# Study on 4-quadrant Converter in VSCF Wind Power Generation System

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**Abstract:** This paper covers a scheme of variable speed constant frequency (VSCF) wind power generation system. Several methods of collecting the wind power are compared. The VSCF wind power generation system composed of PMSM is studied in detail. Then the three-phase 4-quadrent converter that connects the generator and power line is discussed in detail. IGBT is chosen as the power electronics element. The topology and energy flow of the inverter is given. Working principle of acquire unity power factor is studied also. Using state-space averaging model, small inertia current tracking (SICT) control is explained in detail. The system is controlled by digital signal processor using SICT method. Finally, experiment result is given, which prove this scheme can send the energy into power line with high power factor.

**Keywords:** 4-quadrant converter, small inertia current tracking control, unity power factor, VSCF wind power generation system

## I. INTRODUCTION

Wind power is the most fast growing energy source in the world. It has proven to be a potential source for generation of electricity with minimal environmental impact. With the advancement of aerodynamic designs, wind turbines that can capture several megawatts of power are available.

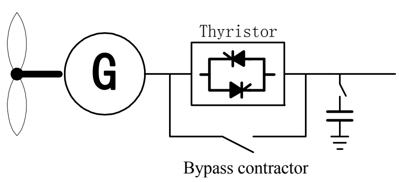
Wind power system can be classified as two types, constant speed constant frequency (CSCF) system, which maintains constant generator speed to acquire constant output frequency, and variable speed constant frequency (VSCF) system, which allows generator run in a wide speed range. Other method is taken to acquire constant output frequency. According to aerodynamic theory, in VSCF system, turbine speed is adjusted as a function of wind speed to maximize output power. Operation at the maximum power point can be realized over a wide power range. So compared to CSCF system, VSCF system can capture more energy with low mechanical stress [1].

Fig 1 (a) shows a system block of a fixed speed Stall-regulated wind power generation system. The fixed speed wind turbine, equipped with a generator connected directly to the grid, a softstarter and a capacitor bank, is the most common type of wind turbine. In order to increase power production, some of the fixed speed wind turbines are equipped with two speed generators instead of with one generator only. Although this kind of system has the deficiency of low efficiency and high mechanical stress, it still takes a great part of the markets of wind power all over the world because of its simplicity and low price of the electrical system.

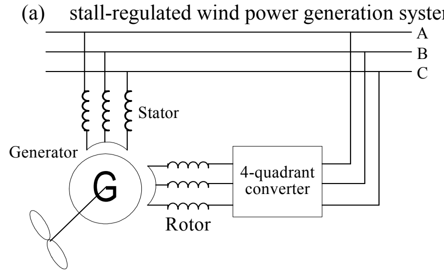
Supported by the National Key Technology R&D Program： Modeling & Simulation of the Wind Turbines。（2009BAA22B03-1）

Doubly fed induction machines (DFIM) VSCF wind power generation system is showed in Fig 1 (b). In this case, the rotor circuit is capable of bidirectional power flow allowing sub synchronous and super synchronous modes of operation. The reactive power can be regulated, and the ratings of the converters are significantly reduced [2]. But the generator has the slip-ring.

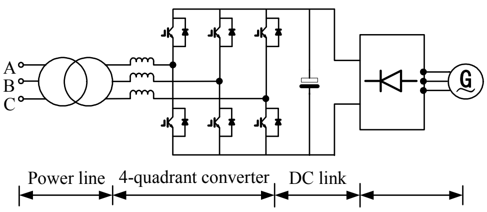
Fig 1 (c) shows a scheme of VSCF wind power generation system composed of permanent magnet excited synchronous machine (PMSM), which can run without gear box. This type of system can run in wider wind speed range, collect more energy in low wind speed. It is low noisy, high reliability power quality and efficient [3]. It is a hot topic in this field. But a full scale rating inverter is needed for convey of the energy. With the advancement of the power electronics, building a large-scale converter is much easier.




(a) stall-regulated wind power generation system




(b) DFIM wind power generation system




(c) PMSM wind power generation system

**Figure 1. Schemes of wind power system**

This paper mainly discusses VSCF wind power generation system composed of PMSM. The generator is connected to the turbine directly. The power output from the generator is rectified by the diode bridge, and conveyed to the power line by the inverter. The control of the operation point is realized by the conditioning of the output current of the inverter to change the DC voltage [4] [5]. The load of the generator is changed, so the speed of the turbine can be controlled.

## II. INVERTER ON THE GRID SIDE

The out put phase current should be sinusoidal, and the power factor should be one. Also the DC voltage should be equal to the reference value, which determined by the desired turbine speed. So the 4-quadrent converter is chosen as the grid side inverter.

### *Principle of the 4-quadrent Converter*

In wind power generation system, the 4-quadrent converter conveys energy to power line, so the power factor should be -1. Fig 2 shows the phasor diagram of 4-quandrent converter. Adjust the inverter output voltage $\dot{U}_S$ change along axis a-b, the magnitude of the output current can be adjusted. And the converter can offer unity power factor.

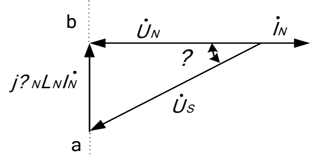



**Figure 2. Phasor diagram of 4QC**

### *Small Inertia Current Tracking Control Method*

Many control methods of the 4-quadrent converter has been bring forward in recent years. Such as phase amplitude control (PAC), hysteresis current control (HCC), PI current control.

Small inertia current tracking control method keeps high dynamic features but operates at a fixed switching frequency [6]. This control method first calculates the necessary voltage required for controlling the line current, then converts it to a quasi-optimal switching pattern. The stress and losses in switching devices are low, and the line current waveform is also improved.

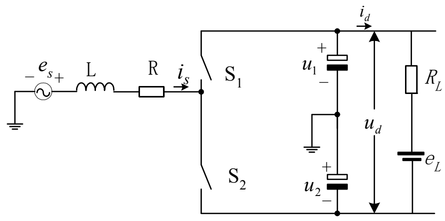



**Figure 3. Single phase 4QC circuit**

A single phase 4-quadrent converter is shown in Fig. 3. R is the sum of internal resistance of the switch and the filter inductor. In one switching period $T$, presume the conducting time of S1 and S2 is $dT$ and $d'T$=(1-$d$)$T$. When S1 is on and S2 is off, the state equation can be written as:

$$\begin{aligned} L\frac{di_s}{dt} &= e_s - u_1 - i_s R \\ C\frac{du_1}{dt} &= i_s - \frac{u_1+u_2-e_L}{R_L} \\ C\frac{du_2}{dt} &= -\frac{u_1+u_2-e_L}{R_L} \end{aligned} \tag{1}$$

The matrix form is:

$$\begin{bmatrix} L\dot{i}_s \\ C\dot{u}_1 \\ C\dot{u}_2 \end{bmatrix} = \begin{bmatrix} -R & -1 & 0 \\ 1 & -1/R_L & -1/R_L \\ 0 & -1/R_L & -1/R_L \end{bmatrix} \begin{bmatrix} i_s \\ u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1/R_L \\ 0 & 1/R_L \end{bmatrix} \begin{bmatrix} e_s \\ e_L \end{bmatrix} \tag{2}$$

When S1 is off and S2 is on,

$$\begin{aligned} L\frac{di_s}{dt} &= e_s + u_2 - i_s R \\ C\frac{du_1}{dt} &= -\frac{u_1+u_2-e_L}{R_L} \\ C\frac{du_2}{dt} &= -i_s - \frac{u_1+u_2-e_L}{R_L} \end{aligned} \tag{3}$$

The matrix form is:

$$\begin{bmatrix} L\dot{i}_s \\ C\dot{u}_1 \\ C\dot{u}_2 \end{bmatrix} = \begin{bmatrix} -R & 0 & 1 \\ 0 & -1/R_L & -1/R_L \\ -1 & -1/R_L & -1/R_L \end{bmatrix} \begin{bmatrix} i_s \\ u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1/R_L \\ 0 & 1/R_L \end{bmatrix} \begin{bmatrix} e_s \\ e_L \end{bmatrix} \tag{4}$$

The single phase 4-qudrent converter can be described in state-space averaging model:

$$\begin{bmatrix} L\dot{i}_s \\ C\dot{u}_1 \\ C\dot{u}_2 \end{bmatrix} = \begin{bmatrix} -R & -d & d' \\ d & -1/R_L & -1/R_L \\ -d' & -1/R_L & -1/R_L \end{bmatrix} \begin{bmatrix} i_s \\ u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1/R_L \\ 0 & 1/R_L \end{bmatrix} \begin{bmatrix} e_s \\ e_L \end{bmatrix} \tag{5}$$

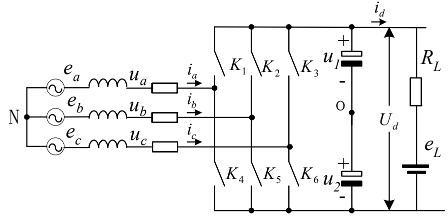



**Figure 4. There phase 4QC circuit**

For a there phase system, if the system has neutral line between O and N, the model of every single phase is:

$$\begin{bmatrix} L\dot{i}_k \\ C\dot{u}_1 \\ C\dot{u}_2 \end{bmatrix} = \begin{bmatrix} -R & -d_k & d'_k \\ d_k & -1/R_L & -1/R_L \\ -d'_k & -1/R_l & -1/R_L \end{bmatrix} \begin{bmatrix} i_k \\ u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 1/R_L \\ 0 & 1/R_L \end{bmatrix} \begin{bmatrix} e_k \\ e_L \end{bmatrix} \quad (6)$$

If the system has no neutral line between O and N, the first line of (6) can be written as:

$$L\dot{i}_k = e_k - i_k R - (u_{ko} + u_{oN}) = e_k - i_k R - (d_k u_1 - d'_k u_2 + u_{oN})$$

Because of $d'_k = 1 - d_k$ and $u_1 = u_2 = u_d / 2$, (6) becomes

$$L\dot{i}_k = e_k - i_k R - [(d_k - \frac{1}{2})u_d + u_{oN}] \quad (k = a,b,c) \tag{7}$$

For a three-phase system without neutral line,
$i_1 + i_2 + i_3 = 0$

If the ac supply is a balanced source, suppose the instantaneous values of three phase voltage are symmetrical, ignore the zero sequence component [6],
$e_1 + e_2 + e_3 = 0$

Add the three equations of (7), the expression of $u_{oN}$ can be derived.

$$u_{oN} = \left(\frac{1}{2} - \frac{1}{3}\sum_{j=1}^{3} d_j\right) u_d \tag{8}$$

Put (8) into (7),

$$L\dot{i}_k = e_k - i_k R - (d_k - \frac{1}{3}\sum_{j=1}^{3} d_j) u_d \tag{9}$$

Use superposition theorem:

$$C(\dot{u}_1 + \dot{u}_2) = \sum_{k=1}^{3}(d_k - d'_k) i_k - \frac{2(u_1 + u_2 - e_L)}{R_L}$$

That is:

$$\frac{C}{2}\dot{u}_d = \sum_{k=1}^{3}(d_k - \frac{1}{2}) i_k - \frac{u_d - e_L}{R_L} \tag{10}$$

From (9), (10), the state-space averaging model of three phase 4-qudrent converter can be written as:

$$\begin{bmatrix} L\dot{i}_1 \\ L\dot{i}_2 \\ L\dot{i}_3 \\ \frac{C}{2}\dot{u}_d \end{bmatrix} = \begin{bmatrix} -R & 0 & 0 & d_M - d_1 \\ 0 & -R & 0 & d_M - d_2 \\ 0 & 0 & -R & d_M - d_3 \\ d_1 - \frac{1}{2} & d_2 - \frac{1}{2} & d_3 - \frac{1}{2} & -1/R_L \end{bmatrix} \begin{bmatrix} i_1 \\ i_2 \\ i_3 \\ u_d \end{bmatrix} + \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1/R_L \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ e_3 \\ e_L \end{bmatrix} \tag{11}$$

In this equation, $d_M$ is mean value of the duty ratio of three phases. Control over three phases is symmetrical. Ignore the zero sequence component in AC component of $d_k$

$$d_M = \frac{1}{3}\sum_{k=1}^{3} d_k = \frac{1}{2} \tag{12}$$

Equation of pulse width in every switching period can be derived:

$$d_k = \frac{1}{u_d}(e_k - Ri_k - L\frac{\mathrm{d}i}{\mathrm{d}t}) + \frac{1}{2} \tag{13}$$

In actual calculation, use switching period $T_s$ substitutes $dt$, and use the error of command current and actual line current substitutes $di$.

$$d_k = \frac{1}{u_d}(e_k - Ri_k - L\frac{i_k^* - i_k}{T_s}) + \frac{1}{2} \tag{14}$$

$i_k^*$ is the command current, while $i_k$ is actual line current.

So, pulse width is calculated in every switch period, which means the actual line current $i_k$ will follow the command current $i_k^*$ with only one switching period $T_s$ delay.

In wind power system, the converter dose not regulate the reactive power and compensate harmonics, and the line voltage dose not distort. So the waveform of the command current keeps a ratio with the line voltage.

$$e_k = ai_k^* = \frac{L}{T_s} pi_k^* \qquad (p = a\frac{T_s}{L}) \tag{15}$$

The calculation of the pulse width can be made easier. Put (15) into (14)

$$d_k = \frac{1}{u_d}(-Ri_k - L\frac{(1-p)i_k^* - i_k}{T_s}) + \frac{1}{2} \tag{16}$$

In (16) calculation dose not need the value of line voltage. The ratio (1-$p$) of $i_k^*$ can be derived in the DC voltage PI regulator automatically. So the equation of the pulse width can be written as:

$$d_k = \frac{1}{u_d}(-Ri_k - L\frac{i_k^* - i_k}{T_s}) + \frac{1}{2} \tag{17}$$

The change of the value of line voltage dose not affects the line current. But (17) dose not suit for the applications in regulating of the reactive power and the conditions that the line voltage distort badly.

## III. IMPLEMENTATION OF THE CONTROL SYSTEM

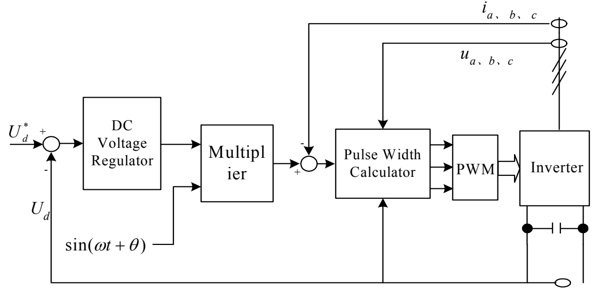


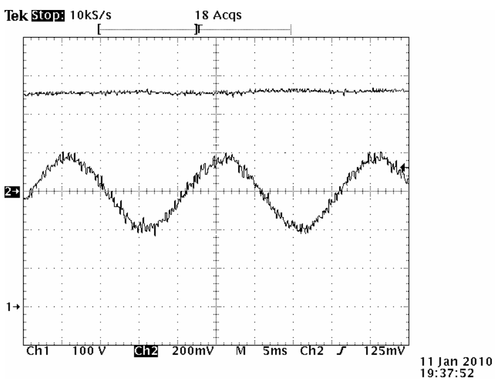

**Figure 5. Control block of SICT**

Control block of SICT is showed in fig. 5. Besides the part of pulse width calculator, DC voltage regulator and sin($\omega t$+$\theta$) (phase lock loop) are also important parts of the control system. The output of DC voltage regulator is the amplitude of the command current, therefore the DC voltage can be adjusted by changing the amplitude of the line current. The current phase signal, which derived by phase lock loop and the line voltage phase, multiplied with the signal of the output of DC voltage regulator. The result is the instantaneous value of command current. The pulse width calculator calculates the duty ratio according to the instantaneous value of command current, actual line current and line voltage. Therefore the two function of 4-quadrent converter is realized: 1. The dc voltage is set to the reference value, 2. Line current keeps synchronous with line voltage, and the power factor is 1.

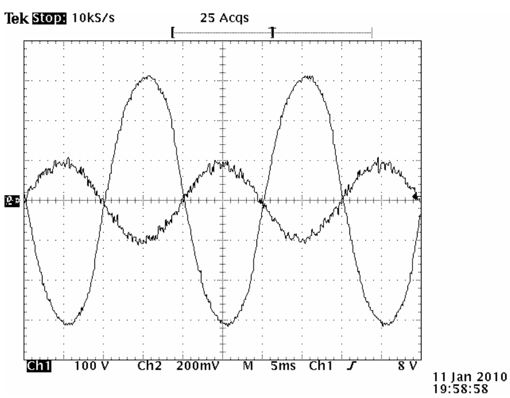
## IV. EXPERIMENTAL RESULTS

Experimental system is showed in Fig. 1. (c). A PMSM of 2kW is droved by a separately excited DC motor. The armature coil of the DC motor in series with a high power resistance, are supplied by a DC voltage source, to simulate the energy captured by the turbine.

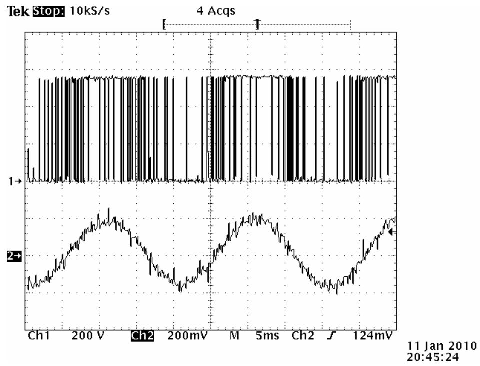
Fig. 6. (a) shows DC voltage and line current, the DC voltage keeps constant. Fig. 6. (b) shows line-to-neutral voltage and line current. The line current is nearly a sine wave with unity power factor. Fig. 6. (c) shows Voltage drop of the switching device and line current.




(a) DC voltage and line current




(b) Line-to-neutral voltage and line current




(c) Voltage drop of the switching device and line current

**Figure 6. Experiment result**

## V. CONCLUSION

A scheme of VSCF wind power generation system is discussed in this paper. The system is composed of PMSM and 4-quadrent converter. It can run in wider wind speed range, collect more energy in low wind speed. It is low noisy, high reliability power quality and efficient.

4-quadrent converter that connects the generator and power line is discussed in detail. The average state-space model of three phase 4QC is build to analyze the current PWM control method of the converter, which called SICT control method. Equation of calculates pulse width is deduced. SICT control method keeps high dynamic features but operates at a fixed switching frequency

An experiment system is built up in the lab. Experiment result is given, which prove this scheme can send the energy into power line with high power factor and low harmonics.

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