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The Grid-side PWM Converter of the Wind Power Generation System Based on Fuzzy Sliding Mode Control

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***Abstract* - With the growing rating of the wind energy generation system, capturing the maximum wind energy and improving the operation efficiency and power quality are becoming more and more important. In Variable Speed Constant Frequency (VSCF) wind energy generation system, the control and design of the grid-side converter is of great importance. This paper expatiates the principle and the mathematic model of the grid-side PWM converter, acquiring the equations of active power and reactive power controlled independently under the d-q frame of axes. The block diagram of the VSCF wind energy generation system with DFIG and the grid-side back-to-back PWM converter is established. Then the fuzzy sliding mode controller is designed suitably. The simulation results show that the grid-side PWM converter adopting fuzzy sliding mode control can adjust power factor and make the current flow flexibly, which realizes the switch between the generation state and the drag state, and the state of the grid-side PWM converter can be held to disturbance and nonlinear variety of load.**

Index Terms - VSCF, the grid-side PWM converter, the fuzzy sliding mode control, power factor, drag state

I. INTRODUCTION

Wind energy is a viable option to complement other types of pollution-free generation, the majority of wind turbines were operated at constant speed. Recently, the number of variable speed wind turbines installed in wind farms has increased and more wind turbine manufacturers are making variable speed wind turbines [1]. Since large wind turbines generally connect to the grid, which demands the frequency generated by wind turbines should be equal to the grid frequency. Variable Speed Constant Frequency is one kind of most popular model wind power generation way, adopting the grid-side PWM converter that is composed of IGBT. The current exchange between the generator rotor and the grid can be accomplished by the grid-side PWM converter. Since the grid-side converter is nonlinear and time-variable system, the traditional controller, such as the PID controller, which did not obtain perfect results [2]. Due to the randomicity and acuteness of wind, wind turbine should have good stability in spacious region [3]. Because wind turbine is a nonlinear multi-input multi-output system, the traditional controller only guarantees the desired closed loop response at the operating point for which the controller was designed. When parameters change, it is possible that the system work in the unstable region. Integrating advantages of the sliding mode control and fuzzy control, which makes that the grid-side PWM converter not only has excellent robust of sliding mode control, but also minimizes vibration. So this paper applies the fuzzy sliding mode control to adjust the active power and reactive power which generated by the large wind turbines.

II. THE STRUCTURE OF VARIABLE SPEED CONSTANT FREQUENCY WIND POWER GENERATION SYSTEM

This paper uses an usual scheme that adopts the doubly-fed induction generator (DFIG).Variable speed constant frequency wind power generation system ,which impose slip frequency voltage(or current) on the rotor, adjusting voltage amplitude, frequency and phase, realizing the constant frequency constant voltage output of stator [4]. The structure of this system is as follows:

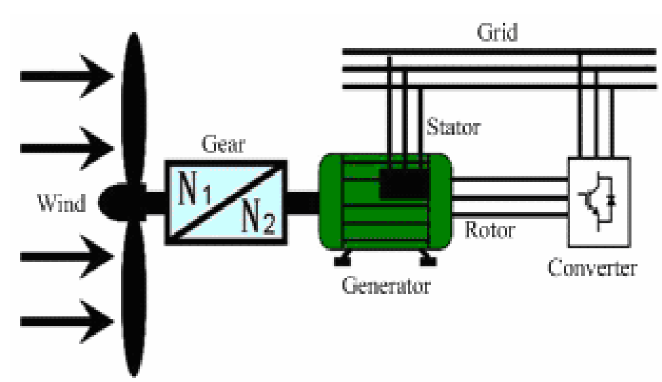

Fig. 1 The structure of variable speed constant frequency doubly-fed wind power generation system

The rotor is connected to grid by two voltage-source PWM converter with back-to-back connection. The converter contains rotor-side converter and grid-side converter, which is named dual PWM converter [5].

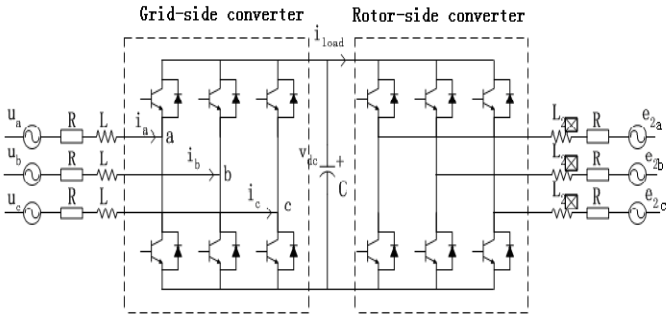

Fig. 2 The circuit structure of PWM converter

As the fig. 2 indicating, the two PWM converters of transducer have the same circuit structure, they alternate the function of rectifier and inverter under different flowing direction of rotor energy, so it can only classified into the gird-side converter and rotor-side converter for an analysis.

The rotor-side converter feeds excitation current into rotor winding and achieves stator flux oriented, catching maximum wind energy and adjusting reactive power output. When the generator speed lags behind synchronous speed, it makes energy flow into rotor, working in inverter state. When the generator speed exceeds synchronous speed, it absorbs energy from the rotor, working in rectifier state. When the generator is working at synchronous speed, it directly feed excitation current into rotor, working as a Chopper. The gird-side converter has the similar work mode, cooperating with rotor-side converter, realizing energy dual direction flowing. Besides, gird-side PWM converter also control DC generatrix voltage constant and adjust gird-side power factor, which makes entire wind power system have more flexible reactive power regulations.

III. THE CONTROL PRINCIPLE AND MATHEMATIC MODEL OF GIRD-SIDE PWM CONVERTER

Assume three phase gird voltage balance, according to the outspread structure chart of gird-side converter, u_a , u_b , u_c are gird voltage, u_{ra}, u_{rb}, u_{rc} are voltage of rotor three-phase winding, L and R are input inductance and equivalent resistance respectively. When dual PWM transducer is working in stable state, the DC voltage is constant and the three-phase bridge arm of gird-side converter is driven by sinusoidal pulse-width modulation rule. When the switch frequency is very high, according to the basic principle of pulse-width modulation, the AC-side voltage of converter contains sine fundamental wave and other high frequency harmonious voltage. Since inductance has filtering function, the current brought by high frequency harmonic voltage is very low, the input current closes to sinusoidal wave. If we only take into account the fundamental wave of voltage and current, seeing from the gird side, the gird-side converter may regard as a controllable three phase AC voltage source [6]. Its fundamental wave equivalent circuit diagram and phase A equivalent phasor diagram are shown respectively as fig. 3 and fig. 4.

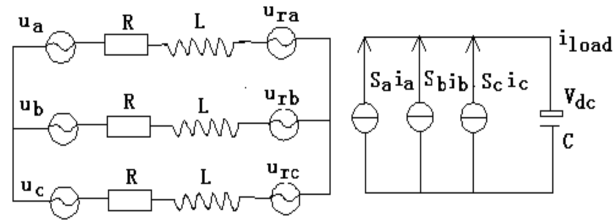

Fig. 3 The fundamental wave equivalent circuit diagram of gird-side converter

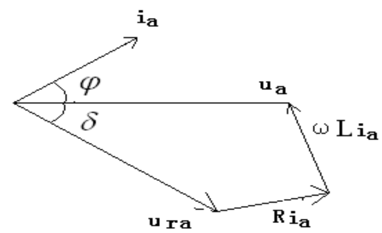

Fig. 4 Phase A equivalent phasor diagram of gird-side converter

The mathematic model of gird-side converter can be given:

$$\begin{cases} \dfrac{di_a}{dt} = -\dfrac{R}{L}\cdot i_a - \dfrac{1}{L}\left(s_a - \dfrac{s_a+s_b+s_c}{3}\right)\cdot v_{dc} + \dfrac{1}{L}u_a \\ \dfrac{di_b}{dt} = -\dfrac{R}{L}\cdot i_b - \dfrac{1}{L}\left(s_b - \dfrac{s_a+s_b+s_c}{3}\right)\cdot v_{dc} + \dfrac{1}{L}u_b \\ \dfrac{di_c}{dt} = -\dfrac{R}{L}\cdot i_c - \dfrac{1}{L}\left(s_c - \dfrac{s_a+s_b+s_c}{3}\right)\cdot v_{dc} + \dfrac{1}{L}u_c \\ \dfrac{dv_{dc}}{dt} = \dfrac{1}{C}\cdot\left(s_a i_a + s_b i_b + s_c i_c\right) - \dfrac{1}{C}\cdot i_{load} \end{cases} \tag{1}$$

Described in matrix form:

$$\begin{bmatrix} \dfrac{di_a}{dt} \\ \dfrac{di_b}{dt} \\ \dfrac{di_c}{dt} \end{bmatrix} = -\frac{R}{L}\cdot\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} - \frac{1}{L}\cdot\begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{3} \\ -\frac{1}{3} & \frac{2}{3} & -\frac{1}{3} \\ -\frac{1}{3} & -\frac{1}{3} & \frac{2}{3} \end{bmatrix}\cdot\begin{bmatrix} s_a \\ s_b \\ s_c \end{bmatrix}\cdot v_{dc} + \frac{1}{L}\cdot\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} \tag{2}$$

The static three-phase axis transform into the static two-phase axis as follow:

$$\begin{bmatrix} \dfrac{di_\alpha}{dt} \\ \dfrac{di_\beta}{dt} \\ \dfrac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} -\dfrac{R}{L} & 0 & -\dfrac{S_\alpha}{L} \\ -w & -\dfrac{R}{L} & -\dfrac{S_\beta}{L} \\ \dfrac{3S_\alpha}{2C} & \dfrac{3S_\beta}{2C} & 0 \end{bmatrix}\cdot\begin{bmatrix} i_\alpha \\ i_\beta \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \dfrac{1}{L} & 0 & 0 \\ 0 & \dfrac{1}{L} & 0 \\ 0 & 0 & -\dfrac{1}{C} \end{bmatrix}\cdot\begin{bmatrix} u_\alpha \\ u_\beta \\ i_{load} \end{bmatrix} \tag{3}$$

The mathematic model of two-phase random speed d-q axis:

$$\begin{bmatrix} \frac{di_d}{dt} \\ \frac{di_q}{dt} \\ \frac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & 0 & -\frac{S_d}{L} \\ -w & -\frac{R}{L} & -\frac{S_q}{L} \\ \frac{3S_d}{2C} & \frac{3S_q}{2C} & 0 \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} & 0 & 0 \\ 0 & \frac{1}{L} & 0 \\ 0 & 0 & -\frac{1}{C} \end{bmatrix} \cdot \begin{bmatrix} u_d \\ u_q \\ i_{load} \end{bmatrix} \tag{4}$$

In the above equations, and s_q are the switch functions. From the above equation, we can conclude:

$$\begin{cases} L\frac{di_d}{dt} = -Ri_d + wLi_q + u_d - S_d v_{dc} \\ L\frac{di_q}{dt} = -Ri_q - wLi_d + u_q - S_q v_{dc} \end{cases} \tag{5}$$

Because of the output voltage of the grid-side converter, it can be set:

$$\begin{cases} u_{rd} = S_d v_{dc} \\ u_{rq} = S_q v_{dc} \end{cases} \tag{6}$$

So equation (5) can be given:

$$\begin{cases} L\frac{di_d}{dt} = -Ri_d + \omega Li_q + u_d - u_{rd} \\ L\frac{di_q}{dt} = -Ri_q - \omega Li_d + u_q - u_{rq} \end{cases} \tag{7}$$

The current of d-axis and q-axis are effected by the control variable u_{rd} , u_{rq} , besides it is effected by the current intercross coupling ωL i_q , -ωL i_d and the grid voltage, so it is necessary to find a way to ravel the current coupling between d-axis and q-axis and to remove the voltage disturb.

Assume:

$$\begin{cases} u_{rd}' = -Ri_d + \omega Li_q + u_d \\ u_{rq}' = -Ri_q + \omega Li_d + u_q \end{cases} \tag{8}$$

Thus it can be achieved:

$$\begin{cases} L\frac{di_d}{dt} + u_{rd} = u_{rd}' \\ L\frac{di_q}{dt} + u_{rq} = u_{rq}' \end{cases} \tag{9}$$

The equations indicate that the current feedback ωL i_q , -ωL i_d can realize decoupling, meantime the gird disturb voltage can carry out forward feed compensation, so the independent control of d, q axis current can be acquired and the system dynamic performance can be improved greatly. In order to simplify control arithmetic, the axis of synchronous speed coordinate can be oriented to a gird voltage vector, in this way, the d, q axis of voltage is given:

$$\begin{cases} u_d = u_m \\ u_q = 0 \end{cases} \tag{10}$$

Where u_m is the amplitude of phase voltage.

In the d-q axis frame, relative to the gird, the active power and the reactive power of gird-side converter are given respectively:

$$\begin{cases} P = \frac{3}{2}(u_d i_d + u_q i_q) = \frac{3}{2}u_m i_d \\ Q = \frac{3}{2}(u_q i_d - u_d i_q) = -\frac{3}{2}u_m i_q \end{cases} \tag{11}$$

From the above equations, if P is greater than zero, the grid-side converter works in rectifier state, absorbing energy from the grid. If P is less than zero, the grid-side converter works in inverter state, feeding energy back to the grid. If Q is greater than zero, the grid-side converter absorbs the lagged reactive power. If Q is less than zero, the grid-side converter absorbs the leading reactive power. So i_d and i_q stand for the active power current and reactive current respectively. When AC-side input power is greater than the load power, the superfluous power can make DC-side capacitance voltage higher. In converse, the capacitance voltage may be lower. Since the d-axis current of converter is ratio to the power absorbed directly, the capacitance voltage can be controlled by using the output of the voltage modifier as the d-axis given current, it reflects the magnitude of the input current of the converter. The control structure of grid-side converter is as follows:

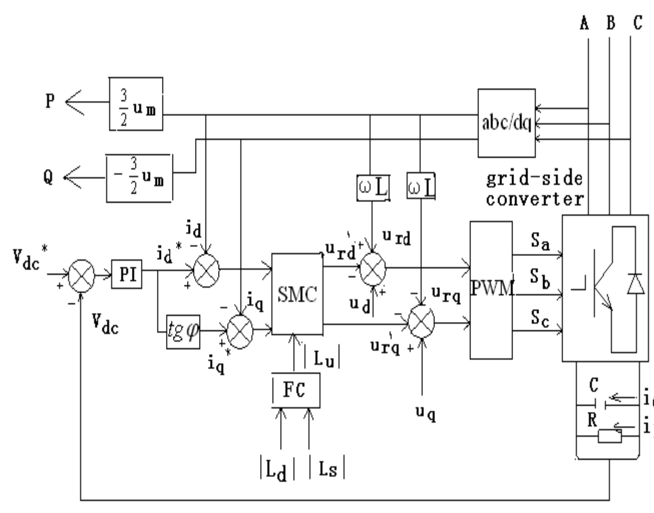

Fig. 5 Fuzzy sliding mode control of grid-side converter block diagram

According to demanded power factor and the given current i_d^* of d-axis, the given current i_q^* of q-axis can be gained. If the power factor equal to one, $tg\varphi$ will equal to zero, so i_q^* constantly equal to zero[7].

IV. THE DESIGN OF FUZZY SLIDING MODEL CONTROLLER

Fuzzy Controller (FC) together with Sliding Mode controller consist of Fuzzy Sliding Mode Controller (FSMC). Fuzzy controller is used to adjust the entire normal moving area in order to weaken shake, sliding mode controller is used to control system and its stability. In fact, the reason for the shake generated by sliding mode control is that the moving speed is too high when it near to the switch line, the finite switch strength and the switch inertia make it hard to move reversely immediately, contributing to generate shake in the to-and-fro through. This paper adopts the measure that when the system state is back to sliding mode line, increasing the control variable can make u_{fuzzy} greater, and quickening the normal moving state response speed [8-12].

When the system is close to sliding mode line, decreasing control level to avoid the system state rushing across switch line in high speed, which can make the system shake. So adjusting fuzzy control part propriety can make the entire system have celerity and decrease wobble.

Define sliding mode function:

$$s=kX_1+X_2 \tag{12}$$

Define approach rate of sliding mode state moving in the normal state:

$$\dot{s}=\varepsilon\ \text{sign(s)}(\ \varepsilon>0\ ) \tag{13}$$

Define the line that cross the origin and apeak the line of sliding mode control line(s=0) is d=0, due to the square sum of distance between state dot to d=0 and state dot to s=0. So the state dot distance line d=0 is more close to s=0 and the scope of u_{fuzzy} is smaller (ε is smaller), whereas it will be bigger. In this way, when decreasing the speed of the system state dot tending to switch surface nearby of switch line s=0 can weaken system wobble.

Design sliding mode control as follows:

$$\begin{cases} s_i=\dfrac{di}{dt}+\dfrac{v_{dc}}{L}-\dfrac{\sqrt{3}}{\sqrt{2}L}|u|\cdot u_d \\ s_v=kC(v_{dc}^*-v_{dc})+C\dfrac{dv_{dc}^*}{dt}+\dfrac{v_{dc}}{R}-(i_R+i_C) \end{cases} \tag{14}$$

Where s_i and s_v are the surface of current and voltage respectively, $|u|=\sqrt{u_d^2+u_q^2}$, k is constant.

The fuzzy control system adopts double inputs and the single output, the two input is the distance between the system state dot to the switch line s=0 to the line d=0, the inputs are L_d and L_s , the output is L_u .

According to the fuzzy rule [13]:

If L_d is LD^i and L_s is LS^j Then u_{fuzzy} is FU^k .

Where LD^i is the language variable of L_d , LS^j is the language variable of L_s , FU^k is the language variable of L_u .

Assuming the language variable LD: PB, PS,NS,NB, the language variable LS: PB,PS,PZ,NZ,NS,NB, the language variable FU: PB,PS,PZ,NZ,NS,NB, where PB is positive big, PS is positive small ,and PZ is positive zero, NZ is negative zero, NS is negative small, NB is negative big.

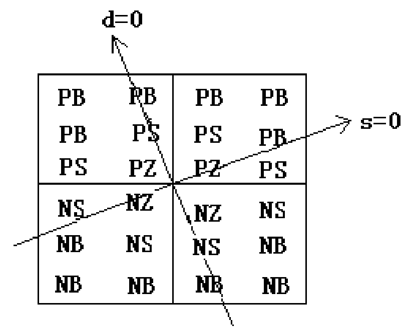

Fig. 6 Diagram of fuzzy control rule

As shown in the four symmetrical part which the plane is cut by the switch line s=0 and the line d=0, so the control scope is also symmetrical, only to choose $|L_d|$ and $|L_s|$ as the inputs of fuzzy controller, $|L_u|$ is considered as the output of fuzzy controller, in this way, the theory field of LD,LS,FU are cut half, cutting the rule 24 to 6, assuming the theory field of $|L_d|$ is X=[0,6] and the theory field of $|L_s|$ is Y=[0,8], the theory field of $|L_u|$ is Z=[0,8], the degree of membership function is triangle [14], besides the degree of membership of the intersect of curve is 0.5, then the degree of membership function of the input and output of the system are as follows:

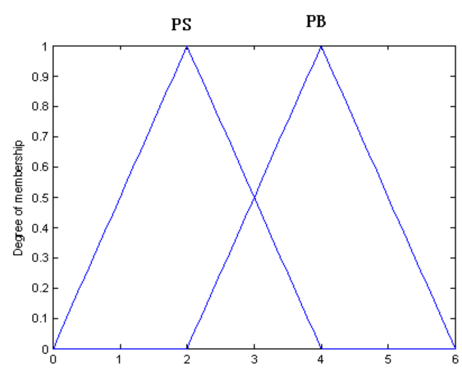

Fig. 7 Input fuzzy variable $|L_d|$

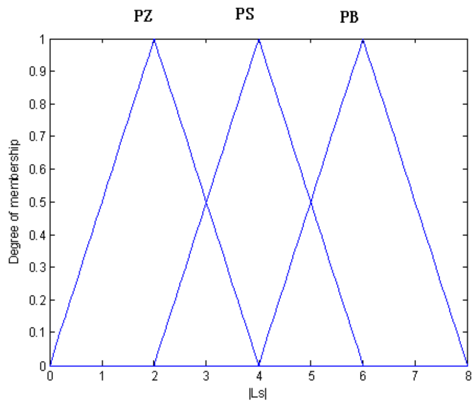

Fig. 8 Input fuzzy variable $|L_s|$

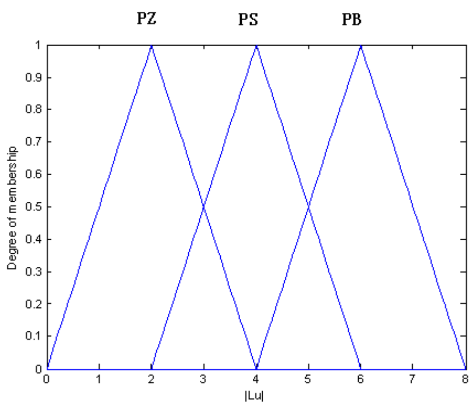

Fig. 9 Output fuzzy variable $|L_u|$

In order to get exact control variable, the output $|L_u|$ can be gained from the barycenter means [15], the results are shown in Table I:

TABLE I
VALUE OF CONTROL VARIABLE $|L_u|$

$\lvert L_s\rvert$ / $\lvert L_d\rvert$	0	1	2	3	4	5	6	7	8
0	0	2.9	0.98	3.48	4	3.58	4.48	5.15	5.11
1	0	1.52	3.76	3.48	4	4.11	4.48	5	6.67
2	0	3	3.52	3.48	4	4.12	4.48	4.19	6.67
3	0	3	3.66	4	4.12	4.12	4.48	5	6.67
4	0	3.33	4	4.33	4.48	4.48	4.48	4.67	6.67
5	0	4	4.28	4.81	5	4.67	4.67	5	6.67
6	0	5.58	4.48	5	6.67	6.44	6.44	6.6	6.67

The control variable is make up of the sliding variable u_{sm} and the fuzzy variable u_{fuzzy}:

$$u = u_{sm} + u_{fuzzy} \tag{15}$$

Where u_{sm} and u_{fuzzy} can be given by the following condition:

$$\frac{ds}{dt} . s < 0 \tag{16}$$

$$\varepsilon = \sigma \cdot u_{fuzzy} \tag{17}$$

Where the σ is constant, the formula (16) can ensure system to satisfy the fuzzy condition, the formula (17) can ensure u_{fuzzy} to keep the sliding mode moving rate.

V. Simulation Results

The parameters of the system used for simulation are as follows:

DFIG: P=1.0MW, p=2
Grid voltage: 690V
Grid frequency: f=50HZ
DC link voltage: 1100V
DC capacitance: C=0.06F
Resistance: R =0.018Ω
Inductance: L =16.2MH
Power factor: $\cos\varphi$ =0.92
Rated wind speed: V_N =12m/s
Sample time: Ts=0.03s
The simulation results are as follows:

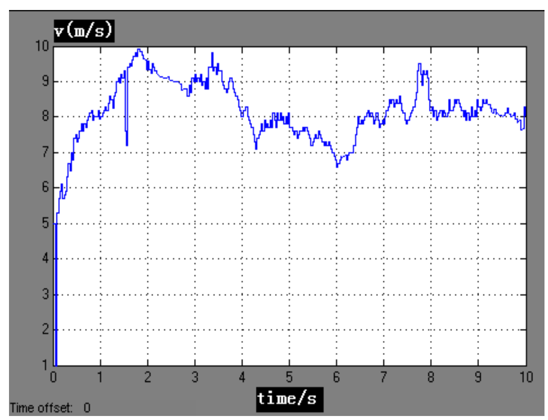

Fig. 10 Wind speed

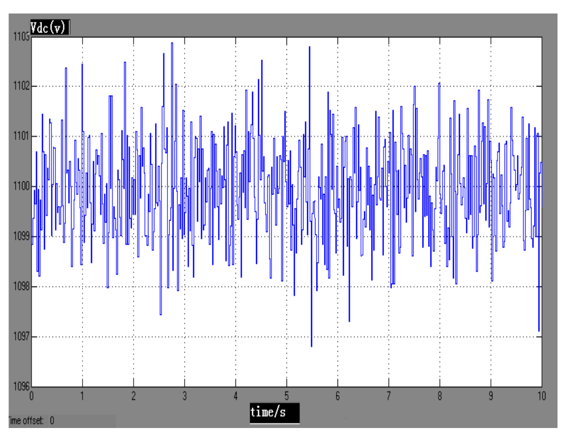

Fig. 11 DC link voltage value

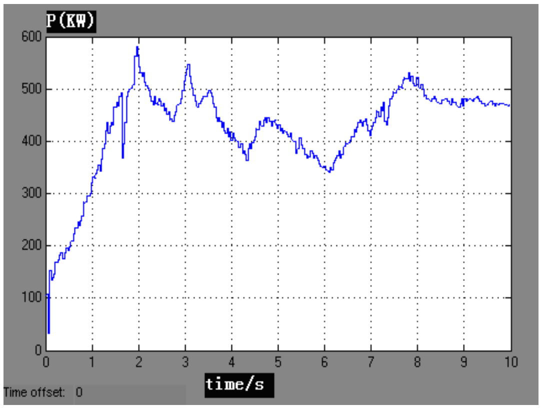

Fig. 12 Active power

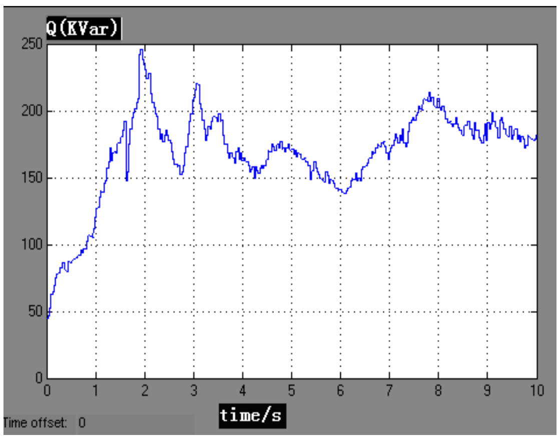

Fig. 13 Reactive power

Fig. 10 shows the input wind speed under rated speed V_N = 12m/s, within the wind speed area, wind turbine works in the tracking the maximum energy from the wind, VSCF wind turbine works mainly under speed control with a certain pitch angle.

Fig. 11 shows the results of grid voltage is balanced. The DC link voltage fluctuates within ±4V. We can draw the conclusion that the converter has good dynamic response.

Fig. 12 shows the active power generated by VSCF wind turbine, keeping the power factor $\cos\varphi$ = 0.92, the grid-side converter works in the inverter state, feeding current to the grid. We see the grid-side converter tracks with the input wind speed well.

Fig. 13 shows the reactive power generated by VSCF wind turbine. Since the grid does not demand the reactive power, it is necessary to make use of some filter to decrease the generated reactive power or to make the power factor close to one.

VI. CONCLUSIONS

The mathematical model of the three-phase grid-side PWM converter in d-q synchronous reference frames is thoroughly investigated. Comparing with the tradition control way of PWM converter, this method doesn't demand high accuracy of mathematic model, and has little sensitivity of parameter change and the external perturbation, which can control a target definitely and realize digitized easily.

Comparative simulation study is carried out to evaluate the performance of the non-coordinated control with current state decoupling and grid voltage feed-forward compensation. The exact feedback linearization scheme based on the fuzzy sliding mode control for the grid-side converter in VSCF wind turbine was proposed and the simulation results shows that the result is satisfied. But this control strategy was based on the abstract and sophisticated differential geometry theory, it is difficult to apply in the engineering area.

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