improvements. Jia presents a variable step length empirical algorithm[14], which does not depend on the turbine parameters and the wind speed. The disturbance step length is adjusted with the change of two continuous sampling power, and the optimal rotating speed point can be automatically searched. As the power increases, the step length decreases to zero. The algorithm effectively reduces the power fluctuation at the maximum power point.

The accurate wind speed measurement is an important but difficult task in the wind power system[15]. Liu first utilizes the support vector machine to estimate the wind speed, then uses the firefly algorithm to optimize the speed, and adjusts the rotating speed to the optimal value according to the TSR method. Finally, the HCS method is adopted to track the maximum output power by small step length[16]. This method not only saves the wind speed measurement devices, but also raises the accuracy of the wind speed estimation. But at the same time, it also brings the complicated control to the system.

The method in [17] combines the TSR method with the HCS method, which is similar to the above method. When the wind speed changes more than 1 m/s, the TSR method is used to control the

rotating speed of the WT to quickly track the reference speed, then to determine whether the error between the real-time speed and the reference speed is less than the predetermined threshold value. If so, the HCS method is selected and used as long as the wind speed changes less than 1m/s.

Tian proposes a variable step length control method based on the mechanical power current variation curve[18]. The perturbation direction of this algorithm is determined by the positive and negative slope of the curve. Moreover, the disturbance step length is exponentially decaying at the maximum power point to improve the tracking efficiency. In addition, during each cycle, the system will initialize the step length when the change of the wind speed exceeds the predefined threshold. This method is flexible in changing the step length, which enhances the accuracy of tracking and the applicability of dealing with the abrupt wind speed.

3.4 The Optimal TSR method and its improvements

3.4.1 The method principle. The core idea of the optimal TSR method is to control the TSR of the wind turbine to its optimal value according to the detected real-time wind speed[19]. So the energy utilization coefficient can reach the maximum value and thus the purpose of MPPT is achieved. The advantage of the optimal TSR method is that the control structure is simple and the system response speed is fast, but it depends on the accurate wind speed measurement. It is difficult to obtain the accurate wind speed due to the fact that there is a certain difference in the wind speed around the blades. So the stability and the accuracy of the system are not guaranteed[20].

3.4.2 Improvements. Han puts forward a double closed loop control structure, which is composed of the power outer loop and the current inner loop[21]. The method utilizes the upper computer to simulate the direct drive wind turbine. According to the current wind speed and the corresponding optimal TSR, the optimal rotating speed is calculated as the speed control instruction to realize MPPT. The double closed loop control strategy improves the robustness and the stability of the traditional TSR method.

In view of the uncertainties, the multiple disturbances, the low efficiency and the strong nonlinearity of the wind power system, Li proposes a method which combines the auto disturbances rejection control (ADRC)[22]. First, the overall disturbance of the system is estimated by the observer, and then the feedback controller is employed to compensate the disturbance. Finally, MPPT is realized with the self-disturbance rejection control and the PID controller. The robustness and the capability to fast response of the system are obviously improved.

3.5 The ESC method and its improvements

3.5.1 The method principle. The ESC method mainly makes use of the principle of calculus. As mentioned above, the power- rotating speed curve of the WTG is the convex function. There must be a unique rotating speed that maximizes the output power. Therefore, the maximum power point can be obtained by taking the derivative of the function with respect to the rotating speed, so that maximal wind energy can be captured[23]. But the ESC algorithm needs to detect the differential of the output power of the system, which will cause the system to be very sensitive to the high frequency signal and the dynamic performance of the system will be affected.

3.5.2 Improvements. To eliminate the influence of the differential, the sliding mode (SM) control and ESC can be combined[24] (SMESC). The key of the SMESC method is two switching functions. One is used to generate the output reference values, and the other is applied to generate the output variables. When the function is cut into the sliding surface under the function of the input variables, the system tracks the given power signal. If the disturbance occurs, the sliding surface is cut out, and then the system runs to the new stable point by changing the rotating speed. The control block diagram is shown in figure 3. The SMESC method not only eliminates the measurement steps of the wind speed

and the turbine parameters, but also avoids the signal loss phenomenon caused by the differential. The reliability and the tracking accuracy of the system are both increased effectively.
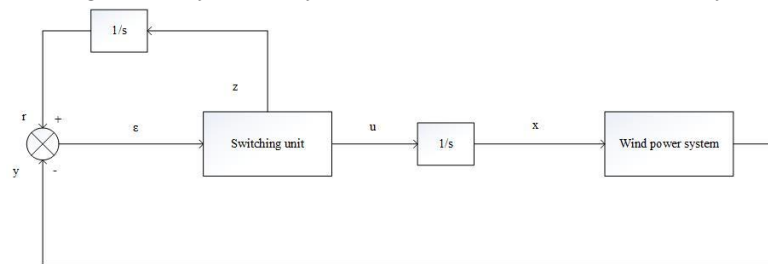

Figure 3. Control block diagram of SM ESC

In [25], first, Fourier transform is used to obtain the phase difference between the TSR and the wind energy utilization coefficient. Next, the softening function is adopted to determine the best reference value of the TSR. Lastly, the PI controller is employed to track the optimal speed. This method does not require the specific system models, and also reduces the operation load of the machine.

3.6 Nonlinear control methods

Since the WTG system is a typical nonlinear complex system, more and more nonlinear modern control algorithms have been proposed by the scholars in recent years[26], such as the speed model predictive control based on the least squares support vector machines[27], the design of nonlinear controllers based on the feedback linearization principle[28], the internal model control design using the exact linearization method and the inverse system theory[29], and the second-order SM control strategy[30], etc. Compared with the traditional linear control methods, the nonlinear controllers improve the response speed and the anti-interference ability of the WTG system, and thus they are more practical in the applications.

In addition, there is a passive MPPT method that changes the system circuit and the WTG structure[31]. The maximum output power of the WTG is reached by matching the generator input power curve and the optimal power curve of the WT.

4. Summary and prospect

The MPPT technology ensures the maximum output power of the WTG under the rated wind speed. It plays an important role in improving the efficiency of the wind energy utilization. In this paper, the existing MPPT control methods are reviewed and summarized, and then the objective evaluations of the various improved strategies as well as their advantages and disadvantages are made. Based on the research of the WTG system and various methods, it can be seen that combining with the artificial intelligence is an overall development trend of the MPPT control strategy. The following future research direction of the MPPT can be expected from two aspects: the basic conditions of the control and the control strategy optimization.

a) Obtaining the accurate wind speed is a prerequisite for several MPPT methods. However, the wind speed is now mostly measured by the wind speed sensor which is not only expensive but also its measurement accuracy cannot be guaranteed. Therefore, the combined prediction model can be used to predict the wind speed. For example, it is viable to combine the artificial intelligence with the physical model as well as the big data analysis to improve the accuracy of prediction.

b) The optimal power curve is also a base for several MPPT methods. However it will change with the change of running time and the external parameters. So the online correction the optimal power curve is one of the important improvement measures to achieve the MPPT.

c) The advantage of the HCS approach is that it does not depend on the system model. The variable step length perturbation method is the mainstream of the current research in the HCS[32]. A searching algorithm with faster tracking capability needs further research.

d) At present, there have been a number of the effective sliding mode variable structure MPPT

control methods. But how to avoid the system buffeting caused by sliding mode structure will be still a research hotspot.

e) The ADRC technology has developed rapidly in recent decades[33]. It will be a feasible research scheme to apply the modified ADRC to the MPPT.

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