Research of Visual Synchronous Technology Based Control Method for PMSG Wind Power System

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Abstract—Commissioned for wind power system there are two main types of generators, one is doubly fed induction generator (DFIG), the other is permanent magnetic synchronous generator (PMSG). Compared to DFIG unit, PMSG wind power system is more economical for manufacturing and maintenance. With the higher penetration rate of wind power generation in the grid, the need for the renewable power units to provide active frequency support yields relevant control characteristics in their power converters, for which the visual synchronous generator control exhibits promising features. This paper proposes a visual synchronous technology based PMSG wind power system. The simulation results verified the effectiveness of this proposed controller.

1. Introduction

Frequency is an important index of the quality of power supply. If the fluctuation of the frequency exceeds the given limitation, the output power of the generator will fluctuate or even be cut off from the grid, and in the worst case will result in collapse of the power system. Because the inertia of rotor of the traditional synchronous generator is very big, and because that the input mechanical torque can be adjusted along with the changes of load, thus the frequency of this kind of generator can be stabilized within the given limitation automatically. Converters of the wind power system can decouple the relationship between the velocity of the wind turbine and the frequency of the power grid\cite{1}. Consequently, the rotor of the wind turbine is not able to support frequency for the system and the inertia of the wind power system is decreased. At the same time, the maximum power point tracking (MPPT)\cite{2} method is adopted to utilize the wind power, and there’s no reserved active power can be used to support the frequency, so the ability of the frequency regulation of the system is decreased either\cite{3, 4}. Recently, as the proportion of the wind power in the power system is increasing, the stability of the power grid will be decreased.

The magnetic field in PMSG is built by the permanent magnet in the rotor, and there’s no excitation coils in the rotor. The rotor of PMSM can simplify the structure of the generator, and decrease the cost of the maintenance. Compared with DFIG, PMSG is more effective and can obtain unit or even leading ahead power factor.
2. Structure of the PMSG system
The typical structure of the direct drive PMSG wind power system is shown in Fig. 1. The wind turbine absorbs the wind energy, drives the rotor of the turbine. Then the emf is produced in the stator winding by cutting the rotating flux of the rotor, and thus the kinetic energy in the wind is transformed into electrical energy. The electro-magnetic power is transported from the machine side converter to the grid side converter. The voltage and the frequency can be adjusted by the controller of the grid side converter and the active power can be transported to power grid.

Fig. 1 Structure of the PMSG wind power system

3. Equations of PMSG

3.1. Voltage equation
The mathematic model of PMSG under three phases static coordination is difficult to analyze and solve. The rotor oriented rotating dq coordination is adopted in this paper. The direction of the permanent magnet of the rotor is the d axis. The q axis leads 90 degrees ahead of the d axis. The voltage equations of PMSG under the dq coordination are shown below:

\[
\begin{align*}
    u_d &= R_i i_d + \frac{d\psi_d}{dt} - \omega_r \psi_q \\
    u_q &= R_i i_q + \frac{d\psi_q}{dt} - \omega_r \psi_d
\end{align*}
\]

(1)

Where: \(u_d\) and \(u_q\) is respectively the d and q axis components of the three phases voltage \(u_a\), \(u_b\), and \(u_c\). \(i_d\), \(i_q\) is respectively the d, q axis components of the three phases current \(i_a\), \(i_b\) and \(i_c\). \(R_i\) is the equivalent resistance of the stator winding. \(\omega_r\) is the angular velocity of the rotor. \(\psi_d\) and \(\psi_q\) is respectively the d and q axis component of flux linkage of the stator. And there is:

\[
\begin{align*}
    \psi_d &= L_d i_d + \psi_f \\
    \psi_q &= L_q i_q
\end{align*}
\]

(2)

Where, \(L_d\) and \(L_q\) is respectively the equivalent inductance of the d and q axis of the stator. \(\psi_f\) is the flux linkage of the rotor. The equations (3) can be obtained from the equation (1) and (2):

\[
\begin{align*}
    u_d &= R_i i_d + L_d \frac{di_d}{dt} - \omega_r L_q i_q \\
    u_q &= R_i i_q + L_q \frac{di_q}{dt} + \omega_r L_d i_d + \omega_r \psi_f
\end{align*}
\]

(3)

3.2. Dynamic equations
If the PMSG and the wind turbine is seen as a whole structure, the dynamic equation of it is:

\[
J \ddot{\theta} = T_m - T_c - D_p \dot{\theta}
\]

(4)
Where \( J \) is the whole rotating inertia of all the rotating components, \( D_p \) is the damping coefficient, \( T_m \) is the mechanic torque of the wind turbine axis to drive the rotor to rotate, \( T_e \) is the electromagnetic torque, and is braking for the axis.

The formula for \( T_e \) is:

\[
T_e = p(\psi i_{s_q} + (L_d - L_q)i_{d}i_{s_q})
\]

(5)

Where, \( p \) is the number of the pairs of the poles on the rotor of the generator.

Because the zero current of the \( d \) axis component is adopt in the vector control of the PMSG, so the formula of \( T_e \) can be simplified to:

\[
T_e = \frac{3}{2} p\psi i_{s_q}
\]

(6)

4. Virtual synchronous machine

The MPPT control is adopted in the existing converter of wind power system, and the current controlling converter is used to output electrical energy to the power grid. Only if this sort of energy occupies a small proportion of the capacity of the power grid, all the random fluctuation in the wind power can be compensated by the control of the traditional generators. But when the proportion of wind power in the grid exceeds a certain amount, the stability of the MPPT control will be disturbed largely. The wind power should be output to the power grid with the form of the voltage source, namely, the same way as the traditional generators. To build model for the dynamic characteristics of the wind power system, and to use this model to simulate the running status of a synchronous generator, this control method is named as visual synchronous generator (VSG).

The VSG is made up of the converters and controllers, and sometimes with energy storage unit. The converters itself are the same with the traditional converters. If put the rotor dynamics and the electro-magnetic equations into the design principle of the controller, the converter can act as the voltage source which can control the power angle and the value of the voltage. And the active power can be adjusted by controlling the phase angle of the voltage. The controller is the running program and is used to control the active and reactive power which is output to the power grid.

The power converter used in the PMSG wind power system is the full power converter. The converter is the back to back frequency transforming system, which is made up of two groups of power electronics elements and is linked by a DC part, which is shown in Fig.1. With the operation of the controller, the active power is transformed to DC power and is transported to the DC bus. Then the power on the DC bus is transformed to AC active power by the grid side converter and is output to the power grid. When the input active power of the DC bus is bigger than the output active power to the power grid, the voltage of the DC bus will rise, and vice versa, the DC voltage will drop. That means, the change of the output power of the generator can be shown by the change of the DC voltage. And by monitoring the fluctuation of the voltage of the DC bus, the amount of the output active current can be obtained. That is, if the voltage of the DC bus can be kept to constant, the input and output power can be kept in balance. There are two parameters of the grid side converter should be adjusted: one is the modulation ratio which can affect value of the voltage, the other is the frequency which can affect the active power.

4.1. Machine side converter

It can be seen from formula (3), the \( d \) and \( q \) components of the stator current have relationship with the \( d \) and \( q \) components of the stator voltage, the coupling voltage \(-\omega L_q i_{d_q}, \omega L_d i_q\) and \(\omega \psi_f\). By regulating the \( d \) and \( q \) current of the stator by the closed loop PI regulator, accompany with the formula (3), the control law can be obtained:
\[
\begin{align*}
\begin{cases}
u_d &= R_i i_d + k_p \frac{t_s + 1}{t_s} (i_d^* - i_d) - \omega L_s i_q \\
u_q &= R_i i_q + k_p \frac{t_s + 1}{t_s} (i_q^* - i_q) + \omega L_s i_d + \omega \psi_f
\end{cases}
\end{align*}
\] (7)

Where, \( k_p \) is the proportion parameter of the PI regulator, and \( t_s \) is the time constant of the PI regulator.

The set power can be obtained based on the MPPT control law. And the instruction of the \( d \), \( q \) current is:

\[
\begin{align*}
i_{sd}^* &= 0 \\
i_{sq}^* &= \frac{2 P_{ref}}{3 \omega n \psi_f}
\end{align*}
\] (8)

Where, \( P_{ref} \) is the reference power, \( n_1 \) is the synchronous speed of the generator, \( \omega_n \) is the angular frequency of the stator, \( \psi_f \) is the flux linkage of the rotor, and it is constant for PMSG. The controller structure of the machine side converter is shown in Fig 2.

In the control law which is described in formula (7), normally is set \( i_{sd} = 0 \). When the line voltage of the stator of generator exceeds the permitted limitation, the voltage can be kept stable by regulating \( i_{sd} \). So the electro-magnetic torque and the active power of the PMSG only can be affected by \( i_{sq} \). And even if \( i_{sd} \) is regulated, the active power can be kept constant.

The field orientation of rotor is adopted in the control system in Fig.2. Based on the tested speed of the rotor field, the rotor angle \( \theta_r \) can be obtained by integrating the speed. Based on the rotor angle, the tested current of the stator in the static three phases coordination can be transformed to the current in rotating dq coordination, namely \( i_{sq} \) and \( i_{sd} \). The two components of the current are used as the feedback of the closed loop current control.

4.2.  Grid side converter

4.2.1.  Structure of the converter. The grid side converter is made up of the power section and the controller. The function of the power section is to transform DC to three phases AC power. It’s shown
in Fig.3. The structure of the controller is shown in Fig.4. It’s used to control the power electrical switch of the converter.

For PMSG, the e.m.f.(electro-magnetic force) induced in the stator is:

\[ e = \phi \omega \sin \phi \tag{9} \]

By using the PWM technology, the average value of the output voltage of the converter, \( e_a \), \( e_b \) and \( e_c \) , which is shown in Fig. 3, within one period, is the same with the result from the formula (9).

4.2.2. Controller. If the current is sinusoidal: \( i = I_s \sin \phi \). If the current of phase a is given, the current of phase b and c can be obtained easily.

The active and reactive power output from the converter is:

\[
\begin{align*}
P &= \frac{3}{2} \phi \omega I_a \cos(\theta - \phi) \\
Q &= \frac{3}{2} \phi \omega I_a \sin(\theta - \phi)
\end{align*}
\tag{10}
\]

From formula (5), the formula below can be obtained:

\[
\dot{\theta} = \frac{1}{J} (T_m - T_e - D_\theta \dot{\theta})
\tag{11}
\]

Where, input is the mechanical torque \( T_m \). It can be seen from the formula (6), the electro-magnetic torque \( T_e \) changes with the variation of \( i \) and \( \theta \). The center of the controller is constructed by formula (6), (10) and (11). It’s shown in Fig. 4.

The speed of the traditional generator is adjusted by the prime motor. The amount of the transported active power is depended on the frequency of the power grid. The generator operates under the frequency droop law. When the active load is increasing, based on formula (11), the speed of the rotor of will decrease. Then the input mechanical energy from the prime motor will increase by the automatic response of the speed control system. For example, open the steam valve wider than before. Then the new balance will be achieved.

But in the wind power system, the mechanical power on the wind turbine is not adjusted based on the demand active power of the grid automatically. The regulation law for wind system which is shown in formula (11) to regulating the rotor speed of the visual generator can be realized by the closed loop control in the controller of the grid side converter. In fact, the damping coefficient \( D_\theta \) can be seen as the frequency droop coefficient. It is defined as below:

\[
D_\theta = \frac{\Delta T}{\Delta \theta} \frac{\Delta T}{\Delta T} \frac{\Delta \theta}{\Delta T} \frac{T_{ma}}{T_{ma}} \frac{\Delta \theta}{\Delta \theta} \frac{T_{ma}}{T_{ma}} \tag{12}
\]
5. Simulation

Based on the principle of the wind power system described in this paper, the simulation model is built\cite{5,6}. The wind speed is set to 12 m/s at first and after 2 seconds, the wind speed is changed to 15 m/s. The simulation results are shown in Fig.5, 6, 7, 8.
Fig. 5 is the rotor speed of PMSG. It’s shown in the figure the speed can be kept stable when the wind speed is changed. Fig. 6 is the voltage of the DC bus. It’s shown the DC voltage is kept stable either. Fig. 7 is the AC current of the grid side current. It’s shown the value of the grid side current can vary depends on the change of the wind speed quickly. Fig 8 indicates that the frequency of the wind power system can be kept stable.

6. Conclusion

Based on the results and discussions presented above, conclusions for the proposed control principle of the PMSG-based wind power system are obtained as below:

(1) The controller of both the machine side and the grid side converters for the proposed control principle is designed. The simulation model of the wind power system is built by MATLAB SIMULINK.

(2) The effectiveness of the proposed control principle is verified by the simulation.

(3) Next research work should be focused on the enhancement of the property of the controller under different operation states.

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