

Improved control strategy for PI-R current of DFIG considering voltage and current harmonics compensation

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Abstract. With the rapid development of wind power generation, the related research of wind power control and integration issues has attracted much attention, and the focus of the research are shifting away from the ideal power grid environment to the actual power grid environment. As the main stream wind turbine generator, a doubly-fed induction generator (DFIG) is connected to the power grid directly by its stator, so it is particularly sensitive to the power grid. This paper studies the improvement of DFIG control technology in the power grid harmonic environment. Based on the DFIG dynamic model considering the power grid harmonic environment, this paper introduces the shortcomings of the common control strategy of DFIG, and puts forward the enhanced method. The decoupling control of the system is realized by compensating the coupling between the rotor harmonic voltage and harmonic current, improving the control performance. In addition, the simulation experiments on PSCAD/EMTDC are carried out to verify the correctness and effectiveness of the improved scheme.

1. Introduction

In recent years, the research on DFIG high-performance control is gradually increased under the condition of unbalanced grid voltage according to papers [1-6]. However, the research on the high-performance control strategy of DFIG wind turbine is relatively few in the case of harmonic. The research of paper [7] shows that, harmonic voltage will create the ripple of electromagnetic torque of the motor, increase the copper loss and iron loss, lead to stator and rotor current distortion and so on. What's worse, electric generator unit may split from the grid. At present, there have been some papers involved in the operation and control methods of DFIG wind power system in harmonic environment at home and abroad. For instance, the stator current harmonic compensation method based on the multiple synchronous rotating coordinate systems from papers [8-10], the multi-objective control method added harmonic calculation instruction according to papers [11-13], control method of harmonic current based on multiple rotating coordinate systems from papers [14-16], and selected harmonic elimination method based on resonant controller according to papers [17-21]. In conclusion, the above methods can be divided into two categories. One can be named as the control strategy of the PI current controller based on multiple rotating dq coordinate systems, which means that PI controller

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is used to control the rotor current after selecting the control target in $(dq)^+$, $(dq)^{5-}$, $(dq)^{7+}$ reference frames. The other is the control strategy of the PI-R current controller based on dq coordinate system, which means using PI-R controller to control the rotor current in unified synchronous speed rotating dq coordinate system. But most of the methods mentioned above ignore the cross coupling characteristics between rotor voltage and current. Some of them only consider the coupling between the fundamental voltage and current without considering the coupling between the harmonic voltage and current. If there is no effective compensation for the coupling in the design of d , q axis rotor current controller, it will affect the speed and accuracy of rotor current control, thereby significantly reducing the dynamic characteristics of the control strategy.

Based on the above reasons, this paper takes the rotor voltage and current coupling characteristics into consideration in order to improve the existing control strategies. The harmonic coupling relationship between voltage and current are concluded after introducing the mathematical model of DFIG in harmonic environment. By increasing the rotor harmonic voltage and current coupling compensation, this paper proposes an improved control strategy of PI-R current controller based on dq coordinate system. A simulation is carried out in PSCAD/EMTDC to prove the effectiveness of the control strategy.

2. DFIG dynamic modelling in harmonic environment

The mathematical model of DFIG in vector form of synchronous speed rotating dq coordinate system is as follows

(1) Voltage equations

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

(2) Flux linkage equations

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

Formula (2) can be expressed as follows

$$\begin{cases} \mathbf{i}_{dq1} = \frac{\psi_{dq1} - L_m \mathbf{i}_{dq2}}{L_1} \\ \psi_{dq2} = \frac{L_m \psi_{dq1}}{L_1} + \sigma L_2 \mathbf{i}_{dq2} \end{cases} \quad (3)$$

Where $\sigma = 1 - L_m^2 / (L_1 L_2)$ is the leakage factor.

Substituting (3) into (1) yields the relationship between rotor voltage and rotor current as follows

$$\mathbf{u}_{dq2} = R_2 \mathbf{i}_{dq2} + \sigma L_2 \frac{d\mathbf{i}_{dq2}}{dt} + \mathbf{j}\omega_s \sigma L_2 \mathbf{i}_{dq2} + \frac{L_m}{L_1} \frac{d\psi_{dq1}}{dt} + \mathbf{j}\omega_s \frac{L_m}{L_1} \psi_{dq1} \quad (4)$$

In the consideration of the three-phase power grid voltage distortion of harmonics at the frequencies of $-5\omega_1$ and $7\omega_1$, DFIG modelling will become more complicated. In the stationary $\alpha\beta$ coordinate system, the space vector of DFIG (such as voltage, current, flux etc.) can be generally expressed as (5) according to the paper [22]

$$\begin{aligned} \mathbf{F}_{\alpha\beta}(t) &= \mathbf{F}_{\alpha\beta}^{(1)}(t) + \mathbf{F}_{\alpha\beta}^{(5)}(t) + \mathbf{F}_{\alpha\beta}^{(7)}(t) \\ &= \left| \mathbf{F}_{\alpha\beta}^{(1)}(t) \right| e^{j(\omega_1 t + \phi^{(1)})} + \left| \mathbf{F}_{\alpha\beta}^{(5)}(t) \right| e^{-j(5\omega_1 t + \phi^{(5)})} + \left| \mathbf{F}_{\alpha\beta}^{(7)}(t) \right| e^{j(7\omega_1 t + \phi^{(7)})} \end{aligned} \quad (5)$$

where superscript (1),(5),(7) respectively on behalf of fundamental positive-sequence, 5th harmonic, 7th harmonic. $\left| \mathbf{F}_{\alpha\beta}^{(1)}(t) \right|$, $\left| \mathbf{F}_{\alpha\beta}^{(5)}(t) \right|$, $\left| \mathbf{F}_{\alpha\beta}^{(7)}(t) \right|$ means the amplitude of 1st, 5th, 7th harmonic vector. $\phi^{(1)}$, $\phi^{(5)}$,

$\varphi^{(7)}$ are the respective initial phase shift for the fundamental positive-sequence and harmonic components of $-5\omega_1$ and $7\omega_1$ according to the paper [23].

In addition to stationary $\alpha\beta$ coordinates, there are forward synchronous speed $(dq)^+$ coordinate system, 5 times the reversal synchronous speed $(dq)^{5-}$ coordinate system and 7 times the synchronous speed $(dq)^{7+}$ coordinate system. The vector transformation between the above coordinate systems and the stationary $\alpha\beta$ coordinates is as follows

$$\begin{cases} \mathbf{F}_{dq} = \mathbf{F}_{\alpha\beta} e^{-j\omega_1 t} \\ \mathbf{F}_{-5dq} = \mathbf{F}_{\alpha\beta} e^{j5\omega_1 t} \\ \mathbf{F}_{+7dq} = \mathbf{F}_{\alpha\beta} e^{-j7\omega_1 t} \end{cases} \quad (6)$$

Substituting (6) into (5) yields

$$\begin{cases} \mathbf{F}_{dq}^{(1)} = |\mathbf{F}_{\alpha\beta}^{(1)}(t)| e^{j\phi^{(1)}} \\ \mathbf{F}_{-5dq}^{(5)} = |\mathbf{F}_{\alpha\beta}^{(5)}(t)| e^{-j\phi^{(5)}} \\ \mathbf{F}_{+7dq}^{(7)} = |\mathbf{F}_{\alpha\beta}^{(7)}(t)| e^{j\phi^{(7)}} \end{cases} \quad (7)$$

Different harmonic vectors will be transformed into straight flow after transformation to the corresponding rotational coordinate system so that the model can be simplified to a certain extent.

2.1. Voltage and flux linkage equations of DFIG considering harmonic

When grid voltage contains 5th and 7th harmonic components, it can be expressed in the form of formula (3) as follows

$$\mathbf{u}_{\alpha\beta 1} = U_{sm}^{(1)} e^{j(\omega_1 t + \phi_0^{(1)})} + U_{sm}^{(5)} e^{-j(5\omega_1 t + \phi_0^{(5)})} + U_{sm}^{(7)} e^{j(7\omega_1 t + \phi_0^{(7)})} \quad (8)$$

where $U_{sm}^{(1)}, U_{sm}^{(5)}, U_{sm}^{(7)}$ are the amplitude of 1st, 5th, 7th harmonic voltage. $\phi_0^{(1)}, \phi_0^{(5)}, \phi_0^{(7)}$ means 1st, 5th, 7th harmonic vector angle.

Grid voltage transforms from stationary $\alpha\beta$ coordinate system to synchronous speed rotating dq coordinate system can be expressed as follows

$$\mathbf{u}_{dq1} = \mathbf{u}_{\alpha\beta 1} e^{-j\omega_1 t} = \mathbf{u}_{dq1}^{(1)} + \mathbf{u}_{-5dq1}^{(5)} e^{-j6\omega_1 t} + \mathbf{u}_{+7dq1}^{(7)} e^{j6\omega_1 t} \quad (9)$$

Formula (9) shows that the fundamental component of the grid voltage is presented as a direct flow and 5th, 7th harmonic component is presented respectively as $+6\omega_1, -6\omega_1$ rotary alternating quantity in the dq coordinate system.

Similarly, expressions of stator current and flux in the dq coordinate system are available. Substituting them into (1) and (2), extracting common factor $e^{-j6\omega_1 t}$ and $e^{j6\omega_1 t}$, stator and rotor voltage equations from paper [13] are as follows

$$\begin{cases} \mathbf{u}_{dq1}^{(1)} = R_1 \mathbf{i}_{dq1}^{(1)} + p\psi_{dq1}^{(1)} + j\omega_1 \psi_{dq1}^{(1)} \\ \mathbf{u}_{dq2}^{(1)} = R_2 \mathbf{i}_{dq2}^{(1)} + p\psi_{dq2}^{(1)} + j\omega_s \psi_{dq2}^{(1)} \\ \mathbf{u}_{-5dq1}^{(5)} = R_1 \mathbf{i}_{-5dq1}^{(5)} + p\psi_{-5dq1}^{(5)} - j5\omega_1 \psi_{-5dq1}^{(5)} \\ \mathbf{u}_{-5dq2}^{(5)} = R_2 \mathbf{i}_{-5dq2}^{(5)} + p\psi_{-5dq2}^{(5)} - j\omega_{5s} \psi_{-5dq2}^{(5)} \\ \mathbf{u}_{+7dq1}^{(7)} = R_1 \mathbf{i}_{+7dq1}^{(7)} + p\psi_{+7dq1}^{(7)} + j7\omega_1 \psi_{+7dq1}^{(7)} \\ \mathbf{u}_{+7dq2}^{(7)} = R_2 \mathbf{i}_{+7dq2}^{(7)} + p\psi_{+7dq2}^{(7)} + j\omega_{7s} \psi_{+7dq2}^{(7)} \end{cases} \quad (10)$$

where $\omega_s = \omega_1 - \omega_r$, $\omega_{5s} = 5\omega_1 + \omega_r$ and $\omega_{7s} = 7\omega_1 - \omega_r$.

The stator and rotor flux linkage equations are as follows

$$\begin{cases} \psi_{dq1}^{(1)} = L_1 \mathbf{i}_{dq1}^{(1)} + L_m \mathbf{i}_{dq2}^{(1)} \\ \psi_{dq2}^{(1)} = L_2 \mathbf{i}_{dq2}^{(1)} + L_m \mathbf{i}_{dq1}^{(1)} \\ \psi_{-5dq1}^{(5)} = L_1 \mathbf{i}_{-5dq1}^{(5)} + L_m \mathbf{i}_{-5dq2}^{(5)} \\ \psi_{-5dq2}^{(5)} = L_2 \mathbf{i}_{-5dq2}^{(5)} + L_m \mathbf{i}_{-5dq1}^{(5)} \\ \psi_{+7dq1}^{(7)} = L_1 \mathbf{i}_{+7dq1}^{(7)} + L_m \mathbf{i}_{+7dq2}^{(7)} \\ \psi_{+7dq2}^{(7)} = L_2 \mathbf{i}_{+7dq2}^{(7)} + L_m \mathbf{i}_{+7dq1}^{(7)} \end{cases} \quad (11)$$

2.2. Power and electromagnetic torque equations of DFIG considering harmonic

The equations of active power P_1 and reactive power Q_1 output from stator side are as follows

$$\begin{cases} P_1 = -\frac{3}{2} \operatorname{Re}(\mathbf{u}_{dq1} \hat{\mathbf{i}}_{dq1}) \\ Q_1 = -\frac{3}{2} \operatorname{Im}(\mathbf{u}_{dq1} \hat{\mathbf{i}}_{dq1}) \end{cases} \quad (12)$$

Where $\hat{\mathbf{i}}_{dq1}$ is the conjugate complex of $\mathbf{i}_{dq1}$.

Substituting (9), (10) into (1) and ignoring stator resistance will result the formulas of stator voltage and current considering harmonic. According to them, (12) could be rewritten as follows according to the paper [24]

$$\begin{cases} P_1 = P_{1,dc} + P_{1,\sin 6} \sin 6\omega_1 t + P_{1,\cos 6} \cos 6\omega_1 t + P_{1,\sin 12} \sin 12\omega_1 t + P_{1,\cos 12} \cos 12\omega_1 t \\ Q_1 = Q_{1,dc} + Q_{1,\sin 6} \sin 6\omega_1 t + Q_{1,\cos 6} \cos 6\omega_1 t + Q_{1,\sin 12} \sin 12\omega_1 t + Q_{1,\cos 12} \cos 12\omega_1 t \end{cases} \quad (13)$$

where $P_{1,dc}$, $Q_{1,dc}$ are the direct current component of stator active and reactive power. $P_{1,\sin 6}$, $P_{1,\cos 6}$, $Q_{1,\sin 6}$, $Q_{1,\cos 6}$ are the peak value of 6th harmonic components (sine and cosine) of stator active and reactive power. $P_{1,\sin 12}$, $P_{1,\cos 12}$, $Q_{1,\sin 12}$, $Q_{1,\cos 12}$ are the peak value of 12th harmonic components (sine and cosine) of stator active and reactive power. The above expressions refer to the paper [25].

The electromagnetic power of DFIG is

$$P_e = -\frac{3}{2} \operatorname{Re}(\mathbf{j}\omega_1 \psi_{dq1} \hat{\mathbf{i}}_{dq1} + \mathbf{j}\omega_s \psi_{dq2} \hat{\mathbf{i}}_{dq2}) \quad (14)$$

Simplify the electromagnetic power into function only related to stator flux and rotor current

$$P_e = -\frac{3\omega_1 L_m}{2L_1} \operatorname{Im}(\psi_{dq1} \hat{\mathbf{i}}_{dq2}) = P_{e,dc} + P_{e,\sin 6} \sin 6\omega_1 t + P_{e,\cos 6} \cos 6\omega_1 t + P_{e,\sin 12} \sin 12\omega_1 t + P_{e,\cos 12} \cos 12\omega_1 t \quad (15)$$

where $P_{e,dc}$ is the direct current component of electromagnetic power. $P_{e,\sin 6}$, $P_{e,\cos 6}$ are the peak value of the 6th harmonic component of electromagnetic power (sine and cosine). $P_{e,\sin 12}$, $P_{e,\cos 12}$ are the peak value of the 12th harmonic component of electromagnetic power (sine and cosine). The above expressions also refer to the paper [20].

The relationship between electromagnetic torque T_e and electromagnetic power P_e is

$$T_e = p_n \frac{P_e}{\omega_r} \quad (16)$$

where means p_n pole pairs of motor.

The derivation and analysis above shows when the power grid contains 5th and 7th voltage harmonic components, not only the stator current will appear 5th and 7th harmonic but stator active power, reactive power and electromagnetic torque will also contain 6th and 12th harmonic components which is adverse to the operation of DFIG.

3. Improved control strategy of DFIG in power grid harmonic environment

DFIG is a complex mechanical and electrical system with a large number of cross coupling and the coupling between rotor voltage and current will weaken the performance of the control system. If the coupling between the rotor voltage and current is effectively compensated, the control performance could be significantly improved.

Although control strategy of PI-R current controller based on dq coordinate system needs resonant controller, it can greatly reducing the number of PI controllers. In addition to this, the control strategy doesn't need to extract the fundamental and harmonic components of the rotor current in rotor current control loop. It will reduce the control delay due to harmonic extraction and improve the dynamic performance of control.

3.1. Improved control strategy of PI-R current controller based on dq coordinate system

In order to clearly show the coupling relationship of DFIG, equation (4) could be rewritten as follows

$$\left\{ \begin{aligned} u_{d2}^{(1)} + u_{-5d2}^{(5)} e^{-j6\omega t} + u_{+7d2}^{(7)} e^{j6\omega t} &= \left(R_2 i_{d2}^{(1)} + \sigma L_2 \frac{di_{d2}^{(1)}}{dt} + \omega_s \sigma L_2 i_{q2}^{(1)} + \frac{L_m}{L_1} \frac{d\psi_{d1}^{(1)}}{dt} + \omega_s \frac{L_m}{L_1} \psi_{q1}^{(1)} \right) \\ &+ \left[R_2 i_{-5d2}^{(5)} + \sigma L_2 \frac{di_{-5d2}^{(5)}}{dt} - (5\omega_1 + \omega_r) \sigma L_2 i_{-5q2}^{(5)} + \frac{L_m}{L_1} \frac{d\psi_{-5d1}^{(5)}}{dt} - (5\omega_1 + \omega_r) \frac{L_m}{L_1} \psi_{-5q1}^{(5)} \right] e^{-j6\omega t} \\ &+ \left[R_2 i_{+7d2}^{(7)} + \sigma L_2 \frac{di_{+7d2}^{(7)}}{dt} + (7\omega_1 - \omega_r) \sigma L_2 i_{+7q2}^{(7)} + \frac{L_m}{L_1} \frac{d\psi_{+7d1}^{(7)}}{dt} + (7\omega_1 - \omega_r) \frac{L_m}{L_1} \psi_{+7q1}^{(7)} \right] e^{j6\omega t} = u_{d2}' + Vu_{d2} \\ u_{q2}^{(1)} + u_{-5q2}^{(5)} e^{-j6\omega t} + u_{+7q2}^{(7)} e^{j6\omega t} &= \left(R_2 i_{q2}^{(1)} + \sigma L_2 \frac{di_{q2}^{(1)}}{dt} - \omega_s \sigma L_2 i_{d2}^{(1)} + \frac{L_m}{L_1} \frac{d\psi_{q1}^{(1)}}{dt} - \omega_s \frac{L_m}{L_1} \psi_{d1}^{(1)} \right) \\ &+ \left[R_2 i_{-5q2}^{(5)} + \sigma L_2 \frac{di_{-5q2}^{(5)}}{dt} + (5\omega_1 + \omega_r) \sigma L_2 i_{-5d2}^{(5)} + \frac{L_m}{L_1} \frac{d\psi_{-5q1}^{(5)}}{dt} + (5\omega_1 + \omega_r) \frac{L_m}{L_1} \psi_{-5d1}^{(5)} \right] e^{-j6\omega t} \\ &+ \left[R_2 i_{+7q2}^{(7)} + \sigma L_2 \frac{di_{+7q2}^{(7)}}{dt} - (7\omega_1 - \omega_r) \sigma L_2 i_{+7d2}^{(7)} + \frac{L_m}{L_1} \frac{d\psi_{+7q1}^{(7)}}{dt} - (7\omega_1 - \omega_r) \frac{L_m}{L_1} \psi_{+7d1}^{(7)} \right] e^{j6\omega t} = u_{q2}' + Vu_{q2} \end{aligned} \right. \quad (17)$$

where $u_{d2}' = G_{PIR}(s)(i_{d2}^* - i_{d2})$, $u_{q2}' = G_{PIR}(s)(i_{q2}^* - i_{q2})$ are rotor voltage decoupling term in dq coordinate system and can be output through regulation of PI-R controller by adjusting the difference between the rotor current command value and the actual value. $G_{PIR}(s)$ is the transfer function of PI-R controller. Vu_{d2} , Vu_{q2} are rotor voltage compensation term. Considering the steady state operation, the amplitude of fundamental and harmonic wave of stator flux is constant (assuming the differential term is zero). According to (17), full compensation term of rotor voltage could be rewritten as follows (including the fundamental and harmonic compensation)

$$\left\{ \begin{aligned} Vu_{d2} &= \omega_s \sigma L_2 i_{q2}^{(1)} - \sigma L_2 (\omega_{5s} i_{-5q2}^{(5)} e^{-j6\omega t} - \omega_{7s} i_{+7q2}^{(7)} e^{j6\omega t}) + \frac{L_m}{L_1} (\omega_s \psi_{q1}^{(1)} - \omega_{5s} \psi_{-5q1}^{(5)} e^{-j6\omega t} + \omega_{7s} \psi_{+7q1}^{(7)} e^{j6\omega t}) \\ Vu_{q2} &= -\omega_s \sigma L_2 i_{d2}^{(1)} + \sigma L_2 (\omega_{5s} i_{-5d2}^{(5)} e^{-j6\omega t} - \omega_{7s} i_{+7d2}^{(7)} e^{j6\omega t}) - \frac{L_m}{L_1} (\omega_s \psi_{d1}^{(1)} - \omega_{5s} \psi_{-5d1}^{(5)} e^{-j6\omega t} + \omega_{7s} \psi_{+7d1}^{(7)} e^{j6\omega t}) \end{aligned} \right. \quad (18)$$

The improved control strategy of the PI-R current controller based on the dq coordinate system considering the rotor voltage and current coupling is shown in Figure 1.

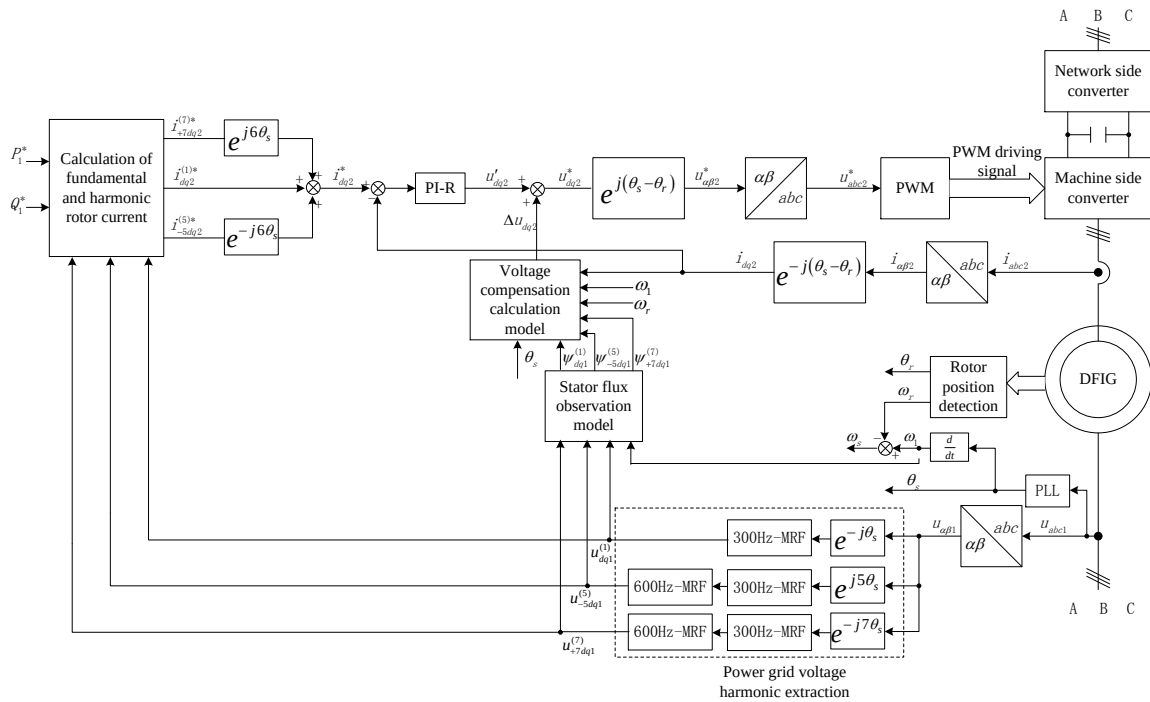


Figure 1. Improved control strategy of PI-R current controller based on dq coordinate system

The fundamental order of rotor current output by instruction calculation module in $(dq)^+$ reference frames, 5th harmonic order in $(dq)^{5-}$ reference frames and 7th harmonic order in $(dq)^{7+}$ reference frames are transformed into $(dq)^+$ reference frames and combined into total current command value. The detected rotor current can be directly transformed into dq coordinate system as feedback value no need the separation between the fundamental and harmonic. The pre compensation rotor voltage decoupling term is obtained by adjusting the PI-R current controller. Adding decoupling term to rotor voltage coupling compensation which is output by voltage compensation calculation model results the directive value of rotor voltage in dq coordinate system. PWM pulse signal of the turn-on and turn-off of the IGBT device of the generator side converter can be got through the PWM modulation link in order to realize power and harmonic control under the specified control target of DFIG.

The stator flux is needed when calculate the compensation voltage. Therefore, the stator flux linkage observation model is added in the control strategy, as shown in figure 2.

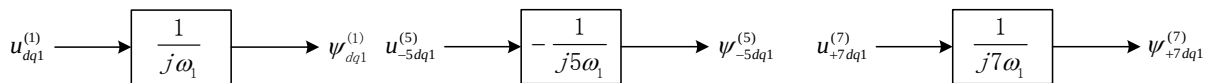


Figure 2. Stator flux observation model

Calculation model of compensation voltage based on the dq coordinate system can be obtained by formula (19), as shown in figure 3.

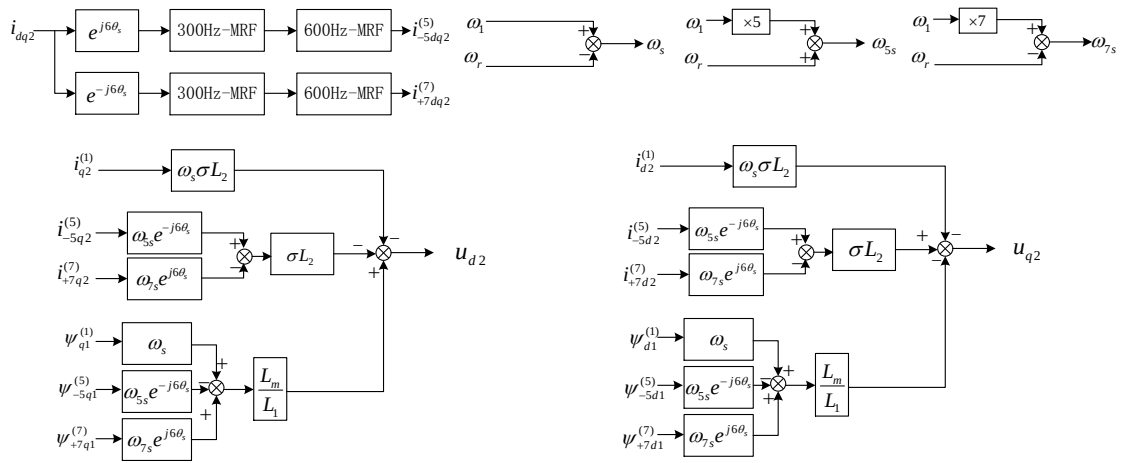


Figure 3. Compensation voltage calculation model.

3.2. Design method of PI-R current controller.

Based on (1), excluding the stator resistance results

$$\psi_{dq1} = \frac{u_{dq1}}{\frac{d}{dt} + j\omega_1} \quad (19)$$

Using Laplace transform to (3), (4) and (19) will obtain the transfer function of the DFIG control model as follows

$$\begin{cases} G_1(s) = 1/(s + j\omega_1) \\ G_2(s) = (s + j\omega_s)L_m/L_s \\ G_p(s) = 1/(\sigma L_2 s + R_2) \end{cases} \quad (20)$$

The control structure diagram of DFIG control system under dq coordinate system can be obtained according to the mathematical model and control strategy above, as shown in figure 4.

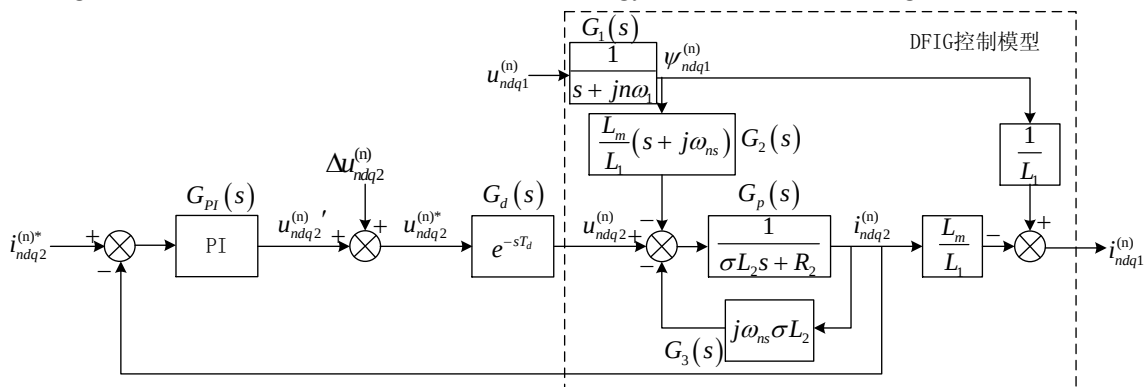


Figure 4. Control structure diagram of DFIG under dq coordinate system

The dotted line in the figure represents the DFIG model. $G_d(s)$ represents the transfer function of the converter action delay according to the paper [26]. Generally, the time delay T_d is equal to the sampling period and equal to 1/2 of the switching period. From the converter parameters in Table 1, the sampling period is 250 μ s.

The transfer function of the PI-R controller is

$$G_{PIR}(s) = K_p + \frac{K_i}{s} + \frac{2K_R\omega_c s}{s^2 + 2\omega_c s + \omega_0^2} \quad (21)$$

where K_p is proportional gain. K_i is integral gain. K_R is the transmission gain of resonant controller at the resonant frequency ω_0 . ω_c is the open loop cutoff frequency of resonant controller when $K_R=1$.

Excluding the compensation items and coupling terms, the structure of the current loop is shown in figure 5.

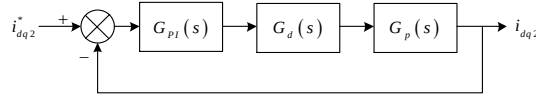


Figure 5. Current loop structure diagram of DFIG control system

ω_{cr} means the open loop crossing frequency. Making $s=j\omega_{cr}$, rotor side time constant $\tau=(\sigma L_2)/R_2$, can get the frequency characteristic expression of rotor current open loop transfer function at the crossover frequency ω_{cr} .

$$G_{i2o}(j\omega_{cr}) = \frac{K_i - \frac{[K_i + 2\omega_c(K_p + K_R)]\omega_{cr}^2}{\omega_0^2} + j\left(K_p\omega_{cr} - K_p\frac{\omega_{cr}^3}{\omega_0^2} + K_i\frac{2\omega_c\omega_{cr}}{\omega_0^2}\right)}{jR_2\omega_{cr}(j\omega_{cr}\tau + 1)\left[1 - \left(\frac{\omega_{cr}}{\omega_0}\right)^2\right]} e^{-j\omega_{cr}T_d} \quad (22)$$

Frequently, the crossing frequency ω_{cr} is slightly larger than the resonant frequency ω_0 of the PI-R controller, and it can be considered that the two are approximately equal according to the paper [27]. Therefore, the real part of the upper numerators is $K_i - K_i\omega_{cr}^2/\omega_0^2 \approx 0$. Because of $2\omega_c \ll \omega_0$, the imaginary part of the upper numerators is $K_i(2\omega_c\omega_{cr})/\omega_0^2 \approx 0$. The time constant of the rotor τ can be calculated by the DFIG simulation experiment parameter in Table 1 which is 11 more than 1. So the denominator $(j\omega_{cr}\tau + 1)$ can be simplified to $j\omega_{cr}\tau$. In summary, the frequency characteristic expression of rotor current open-loop transfer function at the crossing frequency ω_{cr} can be simplified to

$$G_{i2o}(j\omega_{cr}) \approx \frac{2\omega_c(K_p + K_R)\left(\frac{\omega_{cr}}{\omega_0}\right)^2 + jK_p\omega_{cr}\left[\left(\frac{\omega_{cr}}{\omega_0}\right)^2 - 1\right]}{\omega_{cr}^2\sigma L_2\left[1 - \left(\frac{\omega_{cr}}{\omega_0}\right)^2\right]} e^{-j\omega_{cr}T_d} \quad (23)$$

The phase margin ϕ expression of rotor current open-loop transfer function at the crossing frequency ω_{cr} is

$$\phi = \pi + \angle G_{i2o}(j\omega_{cr}) \approx \arctan\left\{\frac{K_p\omega_{cr}}{2\omega_c(K_p + K_R)}\left[1 - \left(\frac{\omega_0}{\omega_{cr}}\right)^2\right]\right\} - \omega_{cr}T_d \quad (24)$$

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

$$|G_{i2o}(j\omega_{cr})| \approx \left| \frac{2\omega_c(K_p + K_R)\left(\frac{\omega_{cr}}{\omega_0}\right)^2 + jK_p\omega_{cr}\left[\left(\frac{\omega_{cr}}{\omega_0}\right)^2 - 1\right]}{\omega_{cr}^2\sigma L_2\left[1 - \left(\frac{\omega_{cr}}{\omega_0}\right)^2\right]} e^{-j\omega_{cr}T_d} \right| = \left| \frac{2\omega_c(K_p + K_R)\left(\frac{\omega_{cr}}{\omega_0}\right)^2 + jK_p\omega_{cr}\left[\left(\frac{\omega_{cr}}{\omega_0}\right)^2 - 1\right]}{\omega_{cr}^2\sigma L_2\left[1 - \left(\frac{\omega_{cr}}{\omega_0}\right)^2\right]} \right| = 1 \quad (25)$$

and

$$\omega_c(K_p + K_R) \approx 0.5\omega_{cr} \left[1 - \left(\frac{\omega_0}{\omega_{cr}} \right)^2 \right] \sqrt{(\omega_{cr}\sigma L_2)^2 - K_p^2} \quad (26)$$

Combine (24) and (26) results

$$K_p \approx \frac{\sigma L_2 \omega_{cr}}{\sqrt{1 + \frac{1}{\tan^2(\phi + \omega_{cr} T_d)}}} \quad (27)$$

Based on the above derivation, the design steps of PI-R current controller in dq coordinates are as follows.

1) Select the appropriate phase margin and open-loop crossover frequency. Phase margin ϕ is usually recommended between 30 degrees to 60 degrees according to the paper [28]. The recommended open-loop crossover frequency ω_{cr} is between 1/10 and 1/5 of the switching frequency.

2) Put predetermined phase margin ϕ and open-loop crossover frequency ω_{cr} into (27) so that the parameter K_p of PI-R controller can be solved.

3) Put K_p, ϕ, ω_{cr} into (24) and the value of $(K_p + K_R)\omega_c$ will be obtained.

4) According to the accuracy of the digital processor, select a smaller value of ω_c . The usual recommended PI-R controller cutoff frequency is between 2rad/s and 10rad/s in the paper [27].

5) The value of K_R can be calculated from the known value of K_p, ω_c and $(K_p + K_R)\omega_c$.

6) In PI-R controller, the parameters of the PI controller mainly control the fundamental component of dq coordinate system through no steady-state error control. The impact of parameters of R controller is very small at the fundamental frequency. So the value of K_I in PI-R controller can be approximated the same as it in PI controller.

7) Check whether the solution of the PI-R parameters meet the control system's steady-state and dynamic performance requirements. If not, re-adjust the value of phase margin, open loop cross frequency and cut off frequency. Repeat the previous steps until the system's steady-state and dynamic performance is optimal.

According to the above steps, phase margin is selected as 30 degree in this paper. Open loop crossing frequency ω_{cr} is selected as 1/6 switching frequency which is $333 \times 2\pi$ rad/s. Cutoff frequency is selected as 5rad/s. So the parameters of the PI-R controller are $K_p=18$ 、 $K_I=405$ 、 $K_R=942$.

4. Simulation

The model of DFIG wind power generation system is built in PSCAD simulation platform, and the system parameters are shown in Table 1 in Appendices according to the paper [29].

In order to verify whether the compensation term optimizes the generator control performance considering DFIG rotor voltage and current coupling, different control strategies are used for the same model, such as the traditional control strategy, control strategy of PI-R current controller without compensation and improved control strategy of PI-R current controller with compensation. Through simulation and comparison, not only can verify the superiority of the control performance of PI-R current controller under the dq coordinate which is better than the traditional control strategy in harmonic environment, but also can verify the superiority of the improved compensation control strategy of PI-R current controller under the dq coordinate which is better than that without compensation.

In the simulation, maintain a constant wind speed 6m/s. The total length of the simulation is 20s. DFIG runs in the state of sub synchronous. The rotor speed is about 0.8p.u. The stator reactive power instruction is 0Var. The grid voltage distortion includes 4% of the 5th negative sequence harmonic components and 4% of the 7th positive sequence harmonic components. The harmonic voltage distortion rate of THD is about 5.66%. The parameters of the PI-R current controller is calculated according to the design value in 2.2. The simulation control target is to balance the rotor current. The

simulation waveform and its spectrogram under different control strategies is shown in Figure 6 and Figure 7. In Figure 6, each simulation waveform from left to right are respectively on behalf of the results of using the traditional PI control strategy, no compensation PI-R control strategy and PI-R control strategy with compensation. In Figure 7, each spectrum analysis diagram from top to bottom are also respectively on behalf of the results of using the traditional PI control strategy, no compensation PI-R control strategy and PI-R control strategy with compensation.

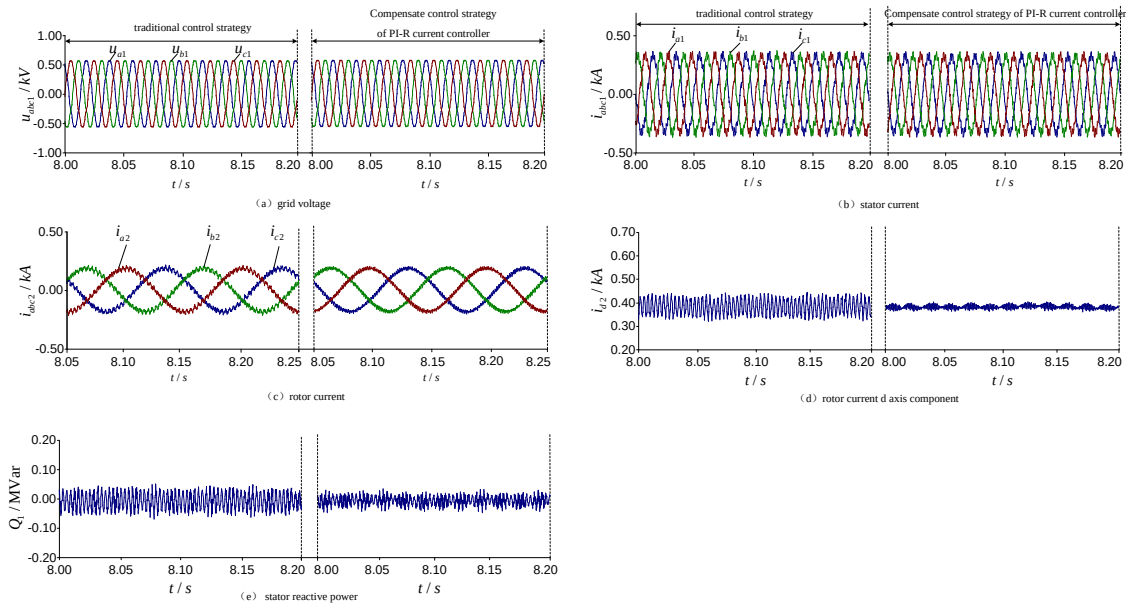


Figure 6. Waveform of different control strategies for balancing the rotor current as the control target

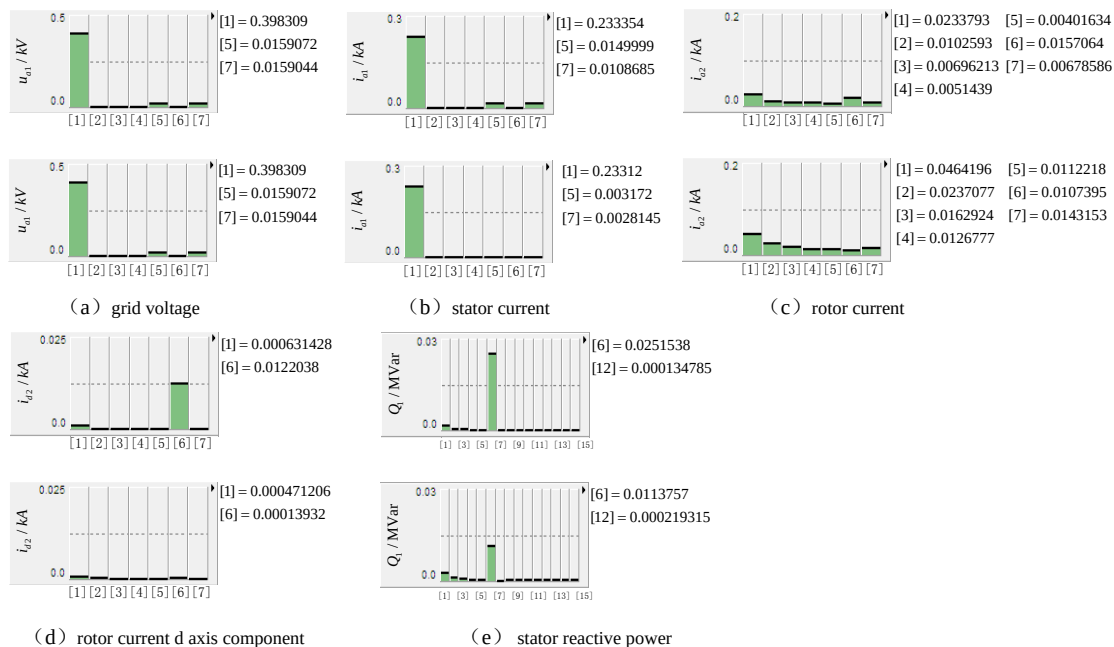


Figure 7. Spectrum analysis chart of different control strategies for balancing the rotor current as the control target

The simulation results of different control strategies can be seen qualitatively according to the waveform. Spectrum analysis chart can be used to quantify the control effect of different control strategies. The numerical value of the spectrum analysis chart is the effective value of the harmonic.

Choosing to balance the rotor current as the control target, the following conclusions can be drawn from figure 6 and Figure 7. (The defined current harmonic suppression effect of a control strategy here means the ratio of the square root of the d, q axis harmonic current in a certain control strategy to the ratio in the traditional control strategy.)

(1) After adding compensation, the control strategy of PI-R current controller based on dq coordinates system can reduce the content of the 5th and 7th harmonic currents in stator current better than the traditional control strategy, making the stator current waveform more tend to be good sine waveform. The harmonic suppression effect of the stator current with compensation is 22.9% and the effect is better after adding compensation.

(2) After adding compensation, the control strategy of PI-R current controller based on dq coordinates system can reduce the content of the 6th harmonic currents in rotor current better than the traditional control strategy, making the rotor current waveform more tend to be good sine waveform. The harmonic suppression effect of the rotor current with compensation is 1.5%. Obviously, the effect is better after adding compensation. Choosing to balance the rotor current as the control target, the harmonic suppression effect of the rotor current is more significant than that of the stator current.

(3) After adding compensation, the control strategy of PI-R current controller based on dq coordinates system can reduce the content of the 6th and 12th harmonic currents in stator reactive power better than the traditional control strategy, making the stator reactive power waveform more and more flat. The harmonic suppression effect of the rotor current with compensation is 45.2% and the effect is better after adding compensation.

5. Conclusion

In this paper, the dynamic modeling of DFIG is carried out under the harmonic environment of power grid. Based on that, the coupling relationship between rotor voltage and current is presented, including the fundamental wave and harmonic wave. The improved control strategy of PI-R current controller based on dq coordinate system is put forward through the full compensation of coupling. In addition, the DFIG control model is established and the method and process of designing the PI-R controller parameters according to the phase margin of the open loop transfer function and the crossing frequency are presented. Theoretical analysis and simulation results show that in the harmonic environment of power grid, the improved control strategy is more effective than the traditional and the unimproved control strategy to suppress the influence of the grid harmonics considering the coupling between DFIG rotor voltage and current. Choosing to balance the rotor current as the control target, the harmonic component of rotor current is effectively controlled and the harmonic component of stator current, stator active and reactive power is restrained to a certain extent along with the suppression of rotor current harmonics at the same time.

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A. 1

NOMENCLATURE

$\mathbf{u}_1, \mathbf{u}_2$	Stator and rotor voltage vectors
$\mathbf{i}_1, \mathbf{i}_2$	Stator and rotor current vectors
$\boldsymbol{\psi}_1, \boldsymbol{\psi}_2$	Stator and rotor flux linkage vectors

$\omega_l, \omega_r, \omega_s$	Stator, rotor, and slip angular frequencies
P_1, Q_2	Stator output active and reactive powers
L_1, L_2	Stator and rotor self-inductances in dq coordinates
L_m	Mutual inductance
Subscripts	
α, β	Stationary α - and β -axis
d, q	Synchronous d - and q -axis
$l, 2$	Stator and rotor
$+, 5-, 7+$	Fundamental, fifth-order and seventh-order components
$dq, -5dq, +7dq$	Vector corresponding coordinate system
Superscripts	
$+, 5-, 7+$	Positive $(dq)^+, (dq)^{5-}, (dq)^{7+}$ reference frames

Table A.1 Simulation parameters of DFIG

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 off wind speed: 25m/s
DFIG parameters	Rated power: 1.5MVA	Rotor stator ratio: 2.5	Pole-pairs:2
	Inertia constant: 1.14s	Stator resistance: $R_1 = 0.00698\Omega$	
	Rotor resistance: $R_2 = 0.008252\Omega$	Stator leakage reactance: $X_{1\sigma} = 0.05618\Omega$	
	Rotor leakage reactance: $X_{2\sigma} = 0.036818\Omega$		
	Mutual inductance between stator and rotor: $X_m = 1.485432\Omega$		
Converter parameters	DC Bus Voltage: 1100V	Switching frequency: 2kHz	Grid side wire inductance: 2mH
	Grid side wire resistance: 0.0003 Ω	DC storage capacity: 8640 μ F	

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