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Abstract

In order to enhance the efficiency of a wind energy conversion system (WECS), the maximum power point tracking (MPPT) algorithm is usually employed. This paper presents an optimal algorithm to extract the maximum available power under a sudden wind speed change condition, which is applied in a permanent magnet synchronous generator (PMSG)-based WECS. The proposed method provides a good tracking performance by means of detecting the variation in the wind speed rapidly. In addition, the implementation does not require the prior information on the wind turbine parameters, air density, or wind speed. By investigating the change directions of the mechanical output power of wind turbine and the rotor speed of generator, the proposed MPPT algorithm is able to determine an optimal speed to achieve the maximum power point (MPP). Then, this optimal speed is set to the reference in speed control loop to force the system to operate at the MPP via a three-phase converter. Conventionally, the mechanical output power of wind turbine is calculated from the mechanical torque which is measured directly by sensor. In this paper, a disturbance observer is employed to estimate the torque for the purpose of eliminating the requirement for additional sensor in WECS. The simulation results based on the PSIM are given to demonstrate the effectiveness of the proposed method.

Keywords: Maximum Power Point Tracking (MPPT), Permanent Magnet Synchronous Generator (PMSG), Torque Observer, Wind Energy Conversion System (WECS).

INTRODUCTION

In recent years, renewable energy resources are attracting great attention due to the scarcity of fossil energy and the requirement of restricting carbon dioxide emission in worldwide [1]. Among renewable energy resources, wind energy is considered as one of the most potential and promising resources [2]. In a wind energy conversion system (WECS), the kinetic energy of wind is transformed into the mechanical energy via a wind turbine, and then, this energy is converted into the electrical energy by using a generator [3]. Even though the wind power is abundant, the output power of wind turbine is unstable due to the variation of wind speed. To deal with this challenge, the maximum power point tracking (MPPT) algorithm is usually employed to enhance the efficiency of WECS [4]. The main role of this algorithm is to maintain the output power of wind turbine at the maximum power point (MPP) irrespective of the wind speed variation. Until now, various MPPT algorithms have been proposed for the purpose of tracking the MPP in a WECS [5]-[11]. In particular, a tip speed ratio (TSR) algorithm has been presented in [5]. The purpose of the study is to keep up the TSR to an optimal value at which the output power of wind turbine is maximized by regulating the generator speed. Though this type of MPPT scheme has a good performance and fast response by utilizing the measured wind speed directly and continuously, it is not accurate enough in tracking the MPP due to the difference of wind speed along the length of turbine blade. Moreover, using the speed sensor increases total cost of whole system. To deal with both the cost increase and the inaccuracy of wind speed measurement in the TSR method, an estimated wind speed method has been proposed in [6]. However, this solution contains a complicated algorithm and requires the knowledge on mechanical parameters of WECS. For the purpose of eliminating the need of wind speed information, the methods based on an optimal torque (OT) and a power signal feedback (PSF) have been suggested in [7] and [8], respectively. To achieve the maximum power of wind turbine at a given wind speed, the torque of a permanent magnet synchronous generator (PMSG) is controlled according to an optimal torque reference curve [7]. However, this method requires the information on the mechanical parameters of turbine and the air density which depends considerably upon various climatic conditions. The strategy in [8] employs a pre-obtained optimal power-speed curve which can be acquired through the simulations or experimental tests for individual wind turbine. The main drawback of this method is the difficulty in determining the optimal power-speed curve of wind turbine which significantly varies by each wind turbine. Moreover, the optimal curve would be varied as the operating environment is changed. To overcome such a disadvantage, a novel control algorithm which can find an optimal power-speed curve of
The mechanical power generated by a wind turbine can be expressed as [12]

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

where \( P_m \) is the mechanical power of the wind turbine, \( \rho \) is the air density, \( R \) is the radius of the blades, \( C_p \) is the power coefficient, \( \beta \) is the blade pitch angle, and \( V \) is the wind speed. The tip speed ratio \( \lambda \) is defined by the relation between the wind speed and the rotor speed of turbine \( \omega_m \) as

\[ \lambda = \frac{\omega m R}{V}. \]  

The power coefficient is described by a nonlinear function of both the tip speed ratio and the blade pitch angle as [12]

\[ C_p(\lambda, \beta) = 0.5176 \left( \frac{116}{\lambda} - 0.4\beta - 5 \right) e^{-\frac{21}{\lambda}} \]  

\[ \frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta - 0.035} \cdot \frac{1}{1 + \beta^4}. \]  

Fig. 1 shows the power coefficient curves for different values of pitch angle. Equation (1) indicates that the mechanical power of wind turbine \( P_m \) depends upon the value of \( C_p \), air density, and turbine parameters at a given wind speed. Assuming that the air density and turbine parameters are known and constant, \( P_m \) would be maximized only if \( C_p \) reaches its maximum value \( (C_p)^{max} \). As shown in Fig. 1, \( C_p^{max} \) can be obtained when \( \lambda \) is optimal \( (\lambda^{opt}) \). In addition, since \( \lambda \) and \( \omega_m \) are directly proportional as shown in (2), the optimal value \( \lambda^{opt} \) is achieved if the turbine rotor speed \( \omega_m \) reaches its optimal value. Consequently, at a given wind speed, there is only one optimal value of turbine rotor speed which maximizes the output power of wind turbine.

**MODELING OF WIND TURBINE**

The dynamic equation of a generator is given as [13]

\[ T_m^{gen} = J \frac{d\omega}{dt} + B\omega + T_e^{gen} \]  

where \( T_m^{gen} \) is the mechanical torque of generator, \( T_e^{gen} \) is the electromagnetic torque of generator, \( \omega \) is the generator rotor speed, \( J \) is the inertia, and \( B \) is the viscous friction coefficient. Assuming that there is no gearbox, the mechanical torque of wind turbine \( T_m \) will be directly transmitted to generator. Hence, (5) can be rewritten as
The tracking sequence of the proposed MPPT algorithm in the first case is shown in Fig. 3 and the illustration of the tracking steps under this case is shown in Fig. 4. Initially, the output power is \( \hat{P}_m[1] \) and the corresponding operating speed is \( \omega[1] \) at the wind speed \( V_1 \). At next step, the output power is calculated as \( \hat{P}_m[2] \) by using the estimated torque \( \hat{T}_m[2] \). Because the power variation \( \Delta\hat{P}_m[2] \) is relatively small and within the bound specified by a threshold value \( \pm T \), the algorithm does not change the generator reference speed. These tracking steps are illustrated by green lines in Fig. 3.

When the wind speed suddenly increases to \( V_2 \) as is shown in Fig. 4, the operating point is changed from \( \hat{P}_m[2] \) to \( \hat{P}_m[3] \) due to the large inertia of turbine. At this instant, the power variation \( \Delta\hat{P}_m[3] \) is sufficiently large and positive. Hence, such a sudden increase in wind speed can be effectively detected in the proposed algorithm by using the relation \( |\Delta\hat{P}_m[3]| > |\Delta\hat{P}_m[2]| \) with the present power variation \( \Delta\hat{P}_m[3] \) and the previous one \( \Delta\hat{P}_m[2] \). In order to mitigate the fluctuation in tracking procedure, the step size \( \Delta\omega[3] \) is determined in proportion to \( \Delta\hat{P}_m[2] \) as \( \Delta\omega[3] = A|\Delta\hat{P}_m[2]| \). In this case, the positive value of \( \Delta\omega[3] \) indicates that the generator speed should be increased to arrive the MPP as can be seen in Fig. 4. These tracking steps are shown by red lines in Fig. 3. If the wind speed change is not significant, the proposed scheme keeps tracking the optimal generator speed by following the tracking steps as shown by blue lines in Fig. 3.

\[ T_m = J \frac{d\omega}{dt} + B\omega + T_{\text{gen}} \]  

(6)

Generally, the information on \( T_m \) would be obtained by using a torque sensor. However, this approach is not desirable because it significantly increases the total cost of a WECS. In this paper, a disturbance observer is introduced as an alternative solution to estimate the mechanical torque of wind turbine. The model of the disturbance observer can be expressed as [14]

\[ \dot{\hat{x}} = A\hat{x} + Bu + K(y - C\hat{x}) \]  

(7)

where the symbol “\(^\hat{}\)” denotes the estimated quantities, \( \hat{x} = [\hat{\omega} \; \hat{T}_m]^T \), and \( K = [k_1 \; k_2]^T \) is the observer gain matrix.

Fig. 2 shows the flowchart of the proposed MPPT algorithm, in which the estimated power is determined as \( \hat{P}_m[k] = \omega[k] \cdot \hat{T}_m[k] \) by using the estimated torque.

**Figure 2.** Flowchart of the Proposed MPPT Algorithm

The operation of the proposed MPPT algorithm is analyzed by taking four typical cases into account as follows:

1. The case when the wind speed increases suddenly at a steady-state of tracking
2. The case when the wind speed decreases suddenly at a steady-state of tracking
3. The case when the wind speed increases suddenly before a steady-state of tracking
4. The case when the wind speed decreases suddenly before a steady-state of tracking.

**Figure 3.** Tracking Sequence of the Proposed MPPT Algorithm under the Case of Sudden Increase in Wind Speed at a Steady-State of Tracking
As the second case, the condition that the wind speed decreases suddenly at a steady-state of tracking is considered. The tracking sequence of the proposed MPPT algorithm and the tracking steps under this case are shown in Fig. 5 and Fig. 6, respectively. Initial output power and operating speed are $\hat{P}_m[1]$ and $\omega[1]$, respectively, at the wind speed $V_2$. Similar to the first case, the proposed MPPT algorithm does not change the generator reference speed when the power variation $\Delta\hat{P}_m[2]$ is relatively small and within the threshold value $\pm T$. These tracking steps are illustrated by green lines in Fig. 5. With $\hat{P}_m[2]$ being the current output power, a sudden decrease of wind speed to $V_1$ results in a shift of operating point from $\hat{P}_m[2]$ to $\hat{P}_m[3]$. At this instant, $\Delta\hat{P}_m[3]$ can be considered large and negative. To reduce the fluctuation in the tracking procedure, the step size $\Delta\omega[3]$ is chosen in proportion to $\Delta\hat{P}_m[2]$ as the relation of $\Delta\omega[3] = -A|\Delta\hat{P}_m[2]|$. These tracking steps are shown by red lines in Fig. 5.

The negative value of $\Delta\omega[3]$ implies that the generator speed should be decreased in the curve to arrive the MPP as can be seen in Fig. 6. If the wind speed does not change any longer, the proposed method keeps tracking the optimal generator speed by following the tracking steps as shown by blue lines in Fig. 5.

As the third case, the condition that the wind speed increases suddenly before the MPPT algorithm reaches a steady-state of tracking is considered. The tracking sequence of the proposed MPPT algorithm and the tracking steps under this case are shown in Fig. 7 and Fig. 8, respectively. It is assumed in this condition that the wind speed suddenly increases to $V_2$ at the current output power of $\hat{P}_m[2]$ before the MPPT algorithm can
find the MPP corresponding to the wind speed $V_1$, as shown in Fig. 8. This change of wind speed results in a large and positive value of $\Delta \dot{P}_m[1]$. Similar to the first case, in order to mitigate the fluctuation in tracking procedure, the step size $\Delta \omega^*[3]$ is also obtained from $\Delta \dot{P}_m[2]$ with a positive coefficient $A$. These tracking steps are shown by red lines in Fig. 7. As is observed in Fig. 8, the operating point moves to the MPP due to the selection of the positive value of $\Delta \omega^*[3]$. Unless the wind speed change is detected, the proposed scheme keeps tracking the optimal generator speed by following the tracking steps illustrated by blue lines in Fig. 7.

As the fourth case, the condition that the wind speed decreases suddenly before the MPPT algorithm reaches a steady-state of tracking is considered. The tracking sequence of the proposed MPPT algorithm and the tracking steps under this case are shown in Fig. 9 and Fig. 10, respectively. Similar to the third case, it is assumed that the wind speed suddenly decreases to $V_1$ at the current output power of $\dot{P}_m[2]$ before the MPPT algorithm can find the MPP corresponding to the wind speed $V_2$, as shown in Fig. 10. This change of wind speed results in a large and negative value of $\Delta \dot{P}_m[3]$. For the purpose of reducing the fluctuation in tracking procedure, the step size $\Delta \omega^*[3]$ is determined by using the power variation $\Delta \dot{P}_m[2]$ with a negative coefficient. These tracking steps are shown by red lines in Fig. 9. Due to proper choice of $\Delta \omega^*[3]$, the operating point moves closely to the MPP as is observed in Fig. 10. Unless the wind speed change is detected, the proposed method keeps tracking the optimal generator speed by following the tracking steps illustrated by blue lines in Fig. 9.

Fig. 11 shows an overall control block diagram of the proposed MPPT algorithm based on a three-phase converter. The determined optimal generator reference speed $\omega^*$ by using the proposed MPPT algorithm is set to the reference value of a speed controller. The synchronous PI decoupling control is employed for a current control in a three-phase converter. To apply the computed reference voltages to three-phase converter, the symmetrical space vector PWM technique is employed. As a result of using three-phase converter, the proposed MPPT algorithm forces the system to operate at the MPP of wind turbine.

The accuracy of the proposed MPPT algorithm primarily depends upon appropriate selections of three coefficients $T$, $D$, and $A$. The coefficient $T$ should be selected as a relatively small value to guarantee that the tracking result is near the theoretical MPP. In the flowchart of the proposed algorithm, the coefficient $D$ is used to detect the change of wind speed by comparing the present power variation $|\Delta \dot{P}_m[k]|$ with $D|\Delta \dot{P}_m[k - 1]|$. Since $|\Delta \dot{P}_m[k]|$ would be significantly larger than $|\Delta \dot{P}_m[k - 1]|$ when the wind speed changes, $D$ should be selected as positive and greater than 1. The coefficient $A$ is used to determine the step size of tracking in the proposed algorithm.
SIMULATION RESULTS

To validate the effectiveness of the proposed MPPT algorithm, the simulations have been carried out using the PSIM software. The simulation configuration of the proposed algorithm which consists of a wind turbine model, a PMSG, and a three-phase converter is constructed as depicted in Fig. 12. The torque observer, wind turbine model, and the proposed MPPT algorithm are implemented by using the PSIM DLL blocks. The PMSG parameters used for the simulations are listed in Table 1.

Fig. 13 shows the simulation results of the proposed MPPT algorithm under the variation of wind speed at steady-state of tracking. As can be observed from Fig. 13(a), the wind speed is initially assumed to be at 8 m/s. It increases suddenly to 11 m/s at t=1 s, and then, decreases to 9 m/s at t=2 s. Table 2 shows the comparison between the theoretical optimal speeds of generator and the tracking values obtained by using the proposed MPPT algorithm under the wind speed of 8 m/s, 9 m/s, and 11 m/s, respectively. As can be seen from Fig. 13(b), the generator speed instantly reaches its steady-state optimal value of 12.95 rad/s under the wind speed of 8 m/s. As soon as the wind speed increases suddenly to 11 m/s at t=1 s, the generator speed is increased accordingly from its current optimal value of 12.95 rad/s into a new optimal value of 17.74 rad/s. Again, once the wind speed decreases from 11 m/s to 9 m/s at t=2 s, the generator speed is decreased from its current optimal value of 17.74 rad/s into a new optimal value of 14.78 rad/s. These operating results totally match with the theoretical analyses which are presented in the first and second cases. Fig. 13(c) shows the desired maximum output power of wind turbine \( P_m^* \) and the extracted power output \( P_m \) obtained by using the proposed MPPT method. This figure clearly indicates that the maximum output power can be drawn from wind turbine irrespective of the wind speed variations. Fig. 13(d) shows the power coefficient of wind turbine. It is well confirmed from this figure that the proposed algorithm forces the wind turbine to operate with its maximum power coefficient value under various conditions of wind speed. Fig. 13(e) shows the actual torque and estimated torque of wind turbine. It is clearly observed that the estimated torque well converges to the actual one, which confirms a fast and stable operation of the observer.
To verify the performance of the proposed method even when the wind speed increases suddenly before the MPPT algorithm reaches steady-state, the simulation results in Fig. 14 are presented. As is shown in Fig. 14(a), the wind speed suddenly increases from 8 m/s to 11 m/s at t=0.003 s, before the generator speed reaches the optimal speed of 12.95 rad/s for the wind speed of 8 m/s. Even in this case, the generator speed is continuously increased until it reaches the optimal value of 17.74 rad/s for the wind speed of $V=11$ m/s, as can be shown in Fig. 14(b). This well proves the performance of the proposed scheme and theoretical analyses presented in the third case.

In addition, Fig. 15 shows the simulation results to verify the performance of the proposed method even when the wind speed decreases suddenly before the MPPT algorithm reaches steady-state. As shown in Fig. 15(a), the wind speed suddenly decreases from 11 m/s to 9 m/s at t=0.005 s, before the generator speed reaches the optimal speed of 17.74 rad/s for the wind speed of 11 m/s. Similarly, the proposed scheme reduces the generator speed to the optimal value of 14.78 rad/s for the wind speed of 9 m/s as can be seen from Fig. 15(b).

### Table 1: Parameters of a PMSG

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator resistance $R_s$</td>
<td>0.64 $\Omega$</td>
</tr>
<tr>
<td>$d$-axis inductance $L_d$</td>
<td>0.82 mH</td>
</tr>
<tr>
<td>$q$-axis inductance $L_q$</td>
<td>0.82 mH</td>
</tr>
<tr>
<td>Number of pole pairs $P$</td>
<td>12</td>
</tr>
<tr>
<td>Inertia $J$</td>
<td>0.111 kgm$^2$</td>
</tr>
<tr>
<td>Viscous friction coefficient $B$</td>
<td>0.011 Nms</td>
</tr>
<tr>
<td>Flux linkage $\psi$</td>
<td>0.18 Wb</td>
</tr>
</tbody>
</table>

### Table 2: Theoretical optimal speed of generator and tracking values obtained by the proposed MPPT algorithm

<table>
<thead>
<tr>
<th>Wind speed $V$</th>
<th>Theoretical optimal speed</th>
<th>Tracking value of the proposed MPPT algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td>8 m/s</td>
<td>13 rad/s</td>
<td>12.95 rad/s</td>
</tr>
<tr>
<td>9 m/s</td>
<td>14.5 rad/s</td>
<td>14.78 rad/s</td>
</tr>
<tr>
<td>11 m/s</td>
<td>18 rad/s</td>
<td>17.74 rad/s</td>
</tr>
</tbody>
</table>

Figure 12. Simulation Configuration of the Proposed MPPT Algorithm based on PSIM
Figure 13. Simulation Results of the Proposed MPPT Algorithm under Variation of Wind Speed at Steady-State of Tracking

(a) Variation of wind speed

(b) Generator speed

(c) Desired maximum power and extracted power obtained with the proposed MPPT algorithm

(d) Power coefficient

(e) Actual and estimated torque of wind turbine

Figure 14. Simulation Results of the Proposed MPPT Algorithm When Wind Speed Increases Suddenly at t=0.003 s before a Steady-State of Tracking

(a) Variation of wind speed

(b) Generator rotor speed
CONCLUSION

In order to improve the efficiency of a wind power system, an optimal MPPT algorithm to extract the maximum available power from a PMSG-based WECS has been proposed in this paper. This proposed method does not require a wind speed sensor as well as the prior information such as the air density and wind turbine parameters. Furthermore, it provides an ability to track the MPP effectively even under a sudden change in wind speed. Conventionally, a torque sensor has been usually employed to measure the mechanical torque of wind turbine. However, using the torque sensor significantly increases the total cost of a WECS. For the purpose of eliminating the requirement for additional sensor in a WECS, a disturbance observer has been introduced in this paper to estimate the torque of wind turbine. To verify the feasibility of the proposed control scheme, integrated simulation studies have been carried out considering the whole variable-speed WECS based on PMSG and power conversion circuits. Theoretical analysis and simulation results have been provided to confirm the effectiveness of the proposed MPPT algorithm.

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