Maximum Power Point Tracking of a DFIG Wind Turbine System

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Abstract

In this dissertation, I proposed two methods and control laws for obtaining maximum energy output of a doubly-fed induction generator wind turbine. The first method aims to improve the conventional MPPT curve method while the second one is based on an adaptive MPPT method. Both methods do not require any information of wind data or wind sensor. Comparing to the first scheme, the second method does not require the precise parameters of the wind turbine. The maximum power point tracking (MPPT) ability of these proposed methods are theoretically proven under some certain assumptions. In particular, DFIG state-space models are derived and control techniques based on the Lyapunov function are adopted to derive the control methods corresponding to the proposed maximum power point tracking schemes. The quality of the proposed methods is verified by the numerical simulation of a 1.5-MW DFIG wind turbine with the different scenario of wind velocity. The simulation results show that the wind turbine implemented with the proposed maximum power point tracking methods and control laws can track the optimal operation point more properly comparing to the wind turbine using the conventional MPPT-curve method. The power coefficient of the wind turbine using the proposed methods can retain its maximum value promptly under a dramatic change in wind velocity while this cannot achieve in the wind turbine using the conventional MPPT-curve. Furthermore, the energy output of the DFIG wind turbine using the proposed methods is higher compared to the conventional MPPT-curve method under the same conditions.

1 Introduction

To optimally utilize wind energy, the energy conversion efficiency of wind turbines must reach the utmost limit. Therefore, maximum power point tracking (MPPT) is an essential target in wind turbine control. To track the maximum power point, the rotor speed of the wind turbine/generator should be adjustable. Hence, the concept of a variable-speed wind turbine (VSWT) was proposed. Compared to a full converter-based VSWT, the use of a DFIG wind turbine is more economical; in fact, DFIG wind turbines are more frequently used in large wind farms. Therefore, control for a MPPT target in DFIG-based wind turbines has become an interesting topic.

To track the maximum power point during operation, a wind turbine must be generally equipped with a good controller integrated with a comprehensive MPPT algorithm. Many MPPT methods have been proposed. Original methods are based on the characteristic curve and they are called wind-data-based methods. Generally, with wind-data-based methods, the MPPT ability of a wind turbine is appreciably high if accurate wind data is available. However, because of the rapid natural fluctuation of wind, wind
speed measurement is hardly reliable. To overcome this drawback, other methods such as the MPPT-curve method and perturbation and observation (P&O) method were suggested. They operate basically on the output of the generator; hence, they are called wind speed-sensorless methods. Compared to the wind-data-based methods, the wind speed-sensorless methods cannot track the optimum point as efficiently as. However, this method is often implemented in wind turbines because there is no requirement for an anemometer. The P&O method is originally applied for extremum seeking in small inertia systems such as photovoltaic power systems or small-size PMSG wind turbines with a DC/DC converter. Unlike the P&O method, the MPPT-curve method can apply to both large- and-small scale wind turbines; it is more efficient and does not require any perturbation signal. However, for the high inertia of a generator wind turbine system, a wind turbine using the MPPT-curve method cannot track the maximum point as rapidly as a wind turbine using the wind-data-based method.

In terms of designing the controller for a wind turbine, traditional proportional-integral (PI) control is used for many purposes, including rotor-speed, current, and power control. A drawback of PI control is that stability is not theoretically guaranteed. Thus, sliding-mode control has been recently developed. In fact, sliding-mode control has been applied to the rotor speed. However, wind speed measurement is prerequisite for sliding mode control.

This research suggests two new schemes to maximize the energy output of a DFIG wind turbine without any information about the wind data or an available anemometer. These proposed schemes are based on the improvement of the wind turbine’s MPPT curve and the adaptation of MPPT curve; their names are improved MPPT-curve method and adaptive MPPT method. The efficiency of the proposed schemes will be verified, analyzed, and compared with the conventional MPPT curve method with PI controllers by the simulation of a 1.5-MW DFIG wind turbine in a MATLAB/Simulink environment.

2 DFIG wind turbine

The DFIG wind turbine in this research is shown in Fig.1.

2.1 Wind turbine

Generally, the dynamic equation for a generator-wind turbine system is used to described

\[ J \frac{d}{dt} \omega_r(t) = T_m(t) - T_e(t), \]  

(1)
where, $J$, $\omega_r$, $T_m$ and $T_e$ are the inertia, rotor speed, mechanical torque of and electrical torque of the turbine system. When the turbine rotates at $\omega_r$ and wind speed is $V_w$, the tip speed ratio is defined by

$$\lambda(\omega_r, V_w) \equiv \frac{R\omega_r}{V_w}, \tag{2}$$

where $R$ is the length of its blade. Mechanical power on its shaft $P_m$ is written as

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

where $\rho$, and $C_p(\lambda, \beta)$ are the air density, and power coefficient, respectively. Throughout this paper, we fix $\beta$ as a constant and we simply denote it as $C_p(\lambda)$. From (2), we can regard $P_m$ as

$$P_m(\omega_r, V_w) = \frac{1}{2} \rho \pi R^2 C_p(\lambda(\omega_r, V_w)) V_w^3. \tag{4}$$

### 2.2 DFIG

In the dq frame, the DFIG can be described as

$$
\begin{align*}
\mathbf{v}_s(t) &= \mathbf{R}_s \mathbf{i}_s(t) + L_s \frac{d}{dt} \mathbf{i}_s(t) + L_m \frac{d}{dt} \mathbf{i}_r(t) + \omega_s \mathbf{\Theta} (L_m \mathbf{i}_s(t) + L_r \mathbf{i}_r(t)) \\
\mathbf{v}_r(t) &= \mathbf{R}_r \mathbf{i}_r(t) + L_r \frac{d}{dt} \mathbf{i}_r(t) + L_m \frac{d}{dt} \mathbf{i}_s(t) + \omega_s \mathbf{s}(t) \mathbf{\Theta} (L_m \mathbf{i}_s(t) + L_r \mathbf{i}_r(t))
\end{align*}
$$

where $\mathbf{v}_s = \begin{bmatrix} v_{sd} & v_{sq} \end{bmatrix}^T$, $\mathbf{v}_r = \begin{bmatrix} v_{rd} & v_{rq} \end{bmatrix}^T$ are the stator-side and rotor-side voltage, $\mathbf{i}_s = \begin{bmatrix} i_{sd} & i_{sq} \end{bmatrix}^T$, $\mathbf{i}_r = \begin{bmatrix} i_{rd} & i_{rq} \end{bmatrix}^T$ are the stator-side and rotor-side current and $\mathbf{\Theta} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$. $\omega$, $R$, $L$ and $s$ represent rotational speed, resistance, inductance and rotor slip, respectively; subscripts $r$, $s$ and $m$ stand for rotor-side, stator-side and magnetization.
**Assumption 1.** The stator flux is constant, and the d-axis of the dq-frame is oriented with the stator flux vector. Hence,

\[
\Psi_s(t) = \begin{bmatrix} \Psi_{sd}(t) \\ \Psi_{sq}(t) \end{bmatrix} \equiv \begin{bmatrix} \Psi_{ad} \\ 0 \end{bmatrix} = L_s \dot{i}_s(t) + L_m \dot{i}_r(t).
\]  

Moreover, the resistance of the stator winding can be ignored, i.e., \( R_s = 0 \).

**Lemma 1.** Under Assumption 1, in a DFIG (5), the rotor-side current \( i_r \) and voltage \( v_r \) satisfy

\[
\frac{d}{dt} i_r(t) = A_i(t) i_r(t) + \sigma^{-1} v_r(t) + d_i(t),
\]  

where

\[
\sigma \triangleq L_r - \frac{L_m^2}{L_s}, A_i(t) \triangleq \begin{bmatrix} -\sigma^{-1} \omega_r s(t) & \omega_s s(t) \\ -\omega_s s(t) & -\sigma^{-1} \omega_r \end{bmatrix}, d_i(t) \triangleq -\frac{L_m}{L_s \sigma} s(t) \begin{bmatrix} 0 \\ V_s \end{bmatrix}.
\]

**Lemma 2.** In addition, under Assumption 1, a state-space representation of the DFIG from (5) is described by

\[
\frac{d}{dt} x_{PQ}(t) = A_{PQ}(t) x_{PQ}(t) + B_{PQ}(t) v_r(t) + d_{PQ}(t),
\]  

where

\[
x_{PQ}(t) = \begin{bmatrix} Q_s(t) \\ P_e(t) \end{bmatrix}, A_{PQ}(t) = \begin{bmatrix} -1 - \frac{R_r}{\sigma} & \omega_s^2 s(t) \\ -\omega_s s(t) & \frac{d}{dt} \omega_r(t) - \frac{R_r}{\sigma} \end{bmatrix},
\]

\[
B_{PQ}(t) = -\frac{V_s}{\sigma} C^{-1}(t), \quad C(t) = \begin{bmatrix} 1 & 0 \\ 0 & \omega_s \end{bmatrix}, d_{PQ}(t) = \frac{V_s^2}{\sigma L_s \omega_r} \begin{bmatrix} R_r \\ L_r \omega_r(t) s(t) \end{bmatrix}.
\]

### 3 Controller design and maximum power strategy

The main objective of this section proposes two new schemes for tracking maximum power point, including improved MPPT scheme and adaptive MPPT scheme, when the wind turbine operates in the optimal power control region. The improved MPPT scheme is independent to the adaptive MPPT scheme. In addition to these schemes, we design two RSC controllers corresponding to these schemes. These RSC controllers are independent together. For the improved MPPT scheme, we design the RSC controller for the power adjustment. For the adaptive MPPT scheme, the RSC controller is designed to adjust the rotor speed and current.
3.1 Design RSC controller for improved MPPT scheme

3.1.1 RSC controller for power adjustment

Lemma 3. When we can measure \( \frac{d}{dt} \omega_r(t) \) for any desired reference \( x_r \), if we use any positive definite matrix \( P \),

\[
   v_r(t) = -B_{PQ}(t)^{-1} \left( A_{PQ}(t)x_{PQ}(t) + P(x_r(t) - x_{PQ}(t)) - \frac{d}{dt}x_r(t) + d_{PQ}(t) \right)
\]

(12)

\[
   x_r^\top = \left[ Q_{ref} \ P_{ref} \right]^\top
\]

(13)

for the DFIG (9), then it is ensured that

\[
   \lim_{t \to \infty} (x_r(t) - x_{PQ}(t)) = 0.
\]

(14)

3.1.2 Improved MPPT scheme

The main objective of this subsection is to propose a new MPPT scheme that improves the conventional MPPT-curve method so that \( P_m \) approaches the neighbor of \( P_{max} \).

Theorem 1. Suppose that we use a positive constant \( \alpha < J, k_{opt} \) and \( P_{ref} \) in (13) for the RSC control (12) as

\[
   P_{ref}(t) = k_{opt}\omega_r^3(t) - \alpha\omega_r(t)\frac{d}{dt}\omega_r(t),
\]

(15)

if there exists a positive constant \( \chi \), such that

\[
   \tilde{P} := 2P - \begin{bmatrix} 0 & 0 \\ 0 & \lambda(t)(J - \alpha)\omega_r^2(t) \end{bmatrix} > 0
\]

(16)

for the definite matrix \( P > 0 \) in (12) and all \( t \), then there exists a time \( t_0 > 0 \), such that

\[
   \left| \lambda(t) - \lambda_{opt} \right| \leq 2(J - \alpha)\gamma \frac{R}{\lambda_{opt}} \max \frac{\omega_r^2(t)}{(2\zeta_r(t) - \chi)V_w(t)},
\]

(17)

for all \( t \geq t_0 \).

3.2 Design RSC controller for adaptive MPPT scheme

3.2.1 RSC control for rotor speed adjustment

Lemma 4. For any reference \( i_{ref} \) and \( \omega_{ref} \), if \( v_r \) of the DFIG (5) is designed as

\[
   v_r(t) = \sigma(-A_i(t)i_r(t) - d_i(t) + \frac{d}{dt}i_{ref}(t) + K(i_{ref}(t) - i_r(t))),
\]

(18)
where, for $k_d > 0$,

$$
\begin{bmatrix}
i_{rd\text{ref}}(t) \\
i_{rq\text{ref}}(t)
\end{bmatrix} =
\begin{bmatrix}
i_{rd}(t) \\
i_{rd}(t) + k_d \frac{d}{dt}(\omega_{\text{ref}}(t) - \omega_r(t)) + k_p(\omega_{\text{ref}}(t) - \omega_r(t))
\end{bmatrix},
$$

(19)

and if the feedback gain $K$ and $k_p$ satisfy

$$
\tilde{Q} \triangleq
\begin{bmatrix}
2k_p & [0 \ -1] \\
0 & K^T + K
\end{bmatrix} > 0,
$$

(20)

then

$$
\lim_{t \to \infty} (i_{\text{ref}}(t) - i_r(t)) = 0, \quad \text{and} \quad \lim_{t \to \infty} (\omega_{\text{ref}}(t) - \omega_r(t)) = 0.
$$

(21)

### 3.2.2 Adaptive MPPT scheme

In this subsection, we propose a new MPPT scheme using no real-time information about $V_w(t)$. The scheme aims to reduce $|\omega_{\text{opt}}(V_w(t)) - \omega_r(t)|$ to achieve the maximum $P(\omega_r, V_w)$.

**Assumption 2.** The precise value of $k_{\text{opt}}$ for the MPPT curve is not available. Instead, we can use the estimate $k'_{\text{opt}}$ with

$$
k'_{\text{opt}} = (1 + \delta)k_{\text{opt}}, \quad |\delta| \leq \delta_{\text{max}}.
$$

(22)

The proposed MPPT scheme is given as the reference $\omega_{\text{ref}}$ in (19) for the RSC control (18) as

$$
\omega_{\text{ref}}(t) \triangleq \left( \frac{\hat{P}_{\text{mppt}}(t)}{\hat{k}_{\text{opt}}(t)} \right)^{1/3},
$$

(23)

$$
\hat{P}_{\text{mppt}}(t) = \omega_r(t) \left( k_1 \frac{d}{dt} \omega_r(t) - k_2 \left( \omega_r(t) - \hat{\omega}_{\text{opt}}(t) \right) \right) + P_v(t),
$$

(24)

$$
\frac{d}{dt} \hat{\omega}_{\text{opt}}(t) \triangleq k_3 \left( \omega_r(t) - \hat{\omega}_{\text{opt}}(t) \right),
$$

(25)

$$
\frac{d}{dt} \hat{k}_{\text{opt}}(t) \triangleq k_4 (k'_{\text{opt}} - \hat{k}_{\text{opt}}(t)) + \omega_r(t)^2 \left( \omega_r(t) - \hat{\omega}_{\text{opt}}(t) \right),
$$

(26)

where $\hat{k}_{\text{opt}}(t)$ and $\hat{\omega}_{\text{opt}}(t)$ are estimations of $k_{\text{opt}}$ and $\omega_{\text{opt}}(V_w(t))$, respectively. The feedback gains $k_1, k_2, k_3, \text{and} \ k_4$ are designed as the conditions in Theorem 2 and

$$
J > k_1 \geq 0.
$$

(27)
Fig. 2: Simulation results: (a) $\omega_r(t) - \omega_{\text{opt}}(V_w(t))$, (b) power coefficient $C_p(\lambda(t))$, (c) $P_{\text{max}}(t) - P_m(t)$, and (d) electrical energy output.

**Theorem 2.** In addition to Assumption 2, we suppose that $\omega_{\text{ref}}$ (23) for the RSC control (18)-(19) is restricted within the optimal control region, if there exist positive constants $\alpha, v, w$ and $q$ satisfying

$$\begin{cases}
\Xi = K^T + K - qI_2 > 0, \\
2k_p - \alpha \hat{\xi}_{\text{opt,ub}}^2 \xi_{\text{max}}^2 \begin{bmatrix} 0 & 1 \\ 1 & 1 \end{bmatrix}^{-1} - qk_d > 0, \\
2\xi_{\text{min}} - (w y + q) J - (k_3 - k_2) - 1 > 0, \\
k_3 - k_2 - \omega_{\text{rated}}^2 - w y - q > 0, \\
(2 - v k_{\text{opt}}) k_4 - \omega_{\text{rated}}^2 - q > 0,
\end{cases}$$

(28)

where

$$\begin{align*}
\xi_{\text{min}} &\triangleq \min \zeta(\omega_r, V_w), \xi(\omega_r, \omega_{\text{ref}}) \triangleq \omega_r^{-1} \omega_{\text{ref}}^2 + \omega_r + \omega_{\text{ref}}, \\
\hat{\xi}_{\text{max}} &\triangleq \max \hat{\xi}(\omega_r, \omega_{\text{ref}}), \hat{J} \triangleq J - k_1 > 0,
\end{align*}$$

(29)-(30)

then, there exists a time $t_o > 0$ such that for all $t \geq t_o$,

$$\left| \omega_r(t) - \omega_{\text{opt}}(V_w(t)) \right| < \frac{1}{\sqrt{q}} \sqrt{1 + \hat{J}^{-1} \frac{w}{v} \gamma + \frac{k_4 \hat{J}^{-1}}{v} k_{\text{opt}} \delta_{\text{max}}^2}.$$  

(31)

4 **Simulation results**

For the above DFIG wind turbine, wind profile, and controllers, the simulation results are shown in Fig. 2. Fig. 2a argues that with the conventional method, the error between $\omega_r(t)$ and $\omega_{\text{opt}}(t)$ is still quite
large, up to 0.3 rad/s. This is unlikely with the proposed methods, as $\omega_r(t)$ always approaches $\omega_{ropt}(t)$ and guarantees that the $|\omega_r(t) - \omega_{ropt}(t)|$ is always very small, below 0.254 rad/s and 0.1795 rad/s, as Theorem 2 and Theorem 1, respectively. Comparing to the case of the improved MPPT method, the adaptive method has a better performance, the maximum of $|\omega_r - \omega_{ropt}(t)|$ is below 0.1 rad/s. Consequently, with the adaptive MPPT method, the power coefficient $C_p$ is virtually maintained around its maximum value $C_{p_{max}} = 0.4$ p.u. during the simulation interval, as displayed clearly by the blue solid line in Fig. 2b. With the improved MPPT method, $C_p$ fails to be maintained around its maximum value $C_{p_{max}} = 0.4$ p.u. as the wind condition starts to change rapidly but it is retained quickly, as the red discontinuous line in Fig. 2b. Certainly, comparing to the adaptive method, the improved method still gives a bigger error between $P_m$ and $P_{max}$ during the dramatic change period of the wind as Fig. 2c. With the proposed strategies, the total electrical energy output of the generator is higher than that with the conventional strategy, as shown in Fig. 2d. This confirms that the quality of the proposed schemes is always better than that of the conventional one.

To evaluate the quality of the RSC controller for the adaptive MPPT method and the improved MPPT method, Fig. 3 is plotted. The RSC controllers which designed for the purposes of the adaptive method and the improved method have qualified performance.

5 Conclusion

In this dissertation, I proposed two methods including improved MPPT method and adaptive one, and respective control laws for the rotor side converter to obtain the maximum power point tracking of Doubly-fed induction generator (DFIG) wind turbine. Both methods do not require any information of wind data
or wind sensor. Comparing to the first scheme, the second method does not require the precise parameters of the wind turbine. The MPPT capability of these proposed schemes is theoretically proven under some certain assumptions. The DFIG state-space model and control techniques based on the Lyapunov function are adopted to derive the RSC control methods corresponding to the proposed MPPT method. The quality of the proposed methods are verified by the numerical simulation of a 1.5-MW DFIG wind turbine. The simulation results show that the wind turbine implemented with these proposed methods can track the optimal operation point properly. Furthermore, the energy output of the DFIG wind turbine using the proposed methods is higher compared to the conventional MPPT-curve method under the same conditions.