Analysis of and Solution to the Slippage of the Torque Limiter of Wind Turbine

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Abstract. As part of the high-speed shaft coupling, the torque limiter used by the wind turbine generator is installed near the generator side. It has the function of overload protection, which can effectively cut off the great torque generated when the low voltage ride through and the motor are short-circuited, and reduce the damage to the transmission system. In actual operation, especially when running at full power, the torque limiter will often slip, which will increase the damage to the transmission system and reduce the power generation efficiency. This paper analysis the principle of vector control on the machine side of the unit, and finds the cause of the slip of the torque limiter and the solution.

1. Introduction
During the operation of large wind turbines, generator short-circuit and low voltage ride-through will cause the instantaneous load to be excessive. At this time, the transmission system cannot limit the strong load, which will cause the transmission system to be damaged. In order to reduce the risk of damage, in the transmission system a mechanical torque limiter with overload protection function needs to be installed in the coupling. The torque limiter is usually installed between the driving shaft and the driven shaft, as shown in Figure 1. The torque limiter plays the role of torque transmission and overload protection in the transmission system. When the driven shaft of the wind turbine is overloaded and the torque value of the driven bearing exceeds the set value, the torque limiter will slip. For the wind turbine, the state at this time is unstable.

This topic takes the actual operating conditions of a full-power wind turbine in a wind power plant as an example. By analyzing the core control process on the generator side of the wind turbine, the cause of slip can be found from the inside of the unit, after corresponding adjustments to avoid slipping of the torque limiter.
2. Analysis of control strategy of generator-side converter

The generator side of the wind turbine control method of the full-power converter is based on the rotor flux-oriented vector control method. The topological structure of the generator side converter is shown in Figure 2:

![Figure 2 Topological diagram of the generator side of a full-power converter in a wind farm](image)

According to the mathematical model of the permanent magnet synchronous motor and the theory of coordinate transformation, the mechanical torque equation under the rotating coordinate system of the permanent magnet synchronous motor can be obtained\(^1\):

\[
T_e = \frac{3}{2} P_n [\psi_f i_q - (L_q - L_d)i_d i_q] \tag{1}
\]

In formula (1), \(L_d\) is the inductance of the direct axis, \(L_q\) is the inductance of the quadrature axis, \(\psi_f\) is the flux linkage formed by the permanent magnet of the motor, \(i_d\) is the current of the direct axis, \(i_q\) is the current of the quadrature axis, and \(P_n\) is the motor pole pair. The first term in the brackets is the torque, which is formed by the combination of the internal magnetomotive force and the corresponding torque component. The second term is obtained by the change of reluctance caused by the salient pole action under the influence of the corresponding magnetomotive force. Torque is also called reluctance torque. In a specific electrical equipment, \(L_d = L_q\) is satisfied, so the term is zero, and the torque equation is simplified to:

\[
T_e = \frac{3}{2} P_n \psi_f i_q \tag{2}
\]

Equation (2) shows that it is the stator current q-axis component that determines the electromagnetic torque, and \(i_q\) is the torque current.

Setting the rotor flux \(\psi_f\) on the d-axis of the synchronous rotating coordinate system, the \(\alpha\)-axis in the two-phase stationary \(\alpha-\beta\) coordinate system coincides with the stator winding a-phase axis, and the no-load potential \(E_s\) is aligned with the q-axis of the synchronous rotating coordinate system. Where \(\theta\) is the position angle of the rotor, the integrated stator current vector is can be decomposed into \(i_d\) and \(i_q\) in the two-phase rotating d-q coordinate system. The rotor flux orientation vector diagram of the permanent magnet synchronous motor is shown in Figure 3\(^2\):

![Figure 3 Vector diagram of rotor flux orientation of permanent magnet synchronous motor](image)
It is the stator current q-axis component that determines the electromagnetic torque, iq is called the torque current, and id is the excitation current. If φ=90° electrical angle (id=0) is controlled, is and Ψf are orthogonal in space, and the stator currents are all torque currents. At this time, although the rotor rotates at electrical angular velocity ω, is and Ψf in the dq axis system always relatively static. According to the rotor magnetic field orientation and the permanent magnet synchronous generator control strategy with id=0, the stator current is decoupled from the rotor permanent magnet flux.[3]

When the torque command is known, the d-q axis current command can be given as:

\[
\begin{align*}
    i_d' &= 0 \\
    i_q' &= \frac{2T_e'}{3P_n\Psi_f}
\end{align*}
\]

(3)

The steady-state control equation of the permanent magnet synchronous generator is:

\[
\begin{align*}
    u_d &= R_i i_d - \omega L_q i_q \\
    u_q &= R_i i_q + \omega L_q i_d + \omega \Psi_f
\end{align*}
\]

(4)

In order to make the actual current better follow the given value, the feedback control quantity needs to be added in the formula (4). When the input signal is a DC signal, the PI regulator can be used to realize its static and stable tracking. After adding the feedback quantity, the final system control equation is:

\[
\begin{align*}
    u_d &= R_i i_d - \omega L_q i_q + K_p \varepsilon_d + K_i \int \varepsilon_d \, dt \\
    u_q &= R_i i_q + \omega L_q i_d + \omega \Psi_f + K_p \varepsilon_q + K_i \int \varepsilon_q \, dt
\end{align*}
\]

(5)

Where Kp is the current loop proportional coefficient, Ki is the current loop integral coefficient, \( \varepsilon_d = i'_d - i_d \), representing the d-axis input feedback error, and \( \varepsilon_q = i'_q - i_q \), representing the q-axis input feedback error.[4]

Figure 4 shows the control principle diagram of the permanent magnet synchronous generator machine-side converter:

![Figure 4 The control principle diagram of the permanent magnet synchronous motor machine-side converter](image)

The inner loop is the stator current control loop, which is composed of two control channels id and iq, both of which use PI-type current regulators with integral and output limiting. The current feedback error is adjusted and output, and feedforward compensation for disturbances such as coupling voltage. When the terms are superimposed, the output can be used as the control value of the stator voltage in the dq coordinate system, and then the Uα and Uβ output in the α-β coordinate system are generated after Park inverse transformation, and the control machine-side converter is generated through the SVPWM vector operation Trigger pulse of the switch state.
The outer loop is the torque control loop, that is, through the control of the permanent magnet synchronous generator torque, the output of the reference torque is realized, and the actual torque feedback value is provided by the main control of the wind turbine. The torque difference obtained after the comparison is input to the PI controller with integral and output limit, and the active current set value $i_d'$ of the output stator is adjusted, and the stator reactive current component set $i_q'$ can be based on the power grid's influence on wind power generation. The reactive power requirement of the system is calculated, and $i_d'=0$ in the current algorithm[5].

3. On-site data analysis
According to the data collected on the site of a wind power plant, when the unit is operating normally, the feedback torque of the converter can closely follow the given torque of the main control, and the given value of torque can be consistent with the actual value, as shown in Figure 5. At the same time, the feedback speed of the converter is fitted with the speed curve measured by the generator proximity switch. As shown in Figure 6. In the following figure:

- B_cvntorque_in--- The feedback torque of the converter;
- B_cvntorque_ref--- The given torque of the master.
- B_cvnspeed_in---Feedback speed of converter
- B_gen_speed_proximity_switch_1--- Rotation speed of proximity switch

![Figure 5 Fitting of the set torque and the feedback torque of the converter](image1)

![Figure 6 Fitting of converter feedback speed and proximity switch speed](image2)

When the unit torque limiter slips, according to the torque value measured on site, it can be found that the feedback torque of the converter cannot track the given torque of the main control, and the given
value of the torque cannot be consistent with the actual value, as shown in Figure 7. At the same time, the feedback speed of the converter cannot fit the speed measured by the generator proximity switch, as shown in Figure 8, which is the cause of the torque limiter slipping.

![Figure 7](image1)

**Figure 7** The set torque does not match the feedback torque of the converter

![Figure 8](image2)

**Figure 8** The feedback speed of the converter does not fit the speed of the proximity switch

According to on-site data, it can be seen that when there is a error between the feedback torque value of the converter and the torque command value issued by the main control, the converter cannot limit the kinetic energy of the unit blades, causing the torque limiter to slip. Therefore, in order to avoid the phenomenon of slip, it should be analyzed from the motor control strategy.
4. Phenomenon analysis and solutions
In combination with the above content, the reasons for the torque limiter slipping are as follows:

1. In the current control loop, the current loop proportional coefficient $K_p$ and the current loop integral coefficient $K_i$ are not set at the optimal value.

   It can be seen from Figure 4 that in the stator current control loop, $i_d$ and $i_q$ are adjusted by PI to obtain the stator voltage control quantities $u_d$, $u_q$, and then after Park inverse transformation, $u_a$ and $u_b$ output in the $\alpha$-$\beta$ coordinate system are generated through SVPWM after vector operation, a trigger pulse is generated to control the switching state of the machine-side converter to control the permanent magnet synchronous motor. In the process of PI adjustment, it can be seen from formula(5)whether the value setting of the proportional coefficient $K_p$ of the current loop and the integral coefficient $K_i$ of the current loop is reasonable can directly affect the stability of $u_a$, $u_b$ output, if the $K_p$ and $K_i$ values are set unreasonably. During the PI adjustment process, it will directly cause $u_d$ and $u_q$ to have a short oscillation. After $u_d$ and $u_q$ undergo park inverse transformation, and then undergo SVPWM modulation, $u_a$, $u_b$, and $u_c$ are formed to drive the permanent magnet. Synchronous motors, oscillating $u_d$, $u_q$ will cause the permanent magnet synchronous motor to lose control, which may cause the torque limiter to slip. Therefore, reasonable setting of $K_p$ and $K_i$ values can make the control of the current loop more stable.

2. There is a delay in the communication between the converter and the main control system.

   The program call cycle of the converter is 20ms, that is, the execution of control logic and communication is 20ms once. If there is a communication delay, suppose there is a strong wind on the blades at $t_k$, and the main control system needs the torque output of the converter to be $T_{ek}$, but there is a communication delay between the converter and the main control system, and the torque executed by the converter still stays at $T_{ek-1}$ in the previous execution cycle. $T_{ek-1}$ cannot limit $T_{ek}$, which will cause the converter to fail. The generator may cause momentary torque vibration, causing the torque limiter to slip. In order to avoid communication delays, shielding measures should be taken to shield the communication line between the converter and the main control system.

3. The voltage and current sampling of the converter CPU board is inaccurate, or there is a problem with sampling filtering.

   It can be seen from Fig. 4 that the sampled value of the three-phase current is converted to the feedback value $i_d$, $i_q$ after the sampled value undergoes park/clarke transformation. When there is an error in the sampling, the feedback value $i_d$ and $i_q$ will have deviations, which may eventually lead to deviations in the torque control output. Therefore, before connecting to the grid, the sampling circuit should be checked for damage to components such as capacitors or resistors.

4. Inaccurate calculation of the position angle of the generator rotor.

   The electrical angular velocity of the generator can be obtained by measuring the rotor position angle. There is no position sensor installed in the large wind turbine generator, but Kalman filter is used to estimate the rotor position angle. If the low-pass filter parameter of the phase-locked loop is high If the frequency part is not filtered out, the rotor position estimation error will occur, resulting in a deviation of the torque control output.

5. Concluding remarks
This article starts with the installation position and basic functions of the torque limiter, and explains the important role of the torque limiter in the generator set. By analyzing the vector control principle of permanent magnet synchronous generator, Combined with the mathematical model of the motor, according to the motor torque equation, d-q axis current command equation, system control equation, etc, from the perspective of automatic control, several reasons and solutions for the slippage of the torque limiter are analyzed. When the wind power plant is actually operating, if the torque limiter slips, it can be solved according to the relevant reasons to achieve the effect of improving the power generation efficiency and maintaining the stability of the generator.
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