

Power Decoupling Control of Open-Winding Brushless Doubly-Fed Reluctance Machine for Wind Power Generator Application

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Abstract

A novel open-winding brushless doubly-fed reluctance machine and its power decoupling control system are proposed for wind power generator application. The control winding of brushless doubly-fed reluctance generator (BDFRG) is designed as open-winding structure, and the double-end power supply cascade two-level inverter is adopted to excite the open-winding BDFRG. This topology structure has better performance and fault redundancy capability, more flexible control modes, lower switching frequency and smaller inverter capacity. Moreover, for the special structure, the conventional vector control method is improved to decouple and to independently control the active and reactive power of open-winding BDFRG, in order to implement maximum power tracking. Finally, the effectiveness and feasibility of the proposed generation system is verified through the simulation study.

Keywords: *wind power generation, brushless doubly-fed reluctance generator (BDFRG), open-winding, decoupling of active and reactive power, maximum power tracking*

1. Introduction

The wind power generation technology has been being rapidly developed with the exploitation and utilization of clean and renewable wind energy recently. Brushless doubly-fed reluctance generator (BDFRG) is very suitable for wind power generation application due to its high reliability, small inverter capacity, easiness to implement variable speed constant frequency (VSCF), and so on [1-3]. However, the complicated internal electromagnetic relation of BDFRG with the two different-poles stator windings makes control difficult.

The maximum power tracking control is one of the core problems in the field of the VSCF brushless doubly-fed wind power generation. In most cases, the field-oriented vector control technology is adopted to decouple and to further independently control the active and reactive power of BDFRG, in order to implement maximum power tracking [4-7]. A novel power control scheme is designed using vector transformation control technology based on the rotor speed d - q coordinate model in literature [8], and the active power P and reactive power Q of the power winding are regarded as the control objectives and then can be independently controlled by decoupling. This power control scheme is studied based on the dual synchronous coordinate model in literature [9-10]. The power winding field-oriented control method is presented based on the stator synchronous speed MT coordinate model [11-12]. The above vector control methods are all applicable to the maximum power tracking control of conventional brushless doubly-fed generator.

In order to enable the brushless doubly-fed wind power generation system to have more flexible control mode, better operation performance and fault redundancy capability, a novel BDFRG with open-winding structure and its vector control system

are proposed. The control winding of BDFRG is design as open-winding structure, and the inverter structure of control winding side is modified to the double-end power supply cascade two-level inverter. This topology structure has lower switching frequency and smaller inverter capacity than the conventional three-phase voltage source inverter. For the special structure, the conventional vector control method is improved to implement the maximum power tracking control of open-winding BDFRG.

2. Novel Open-winding BDFRG System

The structural diagram of the novel open-winding BDFRG wind power system is shown as Figure 1. There are two sets of three-phase symmetrical windings with different pole numbers on the stator of BDFRG, which are respectively called as power winding used for generation and control winding used for excitation. The control winding of BDFRG is designed as open-winding structure, that is, the control winding of BDFRG is completely opened and the six terminals are all drawn out. The two ends of control winding are respectively connected to two two-level inverters and the single DC power is adopted to supply, which forms a cascade topology structure. This topology structure is used to be equivalent to a three-level inverter directly connected to the control winding, but can solve the unbalanced-voltage-division problem of DC capacitor existing in the three-level inverter, which enables the brushless doubly-fed wind power generation system to have more flexible control mode, better operation performance and fault redundancy capability.

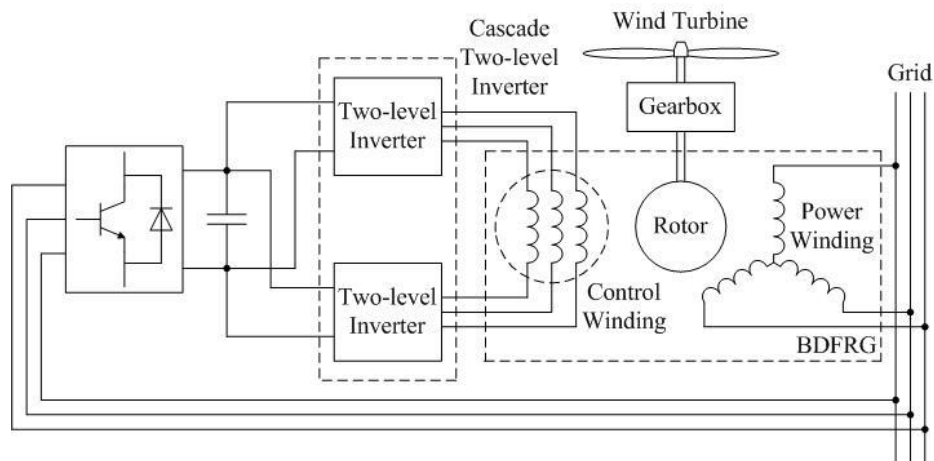


Figure 1. Structural Diagram of Novel Open-winding BDFRG Wind Power System

3. Open-winding BDFRG Modeling

The open-winding BDFRG whose reluctance rotor has no winding is similar to the doubly-fed induction generator (DFIG) from the view of power control. The power winding of open-winding BDFRG is equivalent to the stator winding of DFIG, and the control winding is equivalent to the rotor winding of DFIG. One of the main differences between the two generators is that the two winding magnetic field speeds of open-winding BDFRG are different while the two speeds of DFIG are same, which makes the open-winding BDFRG modeling more difficult.

The reference coordinates are selected shown as Figure 2 at first, where $a_p-b_p-c_p$ is the three-phase static coordinate, $a_c-b_c-c_c$ is the three-phase rotating coordinate and the $a_c-b_c-c_c$ coordinate speed $\omega = 2\pi(f_p - f_c)$. The power winding is established on $a_p-b_p-c_p$ coordinate and the control winding is established on $a_c-b_c-c_c$ coordinate. Then

the magnetic field speeds ω_p and ω_c of power winding and control winding are respectively

$$\begin{cases} \omega_p = 2\pi f_p \\ \omega_c = \omega + 2\pi f_c = 2\pi f_p \end{cases} \quad (1)$$

It can be seen from equation (1) that the magnetic fields of power winding and control winding rotate at the same speed in the reference coordinates when the current frequencies of power winding and control winding are respectively f_p and f_c . Therefore, each vector of power winding and control winding is relatively static in the space through the above coordinates processing, which lays a foundation for the vector control method of DFIG introduced into the open-winding BDFRG control system.

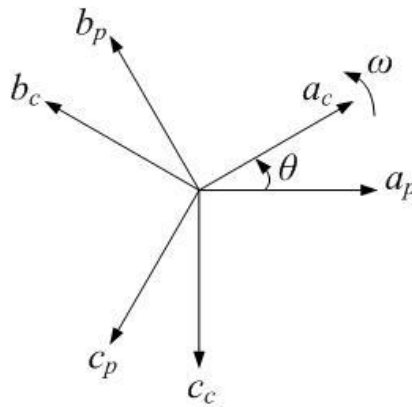


Figure 2. Reference Coordinates

The voltage equation of open-winding BDFRG is

$$\begin{cases} u_{pk} = R_p i_{pk} + \frac{d\psi_{pk}}{dt}, (k = A, B, C) \\ u_{ck} = R_c i_{ck} + \frac{d\psi_{ck}}{dt}, (k = A, B, C) \end{cases} \quad (2)$$

Where u_{pk} , i_{pk} , ψ_{pk} and R_p are respectively the phase voltage, phase current, flux and resistance of power winding, and u_{ck} , i_{ck} , ψ_{ck} and R_c are respectively the phase voltage, phase current, flux and resistance of control winding.

The flux equation is

$$\begin{bmatrix} \psi_{pA} \\ \psi_{pB} \\ \psi_{pC} \\ \psi_{cA} \\ \psi_{cB} \\ \psi_{cC} \end{bmatrix} = \begin{bmatrix} L_{pA} & M_{pAB} & M_{pAC} & M_{pAcA} & M_{pAcB} & M_{pAcC} \\ M_{pBA} & L_{pB} & M_{pBC} & M_{pBcA} & M_{pBcB} & M_{pBcC} \\ M_{pCA} & M_{pCB} & L_{pC} & M_{pCmA} & M_{pCmB} & M_{pCmC} \\ M_{cApA} & M_{cApB} & M_{cApC} & L_{cA} & M_{cAB} & M_{cAC} \\ M_{cBpA} & M_{cBpB} & M_{cBpC} & M_{cBA} & L_{cB} & M_{cBC} \\ M_{cCpA} & M_{cCpB} & M_{cCpC} & M_{cCA} & M_{cCB} & L_{cC} \end{bmatrix} \begin{bmatrix} i_{pA} \\ i_{pB} \\ i_{pC} \\ i_{cA} \\ i_{cB} \\ i_{cC} \end{bmatrix} \quad (3)$$

Where i , ψ , L and M respectively denote the current, flux, self-inductance and mutual-inductance, the subscript p and c respectively denote the power winding and control winding, and the subscript A , B and C respectively denote ABC three-phase winding.

The power winding and control winding of open-winding BDFRG are both three-phase symmetrical windings, so each-phase self-inductances and phase-to-phase mutual inductances are respectively equal. Then equation (3) can be rewritten as

$$\begin{bmatrix} \Psi_p \\ \Psi_c \end{bmatrix} = \begin{bmatrix} L_{pp} & M_{pc} \\ M_{cp} & L_{cc} \end{bmatrix} \begin{bmatrix} I_p \\ I_c \end{bmatrix} \quad (4)$$

Where

$$\Psi_p = [\psi_{pA} \quad \psi_{pB} \quad \psi_{pC}]^T,$$

$$\Psi_c = [\psi_{cA} \quad \psi_{cB} \quad \psi_{cC}]^T,$$

$$I_p = [i_{pA} \quad i_{pB} \quad i_{pC}]^T,$$

$$I_c = [i_{cA} \quad i_{cB} \quad i_{cC}]^T,$$

$$L_{pp} = \begin{bmatrix} L_{pm} + L_{p\sigma} & -\frac{1}{2}L_{pm} & -\frac{1}{2}L_{pm} \\ -\frac{1}{2}L_{pm} & L_{pm} + L_{p\sigma} & -\frac{1}{2}L_{pm} \\ -\frac{1}{2}L_{pm} & -\frac{1}{2}L_{pm} & L_{pm} + L_{p\sigma} \end{bmatrix},$$

$$L_{cc} = \begin{bmatrix} L_{cm} + L_{c\sigma} & -\frac{1}{2}L_{cm} & -\frac{1}{2}L_{cm} \\ -\frac{1}{2}L_{cm} & L_{cm} + L_{c\sigma} & -\frac{1}{2}L_{cm} \\ -\frac{1}{2}L_{cm} & -\frac{1}{2}L_{cm} & L_{cm} + L_{c\sigma} \end{bmatrix},$$

$$M_{pc} = M_{cp}^T = \begin{bmatrix} M_{pcm} \cos \theta & M_{pcm} \cos \left(\theta + \frac{2}{3}\pi \right) & M_{pcm} \cos \left(\theta - \frac{2}{3}\pi \right) \\ M_{pcm} \cos \left(\theta - \frac{2}{3}\pi \right) & M_{pcm} \cos \theta & M_{pcm} \cos \left(\theta + \frac{2}{3}\pi \right) \\ M_{pcm} \cos \left(\theta + \frac{2}{3}\pi \right) & M_{pcm} \cos \left(\theta - \frac{2}{3}\pi \right) & M_{pcm} \cos \theta \end{bmatrix}$$

Where L_{pm} and L_{cm} are respectively the phase-to-phase mutual inductance maximums of power winding and control winding, $L_{p\sigma}$ and $L_{c\sigma}$ are respectively the phase-to-phase leakage inductance maximums of power winding and control winding, M_{pcm} is the mutual inductance maximums between power winding and control winding, and θ is the spatial angular displacement between a_c -axis and a_p -axis in the reference coordinates.

The voltage equation and flux equation are respectively transformed from the three-phase static coordinate and three-phase rotating coordinate into the two-phase rotating coordinate as follows:

$$\begin{bmatrix} u_{pd} \\ u_{pq} \\ u_{cd} \\ u_{cq} \end{bmatrix} = \begin{bmatrix} R_p + L_p p & -\omega_p L_p & L_m p & -\omega_p L_m \\ \omega_p L_p & R_p + L_p p & \omega_p L_m & L_m p \\ L_m p & -\omega_c L_m & R_c + L_c p & -\omega_c L_c \\ \omega_c L_m & L_m p & \omega_c L_c & R_c + L_c p \end{bmatrix} \begin{bmatrix} i_{pd} \\ i_{pq} \\ i_{cd} \\ i_{cq} \end{bmatrix} \quad (5)$$

$$\begin{bmatrix} \psi_{pd} \\ \psi_{pq} \\ \psi_{cd} \\ \psi_{cq} \end{bmatrix} = \begin{bmatrix} L_p & 0 & L_m & 0 \\ 0 & L_p & 0 & L_m \\ L_m & 0 & L_c & 0 \\ 0 & L_m & 0 & L_c \end{bmatrix} \begin{bmatrix} i_{pd} \\ i_{pq} \\ i_{cd} \\ i_{cq} \end{bmatrix} \quad (6)$$

Where p denotes the differential operator, the subscript d and q respectively denote the d -axis and q -axis components in the two-phase rotating coordinate, L_p and L_c are respectively the equivalent self-inductance of power winding and control

winding in the two-phase rotating coordinate, L_m is the mutual-inductance between the coaxial equivalent windings of power winding and control winding in the two-phase rotating coordinate, and $L_m = 1.5M_{pcm}$, $L_p = L_m + L_{p\sigma}$, and $L_c = L_m + L_{c\sigma}$.

It can be seen from the above analysis that the mathematical model mode of open-winding BDFRG is similar to the one of DFIG. Therefore, the vector control idea of DFIG can be introduced to decouple and to further independently control the active and reactive power of open-winding BDFRG, in order to implement maximum power tracking.

4. Vector Control of Open-winding BDFRG

For the large-power grid-connected open-winding BDFRG, its power winding is connected to the grid, so the amplitude and frequency of the power winding voltage are both constant and are easily measured. The power winding resistance R_p can be neglected, the voltage space vector of power winding is oriented on q -axis, and then

$$\begin{bmatrix} \psi_{pd} \\ \psi_{pq} \end{bmatrix} = \begin{bmatrix} \frac{u_{pq}}{\omega_p} \\ 0 \end{bmatrix} = \begin{bmatrix} \frac{\sqrt{3}U_p}{\omega_p} \\ 0 \end{bmatrix} \quad (7)$$

The active power P and reactive power Q of open-winding BDFRG are respectively

$$\begin{cases} P = \sqrt{3}U_p i_{pq} \\ Q = \sqrt{3}U_p i_{pd} \end{cases} \quad (8)$$

The d -axis and q -axis components i_{pd} and i_{pq} of power winding current are derived from equations (6) and (7) as follows.

$$\begin{cases} i_{pd} = \frac{\sqrt{3}U_p}{\omega_p L_p} - \frac{L_m}{L_p} i_{cd} \\ i_{pq} = -\frac{L_m}{L_p} i_{cq} \end{cases} \quad (9)$$

Substitute (9) into (8), and then

$$\begin{cases} P = -\frac{\sqrt{3}U_p L_m}{L_p} i_{cq} \\ Q = \frac{3U_p^2}{\omega_p L_p} - \frac{\sqrt{3}U_p L_m}{L_p} i_{cd} \end{cases} \quad (9)$$

It can be seen from equation (9) that the active power P is only related with the q -axis component i_{cq} of control winding current, and the reactive power Q is only related with the d -axis component i_{cd} of control winding current. Therefore, P and Q can be independently controlled by respectively controlling i_{cq} and i_{cd} .

Substitute (9) into (6), and then

$$\begin{cases} \psi_{cd} = \frac{\sqrt{3}L_m U_p}{\omega_p L_p} + \left(L_c - \frac{L_m^2}{L_p} \right) i_{cd} \\ \psi_{cq} = \left(L_c - \frac{L_m^2}{L_p} \right) i_{cq} \end{cases} \quad (10)$$

The d -axis and q -axis components u_{cd} and u_{cq} of control winding voltage are derived from equations (5) and (6) as follows.

$$\begin{cases} u_{cd} = R_c i_{cd} + p\psi_{cd} - \omega_c \psi_{cq} \\ u_{cq} = R_c i_{cq} + p\psi_{cq} + \omega_c \psi_{cd} \end{cases} \quad (11)$$

Substitute (10) into (11), and then

$$\begin{cases} u_{cd} = R_c i_{cd} + \left(L_c - \frac{L_m^2}{L_p} \right) p i_{cd} - \omega_c \left(L_c - \frac{L_m^2}{L_p} \right) i_{cq} \\ u_{cq} = R_c i_{cq} + \left(L_c - \frac{L_m^2}{L_p} \right) p i_{cq} + \frac{\sqrt{3} \omega_c L_m U_p}{\omega_p L_p} + \omega_c \left(L_c - \frac{L_m^2}{L_p} \right) i_{cd} \end{cases} \quad (12)$$

The voltage components u_{cd} and u_{cq} are respectively decomposed into decoupling term and compensating term, and then equation (12) can be written as

$$\begin{cases} u_{cd} = \hat{u}_{cd} + \Delta u_{cd} \\ u_{cq} = \hat{u}_{cq} + \Delta u_{cq} \end{cases} \quad (13)$$

The decoupling terms are

$$\begin{cases} \hat{u}_{cd} = R_c i_{cd} + \left(L_c - \frac{L_m^2}{L_p} \right) p i_{cd} \\ \hat{u}_{cq} = R_c i_{cq} + \left(L_c - \frac{L_m^2}{L_p} \right) p i_{cq} \end{cases} \quad (13)$$

And the compensating terms are

$$\begin{cases} \Delta u_{cd} = -\omega_c \left(L_c - \frac{L_m^2}{L_p} \right) i_{cq} \\ \Delta u_{cq} = \frac{\sqrt{3} \omega_c L_m U_p}{\omega_p L_p} + \omega_c \left(L_c - \frac{L_m^2}{L_p} \right) i_{cd} \end{cases} \quad (14)$$

According to the vector control idea and above analysis, the principle diagram of open-winding BDFRG vector control system is given as Figure 3.

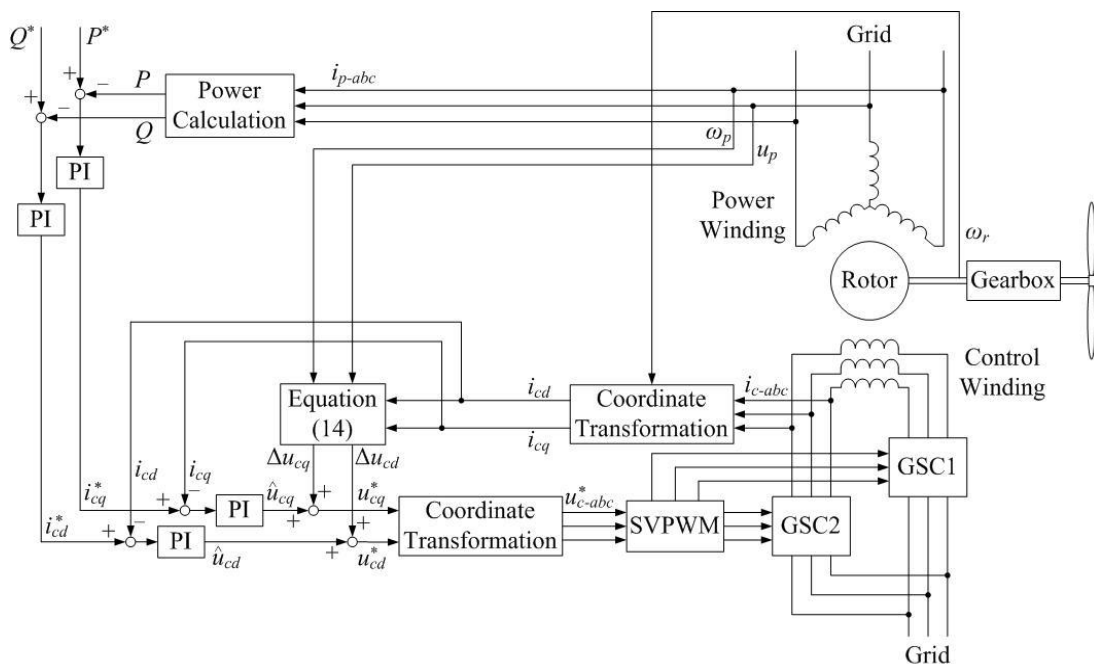


Figure 3. Principle Diagram of Open-winding BDFRG Vector Control System

5. Simulation Results

The simulation model of grid-connected open-winding BDFRG vector control system is established based on its principle diagram shown as Figure 3. The parameters of open-winding BDFRG prototype and wind turbine are respectively given as Table 1 and Table 2.

Table 1. Parameters of Open-winding BDFRG Prototype

Parameter	Value
Nominal power (kW)	1500
Nominal voltage (V)	690
Pole-pairs number of power winding	3
Pole-pairs number of control winding	1
Resistance of power winding (Ω)	0.007
Resistance of control winding (Ω)	0.005
Self-inductance of power winding (H)	0.171
Self-inductance of control winding (H)	0.156
Mutual-inductance between the two stator windings (H)	2.9

Table 2. Parameters of Wind Turbine

Parameter	Value
Nominal power (kW)	1500
Maximum power coefficient	0.5
Optimum tip-speed ratio	9
Radius (m)	30
Transformation ratio of gearbox	3.75

The initial wind speed is set at 7m/s, and then the wind speed steps up to 11m/s as $t = 5$ s and steps down to 9m/s as $t = 9$ s. The power winding and control winding current waveforms of open-winding BDFRG are respectively shown as Figure 4 and Figure 5. It can be seen from Figure 4 and Figure 5 that with the change of wind speed, the control winding current frequency of open-winding BDFRG can rapidly change to ensure the output current frequency of power winding to be 50Hz constantly, and the output current amplitude of power winding is changing.

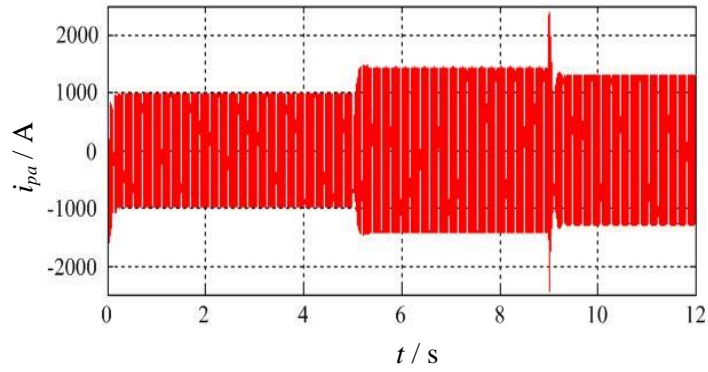


Figure 4. Current Waveform of Power Winding

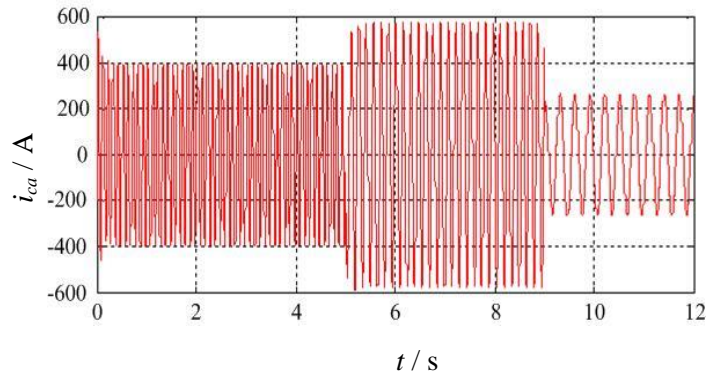


Figure 5. Current Waveform of Control Winding

The active and reactive power waveforms of open-winding BDFRG are shown as Fig.6. It can be seen from Fig.6 that with the change of wind speed, the active power of open-winding BDFRG can rapidly track the maximum power point and the response time is shorter, and the reactive power is close to zero in the process of simulation. The active and reactive power of open-winding BDFRG can be successfully decoupled and independently controlled using the proposed vector control method.

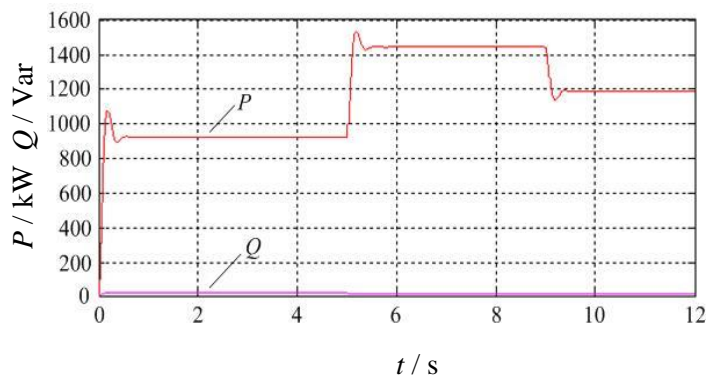


Figure 6. Active and Reactive Power Waveforms

6. Conclusion

A brushless doubly-fed reluctance wind power generator with open-winding structure and its power decoupling control system are proposed, and the double-end power supply cascade two-level inverter is adopted to excite the open-winding BDFRG in this paper.

This topology structure can effectively improve the performance and fault redundancy capability of brushless doubly-fed wind power generation system and can enable control modes more flexible, and has lower switching frequency and less converter capacity than the conventional three-phase voltage source inverter. Moreover, the conventional vector control method is improved to decouple and to independently control the active and reactive power of open-winding BDFRG, in order to implement maximum power tracking. The simulation results show that the output active power of open-winding BDFRG can rapidly track the maximum power point and the response time is shorter, which verifies that the active and reactive power of open-winding BDFRG can be well decoupled and independently controlled, and the maximum power tracking control can be implemented using the proposed vector control method.

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