Study on High Performance Control of the Machine-Side Converter of Doubly-Fed Turbines under Grid Distortion

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Abstract. Two control strategies of DFIG under grid distortion are firstly summarized, namely, the control strategy of PI-R current controller based on dq reference frame and the control strategy of PI current controller based on the multiple rotating dq reference frame, and their advantages and disadvantages are analysed. On the basis of dynamic modelling of DFIG under grid distortion, in view of the defect that DFIG coupling is not considered in the control strategy of PI-R current controller based on dq reference frame, an improved control strategy considering motor coupling is proposed. In the end, the modelling and simulation of the unimproved and improved control strategies of PI-R current controller based on dq reference frame are carried out, and the simulation results verified the effectiveness of the improved control strategy.

1 Preface

Doubly-fed turbines are directly connected to the grid, hence the change of the grid environment will have a direct impact on them. The influence of grid harmonics on doubly-fed wind turbines is a problem not ignorable. The necessity of grid harmonics firstly makes this problem not ignorable. In modern grid, the application of power electronic converters has become a significant feature, but power electronic converters will inevitably induce harmonics with rich frequency. Grid standards such as IEEE 519-1992[1] and IEC 61000-4-1[2] of the International Electrotechnical Commission and Chinese national standard GB/T 14549-93[3] etc. clearly indicate that a certain proportion of harmonics is allowed in the industrial grid, especially at 6.6kV, 11kV and 20kV voltage class, 5th and 7th harmonics not exceeding 3% are allowed. The non-negligible effect of grid harmonics on doubly-fed wind turbines is also reflected in the fact that the low harmonic impedance of the generator itself is small, hence a small low harmonic voltage will produce a large current corresponding to the harmonic order, thus causing electromagnetic torque fluctuation and mechanical components vibration. Take the necessity above into account, more and more attention is paid to the optimal operation research of doubly-fed turbines under grid distortion. At present, the optimal control strategies of the machine-side converter under grid distortion can be mainly classified to two types, namely, the control strategy of PI-R current controller based on dq reference frame and the control strategy of PI current controller based on the multiple rotating dq reference frame. Nowadays control strategies under

harmonic distortion are mainly evolved from the two control strategies above, such as the stator current harmonic direct closed loop control technology[4] for doubly fed wind turbines based on the resonant control, the selective harmonic elimination method[5] based on the resonant controller, the harmonic current control method[6] based on the multiple rotating dq reference frame.

DFIG is a cross-coupled complex system, and the motor coupling is not considered in the above two control strategies. On the basis of the control strategy of the machine-side converter of PI-R current controller based on dq reference frame, considering the coupling shutdown of the motor and implementing decoupling control to it, an improved control strategy is proposed and the design of PI-R current controller is produced in this paper. Finally, simulation results show that the improved control strategy is more effective and superior than the unimproved control strategy of the machine-side converter of PI-R control strategy based on dq reference frame.

2 Conclusion of the two control strategies under harmonic distortion

The control block diagram of the control strategy of the machine-side converter of PI-R current controller based on the multiple rotating dq reference frame is shown in Figure 1. The PI controller is used to control the rotor current in the multiple reference frames of dq, -5dq and +7dq rotating at the synchronous speed, -5times the synchronous speed and +7times the synchronous speed respectively

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Figure 1. The control strategy of the machine-side converter of PI current controller based on the multiple rotating dq reference frame

PI controller is a proportional integral controller, which can only implement floating control to DC value but can do nothing to AC value. Due to this characteristic of the PI current controller, place the doubly-fed turbine models in the rotating reference frame of dq, -5dq and +7dq respectively, then the fundamental wave component, the 5th and 7th harmonic components represent DC characteristic respectively and the PI current controller is used to control each component. The obtained rotor voltage command values are that in the reference frame

of dq, -5dq and +7dq respectively, which are converted to the rotor \$\alpha\beta\$ reference frame and added together to obtain the complete rotor voltage command value under harmonic conditions. Finally, through PWM modulation drive signal to drive the converter IGBT tube on or off.

The control block diagram of the control strategy of the machine-side converter of PI-R current controller based on dq reference frame is shown in figure 2. PI-R controller is used to control the rotor current in dq reference frame.

Figure 2. The control strategy of the machine-side converter of PI current controller based on the multiple rotating dq reference frame

The PI-R controller is called the proportional integral and resonant controller, and it consists of the PI proportional integral controller and the R resonant controller. The R resonant controller is a generalized AC integrator, which

has a high control gain at the set resonant frequency, and a fast attenuation of the control gain outside the resonance frequency, with good frequency selectivity. The combination of PI and R controllers can not only

realize the floating control of the DC value, but also the floating control of the AC value with a certain frequency. In the synchronously rotating dq reference frame, the fundamental wave component of DFIG is shown as DC value, meanwhile the 5th and 7th harmonics are shown as 6 times frequency component. Therefore, only a PI-R controller with resonant frequency of $6\omega_1$ is needed to realize the synchronous control of the rotor current fundamental wave and the 5th and 7th harmonics. The voltage command value obtained by the current controller is the rotor voltage command value in dq reference frame, including the fundamental wave and harmonic component. It is then converted in the rotor $\alpha\beta$ reference frame to drive on or off the IGBT pipe of the machine-side converter by signal modulation.

The control strategy of the machine-side converter of PI current controller based on the multiple rotating dq reference frame is easy to achieve and does not require the resonant controller. However, any harmonic control loop consists of a positive transformation of coordinates, harmonic extraction, PI controller and an inverse transformation of coordinates, thus when the harmonic order is much, it takes a lot of computation and a lot of digital resources. The control strategy of the machine-side converter of PI current controller based on dq reference frame needs the resonant controller, but the number of PI controllers can be largely reduced. In addition, in the rotor current control loop, the control strategy of PI-R current controller does not need to extract the fundamental wave and each harmonic component of the rotor current, which reduces the delay of the control loop caused by harmonic extraction. For the control strategy of PI current controller based on the multiple rotating dq reference frame, the rotor current control loop must include the rotor current fundamental wave and each harmonic extraction part, thus the time delay induced by harmonic extraction may reduce the control precision.

3 Dynamic modelling of DFIG under grid distortion

The voltage equation of DFIG in dq reference frame is:

$$\begin{cases} u_{dq1} = R_1 i_{dq1} + \frac{d\psi_{dq1}}{dt} + j\omega_1 \psi_{dq1} \\ u_{dq2} = R_2 i_{dq2} + \frac{d\psi_{dq2}}{dt} + j\omega_s \psi_{dq2} \end{cases} \quad (1)$$

The flux linkage equation is:

$$\begin{cases} \psi_{dq1} = L_1 i_{dq1} + L_m i_{dq2} \\ \psi_{dq2} = L_m i_{dq1} + L_2 i_{dq2} \end{cases} \quad (2)$$

Where, u_{dq1} and u_{dq2} are the stator and rotor voltage respectively, i_{dq1} and i_{dq2} are the stator and rotor current respectively, ψ_{dq1} and ψ_{dq2} are the stator and rotor flux linkage respectively, R_1 and R_2 are the stator and rotor resistance respectively, L_m , L_1 and L_2 are the mutual inductance and the stator and rotor inductance

respectively, ω_1 and ω_r are the synchronous angular velocity and rotational angular velocity respectively.

After deformation, equation (2) can be obtained as follows:

$$\psi_{dq2} = \frac{L_m \psi_{dq1}}{L_1} + \sigma L_2 i_{dq2} \quad (3)$$

Where, $\sigma = 1 - \frac{L_m^2}{L_1 L_2}$ is the magnetic flux leakage coefficient.

Substituting equation (3) into equation (1), the relationship between rotor voltage and rotor current can be obtained as follows:

$$u_{dq2} = R_2 i_{dq2} + \sigma L_2 \left(\frac{di_{dq2}}{dt} + j\omega_s i_{dq2} \right) + \frac{L_m}{L_1} \left(\frac{d\psi_{dq1}}{dt} + j\omega_s \psi_{dq1} \right) \quad (4)$$

When considering harmonics, the grid voltage can be expressed as:

$$u_{\alpha\beta 1} = U_{sm}^{(1)} e^{j(\omega_1 t + \phi_0^{(1)})} + U_{sm}^{(5)} e^{-j(5\omega_1 t + \phi_0^{(5)})} + U_{sm}^{(7)} e^{j(7\omega_1 t + \phi_0^{(7)})} \quad (5)$$

Subscript $\alpha\beta$ represents the corresponding reference frames, superscript (1), (5), (7) respectively represent the fundamental wave, the 5th and 7th harmonics, U_{sm} is the amplitude of the grid voltage, ϕ_0 is the initial phase angle of the grid voltage vector.

Transforming the coordinate of the grid voltage, the transformation from the stationary reference frame to the dq synchronously rotating reference frame is:

$$u_{dq1} = u_{\alpha\beta 1} e^{-j\omega_1 t} = u_{dq1}^{(1)} + u_{-5dq1}^{(5)} e^{-j6\omega_1 t} + u_{+7dq1}^{(7)} e^{j6\omega_1 t} \quad (6)$$

$U_{dq1}^{(1)}$ is the fundamental wave component of the grid voltage in dq reference frame, $U_{-5dq1}^{(5)}$ is the fifth harmonic component of the grid voltage in the -5dq reference frame, and $U_{+7dq1}^{(7)}$ is the seventh harmonic component of the grid voltage in the +7dq reference frame.

Similarly, the expressions of the stator current and stator flux linkage in dq reference frame are as follows:

$$i_{dq1} = i_{dq1}^{(1)} + i_{-5dq1}^{(5)} e^{-j6\omega_1 t} + i_{+7dq1}^{(7)} e^{j6\omega_1 t} \quad (7)$$

$$\psi_{dq1} = \psi_{dq1}^{(1)} + \psi_{-5dq1}^{(5)} e^{-j6\omega_1 t} + \psi_{+7dq1}^{(7)} e^{j6\omega_1 t} \quad (8)$$

Substituting equations (6), (7) and (8) into equations (1) and (2), the stator voltage and flux linkage equation under harmonic conditions can be obtained as follows:

$$\begin{cases} u_{dq1}^{(1)} = R_1 i_{dq1}^{(1)} + p\psi_{dq1}^{(1)} + j\omega_1 \psi_{dq1}^{(1)} \\ u_{dq2}^{(1)} = R_2 i_{dq2}^{(1)} + p\psi_{dq2}^{(1)} + j\omega_s \psi_{dq2}^{(1)} \\ u_{-5dq1}^{(5)} = R_1 i_{-5dq1}^{(5)} + p\psi_{-5dq1}^{(5)} - j5\omega_1 \psi_{-5dq1}^{(5)} \\ u_{-5dq2}^{(5)} = R_2 i_{-5dq2}^{(5)} + p\psi_{-5dq2}^{(5)} - j\omega_s \psi_{-5dq2}^{(5)} \\ u_{+7dq1}^{(7)} = R_1 i_{+7dq1}^{(7)} + p\psi_{+7dq1}^{(7)} + j7\omega_1 \psi_{+7dq1}^{(7)} \\ u_{+7dq2}^{(7)} = R_2 i_{+7dq2}^{(7)} + p\psi_{+7dq2}^{(7)} + j\omega_s \psi_{+7dq2}^{(7)} \end{cases} \quad (9)$$

$$\begin{cases} \psi_{dq1}^{(1)} = L_1 i_{dq1}^{(1)} + L_m i_{dq2}^{(1)} \\ \psi_{dq2}^{(1)} = L_2 i_{dq2}^{(1)} + L_m i_{dq1}^{(1)} \\ \psi_{-5dq1}^{(5)} = L_1 i_{-5dq1}^{(5)} + L_m i_{-5dq2}^{(5)} \\ \psi_{-5dq2}^{(5)} = L_2 i_{-5dq2}^{(5)} + L_m i_{-5dq1}^{(5)} \\ \psi_{+7dq1}^{(7)} = L_1 i_{+7dq1}^{(7)} + L_m i_{+7dq2}^{(7)} \\ \psi_{+7dq2}^{(7)} = L_2 i_{+7dq2}^{(7)} + L_m i_{+7dq1}^{(7)} \end{cases} \quad (10)$$

Where $\omega_s = \omega_l - \omega_r$, $\omega_{5s} = 5\omega_l + \omega_r$, $\omega_{7s} = 7\omega_l - \omega_r$.

4 The control strategy of the machine-side converter of PI current controller based on dq reference frame

Generally, according to the operation requirements of the grid and units, the control target of the machine-side converter can be set in one of the following four forms.

Goal 1: Balanced stator current to ensure the stator windings heat evenly.

Goal 2: Balanced rotor current to ensure the rotor windings heat evenly.

Goal 3: Balanced stator active power and stator reactive power.

Goal 4: Balanced stator reactive power and electromagnetic torque to reduce mechanical stress on wind turbines shafting.

Select different control targets. According to the motor equation, the command value of the rotor current under corresponding control targets can be inversely solved as follows:

Goal 1

$$\begin{cases} i_{-5dq2}^{(5)*} = \frac{\psi_{-5dq1}^{(5)}}{L_m} \\ i_{+7dq2}^{(7)*} = \frac{\psi_{+7dq1}^{(7)}}{L_m} \end{cases} \quad (11)$$

Goal 2

$$\begin{cases} i_{-5dq2}^{(5)*} = 0 \\ i_{+7dq2}^{(7)*} = 0 \end{cases} \quad (12)$$

Goal 3

$$\begin{cases} i_{-5dq2}^{(5)*} = \frac{\psi_{-5d1}^{(5)} + 7\psi_{+7d}^{(7)}}{L_m} - 7\lambda_{+7d} i_{d2}^{(1)} - 7\lambda_{+7q} i_{q2}^{(1)} \\ i_{-5q2}^{(5)*} = \frac{\psi_{-5q1}^{(5)} - 7\psi_{+7q}^{(7)}}{L_m} + 7\lambda_{+7q} i_{d2}^{(1)} + 7\lambda_{+7d} i_{q2}^{(1)} \\ i_{+7d2}^{(7)*} = \frac{-5\psi_{-5d1}^{(5)} + \psi_{+7d}^{(7)}}{L_m} + 5\lambda_{-5d} i_{d2}^{(1)} + 5\lambda_{-5q} i_{q2}^{(1)} \\ i_{+7q2}^{(7)*} = \frac{5\psi_{-5q1}^{(5)} + \psi_{+7q}^{(7)}}{L_m} - 5\lambda_{-5q} i_{d2}^{(1)} + 5\lambda_{-5d} i_{q2}^{(1)} \end{cases} \quad (13)$$

In the equation above, $\lambda_{-5d} = \frac{\psi_{-5d1}^{(5)}}{\psi_{d1}^{(1)}}$, $\lambda_{-5q} = \frac{\psi_{-5q1}^{(5)}}{\psi_{d1}^{(1)}}$,

$$\lambda_{+7d} = \frac{\psi_{+7d1}^{(7)}}{\psi_{d1}^{(1)}}, \lambda_{+7q} = \frac{\psi_{+7q1}^{(7)}}{\psi_{d1}^{(1)}}.$$

Goal 4

$$\begin{cases} i_{-5d2}^{(5)*} = \frac{-2\psi_{-5d1}^{(5)} + 4\psi_{+7d1}^{(7)}}{L_m} + (3\lambda_{-5d} - 4\lambda_{+7d}) i_{d2}^{(1)} + (3\lambda_{-5q} - 4\lambda_{+7q}) i_{q2}^{(1)} \\ i_{-5q2}^{(5)*} = \frac{-2\psi_{-5q1}^{(5)} - 4\psi_{+7q1}^{(7)}}{L_m} + (3\lambda_{-5q} + 4\lambda_{+7q}) i_{d2}^{(1)} - (3\lambda_{-5d} - 4\lambda_{+7d}) i_{q2}^{(1)} \\ i_{+7d2}^{(7)*} = \frac{-2\psi_{-5d1}^{(5)} + 4\psi_{+7d1}^{(7)}}{L_m} + (2\lambda_{-5d} - 3\lambda_{+7d}) i_{d2}^{(1)} + (2\lambda_{-5q} - 3\lambda_{+7q}) i_{q2}^{(1)} \\ i_{+7q2}^{(7)*} = \frac{2\psi_{-5q1}^{(5)} + 4\psi_{+7q1}^{(7)}}{L_m} - (2\lambda_{-5q} + 3\lambda_{+7q}) i_{d2}^{(1)} + (2\lambda_{-5d} + 3\lambda_{+7d}) i_{q2}^{(1)} \end{cases} \quad (14)$$

See literature [8] for its theoretical derivation.

It can be seen from equation (4) that the d and q axis components of the rotor voltage are related not only to the d and q axis components of the rotor current, but also to the q and d axis components of the stator flux linkage.

Considering the harmonic, the rewritten formula (4) can clearly express the coupling relationship by writing the D and Q axes separately:

$$\begin{cases} u_{d2}^{(1)} + u_{-5d2}^{(5)} e^{-j6\omega_1 t} + u_{+7d2}^{(7)} e^{j6\omega_1 t} = \left(R_2 i_{d2}^{(1)} + \sigma L_2 \frac{di_{d2}^{(1)}}{dt} + \omega_s \sigma L_2 i_{q2}^{(1)} + \frac{L_m}{L_1} \frac{d\psi_{d1}^{(1)}}{dt} + \omega_s \frac{L_m}{L_1} \psi_{q1}^{(1)} \right) \\ + \left[R_2 i_{-5d2}^{(5)} + \sigma L_2 \frac{di_{-5d2}^{(5)}}{dt} - (5\omega_l + \omega_r) \sigma L_2 i_{-5q2}^{(5)} + \frac{L_m}{L_1} \frac{d\psi_{-5d1}^{(5)}}{dt} - (5\omega_l + \omega_r) \frac{L_m}{L_1} \psi_{-5q1}^{(5)} \right] e^{-j6\omega_1 t} \\ + \left[R_2 i_{+7d2}^{(7)} + \sigma L_2 \frac{di_{+7d2}^{(7)}}{dt} + (7\omega_l - \omega_r) \sigma L_2 i_{+7q2}^{(7)} + \frac{L_m}{L_1} \frac{d\psi_{+7d1}^{(7)}}{dt} + (7\omega_l - \omega_r) \frac{L_m}{L_1} \psi_{+7q1}^{(7)} \right] e^{j6\omega_1 t} \\ = u_{d2}' + \Delta u_{d2} \\ u_{q2}^{(1)} + u_{-5q2}^{(5)} e^{-j6\omega_1 t} + u_{+7q2}^{(7)} e^{j6\omega_1 t} = \left(R_2 i_{q2}^{(1)} + \sigma L_2 \frac{di_{q2}^{(1)}}{dt} - \omega_s \sigma L_2 i_{d2}^{(1)} + \frac{L_m}{L_1} \frac{d\psi_{q1}^{(1)}}{dt} - \omega_s \frac{L_m}{L_1} \psi_{d1}^{(1)} \right) \\ + \left[R_2 i_{-5q2}^{(5)} + \sigma L_2 \frac{di_{-5q2}^{(5)}}{dt} + (5\omega_l + \omega_r) \sigma L_2 i_{-5d2}^{(5)} + \frac{L_m}{L_1} \frac{d\psi_{-5q1}^{(5)}}{dt} + (5\omega_l + \omega_r) \frac{L_m}{L_1} \psi_{-5d1}^{(5)} \right] e^{-j6\omega_1 t} \\ + \left[R_2 i_{+7q2}^{(7)} + \sigma L_2 \frac{di_{+7q2}^{(7)}}{dt} - (7\omega_l - \omega_r) \sigma L_2 i_{+7d2}^{(7)} + \frac{L_m}{L_1} \frac{d\psi_{+7q1}^{(7)}}{dt} - (7\omega_l - \omega_r) \frac{L_m}{L_1} \psi_{+7d1}^{(7)} \right] e^{j6\omega_1 t} \\ = u_{q2}' + \Delta u_{q2} \end{cases} \quad (15)$$

Where,

$$u_{d2}' = G_{PIR}(s)(i_{d2}^* - i_{d2})$$

$u_{q2}' = G_{PIR}(s)(i_{q2}^* - i_{q2})$ is the output of the PIR controller in dq reference frame, $G_{PIR}(s)$ is the transfer function of the PIR controller, Δu_{d2} and Δu_{q2} are the compensation terms of the rotor voltage in dq reference frame. Considering the constant amplitude of the stator flux fundamental wave and each harmonic wave during the steady-state operation of the unit, the compensation terms can be simplified as follows:

$$\begin{cases} \Delta u_{d2} = \omega_s \sigma L_2 i_{q2} - 6\omega_l \sigma L_2 (i_{-5d2}^{(5)} e^{-j6\omega_1 t} - i_{+7d2}^{(7)} e^{j6\omega_1 t}) \\ + \frac{L_m}{L_1} (\omega_s \psi_{q1}^{(1)} - \omega_{5s} \psi_{-5q1}^{(5)} e^{-j6\omega_1 t} + \omega_{7s} \psi_{+7q1}^{(7)} e^{j6\omega_1 t}) \\ \Delta u_{q2} = -\omega_s \sigma L_2 i_{d2} + 6\omega_l \sigma L_2 (i_{-5d2}^{(5)} e^{-j6\omega_1 t} - i_{+7d2}^{(7)} e^{j6\omega_1 t}) \\ - \frac{L_m}{L_1} (\omega_s \psi_{d1}^{(1)} - \omega_{5s} \psi_{-5d1}^{(5)} e^{-j6\omega_1 t} + \omega_{7s} \psi_{+7d1}^{(7)} e^{j6\omega_1 t}) \end{cases} \quad (16)$$

The control block diagram of the improved control strategy of the machine-side converter of PI-R current controller based on dq reference frame is shown in

Figure 3. According to different control targets, transfer the fundamental wave command in dq reference frame, the 5th harmonic command in -5 dq reference frame and +7th harmonic command in +7 dq reference frame calculated by the fundamental wave and harmonic rotor current command calculation module to the current command value in dq reference frame, the rotor current is directly transformed in dq reference frame as the

feedback value without the fundamental wave and harmonic extraction, after the voltage compensation of coupling term, the command value of rotor voltage in dq reference frame is obtained, finally coordinate transformation and PWM signal modulation are adopted to drive on and off the IGBT pipe of the machine-side converter, so as to realize power and harmonic control under the specified control target of DFIG.

Figure 3. The improved control strategy of machine-side converter of PI-R current controller based on dq reference frame

The compensation voltage calculation model based on dq reference frame is shown in Figure 4. After the transformation of equation (16), in the calculation of compensation voltage, only the 5th and 7th harmonic

components of the rotor current need to be extracted instead of the fundamental component, which reduces the complexity of the control system and avoids the delay caused by the fundamental wave extraction.

Figure 4. Compensation voltage calculation model based on dq reference frame

5 Design of PI-R controller

Combined with the mathematical model of DFIG in section 2 and the control strategy in section 3, the

structure block diagram of the doubly-fed wind turbine control system in dq reference frame can be drawn, as shown in Figure 5.

Figure 5. The structure block diagram of doubly-fed wind turbine control system in dq reference frame

In the figure above, the dotted line represents the DFIG model, and $G_1(s)$, $G_2(s)$, $G_3(s)$ and $G_p(s)$ are the four square transfer functions in the doubly fed generator model. $G_d(s)$ is the sampling period calculation delay function induced by digital control system. The delay time T_d is equal to the sampling period and also equal to half of the switching period. According to the converter parameters in Table 1, the sampling period in this paper is $250\mu s$. $G_{PIR}(s) = K_p + \frac{K_I}{s} + \frac{2K_R\omega_c s}{s^2 + 2\omega_c s + \omega_0^2}$ Is PI-R controller transfer function.

Assuming that the compensation term can accurately compensate to realize good decoupling of the dq axis, and the compensation term and the coupling term can be ignored, the current loop structure block diagram is shown in Figure 6.

Figure 6. The current loop structure diagram of doubly-fed wind turbine control system

At this point, the rotor current loop open-loop transfer function is:

$$G_{i2o}(s) = G_{PIR}(s)G_d(s)G_p(s) = \left(K_p + \frac{K_I}{s} + \frac{2K_R\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \right) \frac{1}{\sigma L_2 s + R_2} e^{-sT_d}$$

$$= \left\{ \frac{K_I}{R_2} \left(\frac{K_p}{\tau s + 1} + \frac{1}{s} \right) + \frac{K_I}{R_2} \frac{2K_R\omega_c s}{\left(\frac{s}{\omega_0} \right)^2 + \frac{2\omega_c}{\omega_0^2} s + 1} \right\} e^{-sT_d}$$

$$= \frac{K_I}{R_2} \frac{\frac{K_p}{K_I\omega_0^2} s^3 + \frac{2(K_p + K_R)\omega_c + K_I}{K_I\omega_0^2} s^2 + \left(\frac{K_p}{K_I} + \frac{2\omega_c}{\omega_0^2} \right) s + 1}{s(\tau s + 1) \left[\left(\frac{s}{\omega_0} \right)^2 + \frac{2\omega_c}{\omega_0^2} s + 1 \right]} e^{-sT_d} \quad (17)$$

Where, $\tau = \frac{\sigma L_2}{R_2}$ is the rotor side time constant.

Substituting $s = j\omega_{cr}$ in equation (17), the rotor current loop open-loop transfer function in the crossover frequency ω_{cr} is:

$$G_{i2o}(j\omega_{cr}) = \frac{K_I - \frac{[K_I + 2\omega_c(K_p + K_R)]\omega_{cr}^2}{\omega_0^2} + j \left(K_p\omega_{cr} - K_p \frac{\omega_{cr}^3}{\omega_0^2} + K_I \frac{2\omega_c\omega_{cr}}{\omega_0^2} \right)}{jR_2\omega_{cr}(j\omega_{cr}\tau + 1) \left[1 - \left(\frac{\omega_{cr}}{\omega_0} \right)^2 \right]} e^{-j\omega_{cr}T_d} \quad (18)$$

In general, if the crossover frequency ω_{cr} is slightly greater than the resonant frequency ω_0 of PI-R controller, they can be considered to be approximately equal, so in the real part of the above formula molecule

$K_I - K_I \frac{\omega_{cr}^2}{\omega_0^2} \approx 0$. And since $2\omega_c \ll \omega_0$, in the imaginary part $K_I \frac{2\omega_c\omega_{cr}}{\omega_0^2} \approx 0$. According to DFIG parameter, it

can be calculated that the rotor time constant is about 11, which is much greater than 1. Therefore, the term $(j\omega_{cr}\tau + 1)$ in the denominator of the above formula can be simplified to $j\omega_{cr}\tau$. After the above treatment, the frequency characteristic expression of the rotor current loop open loop transfer function at the crossover frequency can be simplified as:

$$G_{i2o}(j\omega_{cr}) \approx \frac{2\omega_c(K_p + K_R) \left(\frac{\omega_{cr}}{\omega_0} \right)^2 + jK_p\omega_{cr} \left[\left(\frac{\omega_{cr}}{\omega_0} \right)^2 - 1 \right]}{\omega_{cr}^2 \sigma L_2 \left[1 - \left(\frac{\omega_{cr}}{\omega_0} \right)^2 \right]} e^{-j\omega_{cr}T_d} \quad (19)$$

The phase margin of the rotor current loop open loop transfer function at the crossover frequency is expressed as:

$$\phi = \pi + \angle G_{i2o}(j\omega_{cr}) \approx \arctan \left\{ \frac{K_p\omega_{cr}}{2\omega_c(K_p + K_R)} \left[1 - \left(\frac{\omega_0}{\omega_{cr}} \right)^2 \right] \right\} - \omega_{cr}T_d \quad (20)$$

The gain of the open-loop transfer function at the open-loop crossing frequency should be 1, that is:

$$\begin{aligned} |G_{i2o}(j\omega_{cr})| &\approx \left| \frac{2\omega_c (K_p + K_R) \left(\frac{\omega_{cr}}{\omega_0}\right)^2 + jK_p\omega_{cr} \left[\left(\frac{\omega_{cr}}{\omega_0}\right)^2 - 1\right]}{\omega_c^2 \sigma L_2 \left[1 - \left(\frac{\omega_{cr}}{\omega_0}\right)^2\right]} e^{-j\omega_{cr}T_d} \right| \\ &= \left| \frac{2\omega_c (K_p + K_R) \left(\frac{\omega_{cr}}{\omega_0}\right)^2 + jK_p\omega_{cr} \left[\left(\frac{\omega_{cr}}{\omega_0}\right)^2 - 1\right]}{\omega_c^2 \sigma L_2 \left[1 - \left(\frac{\omega_{cr}}{\omega_0}\right)^2\right]} \right| = 1 \end{aligned} \quad (21)$$

It can be deduced that:

$$\omega_c (K_p + K_R) \approx 0.5\omega_{cr} \left[1 - \left(\frac{\omega_0}{\omega_{cr}}\right)^2\right] \sqrt{(\omega_{cr}\sigma L_2)^2 - K_p^2} \quad (22)$$

Combining equations (20) and (22), it can be concluded that:

$$K_p \approx \frac{\sigma L_2 \omega_{cr}}{\sqrt{1 + \frac{1}{\tan(\phi + \omega_{cr}T_d)}}} \quad (23)$$

Based on the above derivation, the design steps of PI-R current controller in dq reference frame are as follows:

1) Select appropriate phase margin and open loop crossover frequency. The generally recommended phase margin ϕ should be between 30° and 60° [9]. The recommended open-loop crossover frequency ω_{cr} is between 1/10 and 1/5 switching frequency.

2) By substituting the set phase margin and the open-loop crossover frequency into equation (19), the parameter value K_p of PI-R controller can be obtained.

3) Substitute K_p, ϕ, ω_{cr} into equation (22) to get the value of $(K_p + K_R)\omega_c$.

4) According to the operational accuracy of the digital processor, select the smaller ω_c , usually the recommended PI-R controller cutoff frequency is between 2rad/s and 10rad/s.

5) Calculate K_R from the known $K_p, \omega_c, (K_p + K_R)\omega_c$.

6) In PI - R controller, the parameters of PI controller mainly perform floating control to the fundamental component in dq reference frame, R controller parameters under the fundamental frequency effect is very small. Therefore, When determining the K_i parameter value in PI-R controller, make it consistent with the K_i parameter value in PI controller. See literature [10] for the parameter design method of PI controller.

7) Check whether the solved PI-R parameters meet the requirements of steady and dynamic performance of the control system. If not, adjust the phase margin and

the selection of open loop crossover frequency and cut-off frequency, and repeat the above steps until the steady and dynamic performance of the system is optimal.

In accordance with the above steps, the phase margin ϕ in this paper is selected as 30° , the open loop crossover frequency ω_{cr} is selected as 1/6 switching frequency, namely $333 \times 2 \pi$ rad/s, and the cut-off frequency ω_c is selected as 5rad/s. The parameters of the PI-R controller are obtained as $K_p=18, K_i=405, K_R=942$.

Controlling the rotor current according to the designed PI and PI-R controller parameters, the amplitude-frequency characteristic curve of the closed loop transfer function $\frac{i_{dq2}}{i_{dq2}^*} = \frac{G_{i2o}(s)}{1 + G_{i2o}(s)}$ of the rotor current loop is shown in Fig.7.

Figure 7. Amplitude-frequency characteristics of the closed-loop transfer function of rotor current

It can be seen from the figure that the amplitude of the PI-R controller's control strategy curve at 0Hz and 300Hz is basically equal to 0dB, indicating that the PI-R controller can make the DC value and the 6 times frequency AC value of the rotor current track the DC value and the 6 times frequency AC value respectively, and the amplification gain is approximately equal to 1. However, PI controller can only implement floating control to the DC component of rotor current, but can do nothing with 6 times frequency AC component. Therefore, PI-R current controller in dq reference frame can effectively control the fundamental wave and the 5th and 7th harmonic components.

6 Simulation results and conclusions

In PSCAD, the modeling and simulation of the unimproved and improved control strategies of the machine-side converter of PI-R current controller based on dq reference frame are carried out respectively. The parameters of the doubly-fed wind power generation system used in simulation are shown in Table 1.

Table 1. The parameters of DFIG system

Wind turbine parameters	Rated power: 1.5MW	Blade radius: 35m
	Air density: 1.225kg/m ³	Rated wind speed: 12m/s
	Cut in wind speed: 3m/s	Cut out wind speed: 25m/s
DFIG parameters	Rated power: 1.5MVA	Rotor stator ratio: 2.5
	Number of pole pairs: 2	Inertia constant: 1.14s

Converter parameters	Stator resistance: $R_1 = 0.00698\Omega$ Rotor resistance: $R_2 = 0.008252\Omega$	
	Stator reactance: $X_{1\sigma} = 0.05618\Omega$ Rotor reactance: $X_{2\sigma} = 0.036818\Omega$	
	Mutual inductance: $X_m = 1.485432\Omega$	
	DC bus voltage: 1100V	Operating frequency: 2kHz
	Grid side inductance: 8mH	Grid side resistance: 0.0003 Ω
	DC storage capacitor: 8640 μ F	

In the simulation, the wind speed is kept unchanged at 6m/s, DFIG operates in a sub-synchronous state, and the rotor speed is about 0.8p.u. The stator reactive power instruction is 0Var. The distortion voltage of the power grid is composed of 4% 5th negative order harmonic components and 4% 7th positive order harmonic components of. The harmonic distortion rate THD of the

power grid voltage is about 5.66%. The parameters of PI-R current controller refer to the design values in Section 4. Take Goal 1 as the control goal.

The simulation result of the control strategy of the machine-side converter of PI-R current controller based on dq reference frame is shown in Figure 8.

Figure 8. the simulation result of the unimproved control strategy

The simulation result of the improved control strategy of the machine-side converter of PI-R current controller based on dq reference frame is shown in Figure 9.

Figure 9. the simulation result of the improved control strategy

By comparing FIG. 8 and FIG. 9, it can be seen that under the control objective of balanced stator current, the improved control strategy not only reduces the harmonic content of stator current compared with that of the unimproved control strategy, but also optimizes the equivalent values of rotor current, electromagnetic torque and active power.

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