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LVRT Research of PMSG Wind Turbine Using Feedback Linearization

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ABSTRACT

Analyzing the wind turbine with a direct-driven PMSG, this paper proposes a low voltage ride through scheme of PMSG wind power systems based on feedback linearization. The DC-Link voltage is controlled by the generator-side converter rather than the grid-side converter. Considering the nonlinear relationship between the DC-Link voltage and the generator rotor speed, the controller of DC-Link voltage uses a feedback linearization technology. The grid-side converter which controls the grid active power according to the maximum power point tracking adds a judgment link for the generator speed reference. The model of 2 MW PMSG wind power system was simulated by using PSCAD. The simulation result has verified the validity of the proposed control scheme.

Keywords: PMSG; DC-Link Voltage; Converter; PSCAD

1. Introduction

Among various renewable energy sources, the application of wind power generation in the world has been rapidly growing. Unlike the DFIG (double fed induction generator) wind power system, direct-drive PMSG (permanent magnet synchronous) wind power system have some advantages such as simple structure, high power generation efficiency, high precision and high operating reliability[1].

Because of the growing proportion of the wind field, the grid-connected conditions of wind power generator are more and more important. In recent years, many countries in the world have promulgated special interconnection rules and processes for large-scale wind power units through a grid code [2,3].

Scholars at home and abroad have proposed a large number of schemes for the LVRT (low voltage ride through) capability of the DFIG wind turbines [4-7],but researches on direct-drive PMSG is very limited. Reference [8] increased the speed of the generator and reduced the converter input power in order to realize the LVRT, but the improving level is very limited and the DC-Link voltage may exceed the limit. In [9] and [10], Crowbar circuit absorbed the unbalanced power in the power grid fault, however, in this way, the unbalanced power would be completely waste, which needing the support of load

and heat dissipation. The STATCOM can be used to supply the reactive power compensation for wind power turbines in the power grid fault [11], however, when the fault occurs and ends, the cut-in and cut-out of the STATCOM make the control more complex, and investment cost is also great.

For PMSG wind power system with back-to-back PWM converters, in the conventional control method [12], the generator rotor speed is controlled by the generator-side converter, and the grid-side converter control the DC-Link voltage. Considering the nonlinear relationship between the DC-Link voltage and the generator rotor speed, this paper proposes an improved control method of the power conversion. The DC-Link voltage is maintained within regular range by the generator-side converter which introduces feedback linearization control technology. The generator speed reference ω^* is output by the grid-side converter for the maximum power point tracking, and the ultimate value ω_w^* is got after comparative judgment with ω^*.

2. Mathematical Model of PMSG Wind Power Sysrem

According to the aerodynamics，the simplified mathematical model of wind turbine is formulated as[13]:

$$\begin{cases} P_w = \dfrac{1}{2}\rho\pi R^2 v^3 C_p(\theta,\lambda) \\ \lambda = \omega_w R / v \end{cases} \quad (1)$$

where P_w is the extracted wind power, ρ the air density, v the wind speed, R the rotor radius, ω_w the wind turbine speed, C_p the efficiency coefficient.

In the synchronous d-q coordinates, the mathematical model of PMSG are[14]:

$$\begin{cases} u_{sd} = R_s i_{sd} + L_d \dfrac{di_{sd}}{dt} - L_q \omega i_{sq} \\ u_{sq} = R_s i_{sq} + L_q \dfrac{di_{sq}}{dt} + L_d \omega i_{sd} + \omega\psi \end{cases} \quad (2)$$

where u_{sd} and u_{sq} are the d-q stator voltage, i_{sq} and i_{sq} the d-q stator currents, R_s and L_s are stator resistance and inductance, ω the generator speed, ψ magnet flux.

Using the control strategy of $i_d = 0$, the generator electromagnetic torque is:

$$T_e = \frac{3}{2} p_n \psi i_{sq} \quad (3)$$

where p_n is the number of pole pairs.

Neglecting the loss of converter and generator, the generator power and the DC-Link capacitor C are:

$$P_g = P_w - J\omega_w \frac{d\omega_w}{dt} \quad (4)$$

$$P_c = u_{dc} C \frac{du_{dc}}{dt} = P_g - P_{grid} \quad (5)$$

where P_g is the generator power, u_{dc} the DC-Link voltage, P_{grid} the gird power.

Combining Equations (4) and (5), a dynamic equation can be introduced:

$$u_{dc} C \frac{du_{dc}}{dt} = \frac{1}{2}\rho\pi R^5 C_p \frac{1}{\lambda^3}\omega_w^3 - J\omega_w \frac{d\omega_w}{dt} - P_{grid} \quad (6)$$

In the above Equation (6), the nonlinear relationship between u_{dc} and ω_w can be shown.

3. Control Strategy
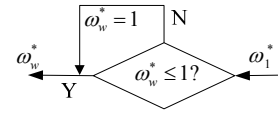
3.1. Control Scheme of the Grid-side PWM Converter

When the wind turbine power P is less than the rated power, the rotor speed reference $\omega_w{}^*$ can be expressed as follows by P[15]:

$$\omega_w^* = -0.67P^2 + 1.42P + 0.51 \quad (7)$$

According to Equation (7) for the MPPT, the rotor speed reference $\omega_w{}^*$ can be got.

As shown in **Figure 1**, when the rotor speed is greater than 1p.u, $\omega_w{}^*$ is set to 1 in order to make the generation system can according to the active power demand of the gird-side ensure that the generator rotor work in the best reference.

The control block diagram of the grid-side PWM converter is shown in **Figure 2**.

Figure 1.Control block diagram of the grid-side PWM converter.
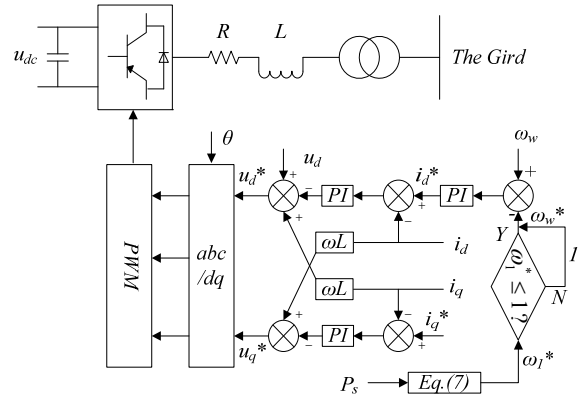
Figure 2.Control block diagram of the grid-side PWM converter.

3.2. Control Scheme of the Generator-side PWM Converter

The state equations of a single input and single output system can be represented as follows:

$$\begin{cases} \dot{x} = f(x) + g(x)u \\ y = h(x) \end{cases} \quad (8)$$

Where x is the state vector, u the control input, y the output, h the smooth scalar function, f and g are the n dimensional smooth vector field.

The nonlinear Equations (4) (5) can be written in the state equations as follows:

$$\begin{bmatrix} \dot{u}_{dc} \\ \dot{\omega}_w \end{bmatrix} = \begin{bmatrix} -\dfrac{1}{u_{dc}C}P_{grid} \\ \dfrac{1}{J\omega_w}P_w \end{bmatrix} + \begin{bmatrix} \dfrac{1}{u_{dc}C} \\ -\dfrac{1}{J\omega_w} \end{bmatrix} P_g \quad (9)$$

For the system design methodology, the DC-Link voltage is used as the control input. In order to realize the linear process, the output y is for the difference.

$$\dot{y} = \Delta h(f + g \cdot u) = L_f h(x) + L_g h(x) \cdot u \quad (10)$$

where $L_f h(x)$ is the first order Lie derivatives of $h(x)$ along f, $L_g h(x)$ along g. Here, the first order Lie derivatives is defined as follows:

$$L_f h = \Delta h f = \frac{\partial h}{\partial x} \cdot f$$

$$L_g h = \Delta h g = \frac{\partial g}{\partial x} \cdot f \quad (11)$$

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Without loss of generality，Equation (12) is given as:

$$\begin{cases} L_g h(x) = A(x) \\ L_f h(x) = B(x) \end{cases} \quad (12)$$

Hence, Equation (13) can be derived from Equations (10) and (12).

$$\dot{y} = B(x) + A(x) \cdot u \quad (13)$$

Combining Equations (9) and (13), Equation (14) is represented as follows:

$$\begin{cases} A(x) = -\dfrac{1}{u_{dc}C} P_{grid} \\ B(x) = \dfrac{1}{u_{dc}C} \end{cases} \quad (14)$$

Feedback law can generally be written as:

$$u = \frac{1}{A(x)}\big[-B(x) + v\big] \quad (15)$$

where v is the equivalent input.

In order to eliminate and reduce the steady-state error of the system, Equation (16) can be deduced from the PI control.

$$v = \dot{y}_{ref} - k_1\left(y - y_{ref}\right) - k_2\int\left(y - y_{ref}\right)dt \quad (16)$$

where y_{ref} is the reference value, k_1 and k_2 are the adjustable gains.

The control block diagram of the nonlinear DC-Link voltage and the generator-side PWM converter is shown in **Figure 3**.

4. Simulation and Analysis

To verify the validity of the proposed algorithm, this paper simulates 2 MW PMSG wind power system based on PSCAD. Imitating the grid connection point voltage drops to 50% in 1 s -1.5 s, the proposed new method is compared with the conventional method in this paper. The system parameters are as follow.

- PMSG: Stator rated voltage 690 V, Magnetic induction 1$p.u$, Stator phase resistance 0.008 $p.u$, Direct-axis inductance X_d 0.062 $p.u$，Quadrature axis inductance X_q 1.1477 $p.u$.
- Wind Turbine: Air density 1.225 kg/m^3, Rated wind speed 10m/s.
- Converter: DC-Link voltage 1100V, Rated output voltage 690 V, Reactive power setting value 0 $Mvar$, Grid frequency 50 Hz.

The grid output power is minished along with the grid connection point voltage drops to 50%, which, at the same time, causing the generator output power reduction. The unbalanced power between the grid-side and the generator-side will cause DC-Link voltage rise to 1.3 $p.u$. The performance of DC-Link voltage u_{dc} for the conventional method is as shown in **Figure 4(b)**. However, in the new method, u_{dc} is almost constant, as shown in **Figure 5(b)**. Because of the unbalanced power, a portion of energy has stored in the wind turbine, thus, the rotor speed ω_w would enhance. But the rising is less than 0.08 $p.u$ which is within the safe range, as shown in **Figure 4(c)** and **Figure 5(c)**. With the failure to eliminate, it turns back to the normal value.

5. Conclusions

This paper proposes a low voltage ride through scheme of PMSG wind power systems based on feedback linearization. The DC-Link voltage is maintained and regulated by generator-side converter. The control scheme of the generator-side converter has been designed using
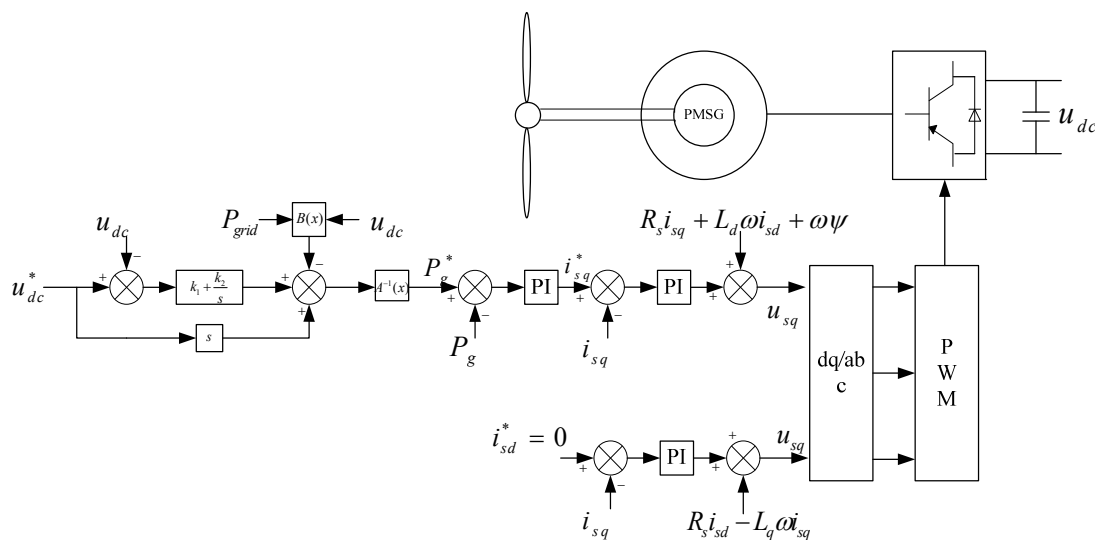

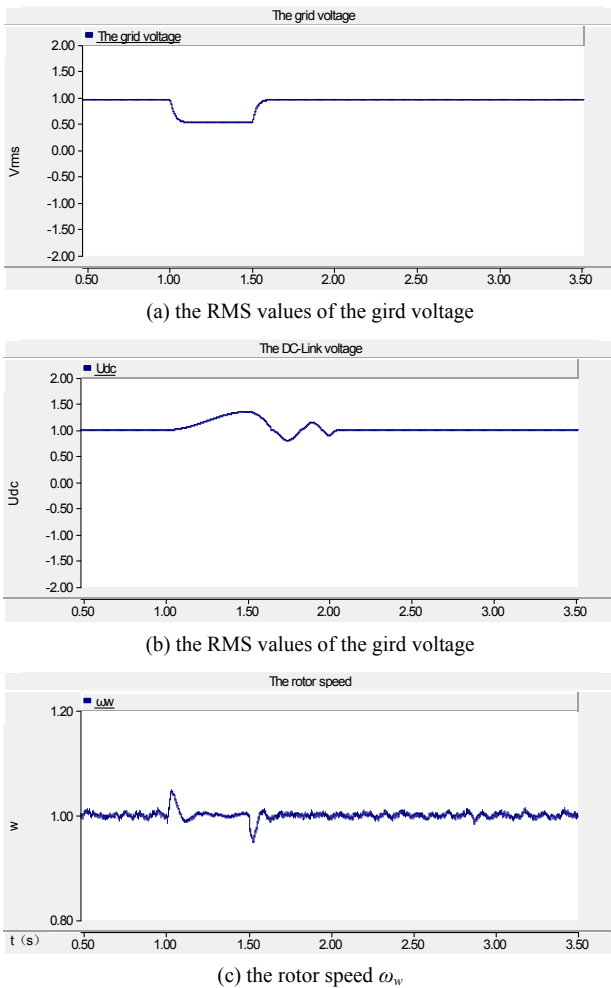**Figure 3.Control block diagram of the grid-side PWM converter.**

The grid voltage

(a) the RMS values of the gird voltage

The DC-Link voltage

(b) the RMS values of the gird voltage

The rotor speed

(c) the rotor speed ω_w

Figure 4. Simulation of the conventional method for power system fault.

The gird voltage

(a) the RMS values of the gird voltage

The DC-Link voltage

(b) the RMS values of the gird voltage

The rotor speed

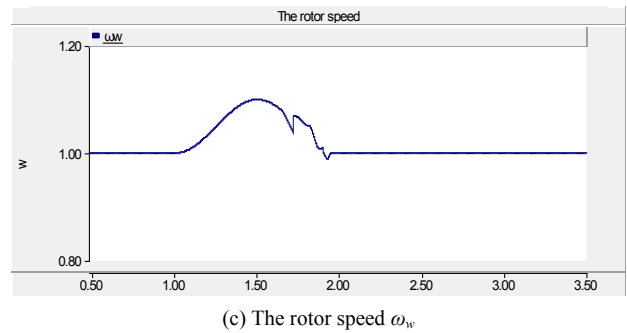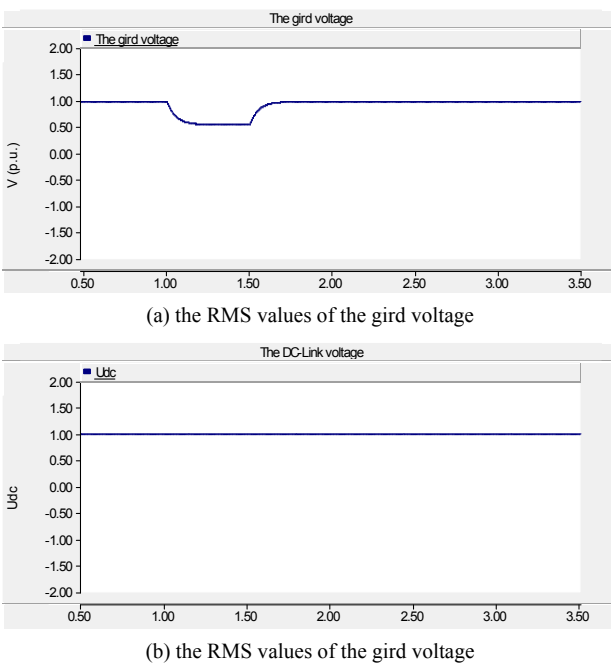(c) The rotor speed ω_w

Figure 5. Simulation of the new method for power system fault.

feedback linearization, and the grid-side converter regulates the power for MPPT. The simulation result demonstrates the validity of the method. When the grid voltage sags to 50%, the proposed algorithm can effectively decrease the rising of DC-Link voltage, and keep it almost invariable so that the LVRT capability of PMSG wind power systems is improved. Wind turbines can still run in parallel operation until return to normal operating condition during power system fault.

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