One novel Variable-speed wind energy system based on PMSG and super sparse matrix converter

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***Abstract*-Aim to reduce the cost of wind energy conversion system and improve its performance, a novel Variable-speed wind energy generation scheme which is based on the combination of PMSG and super sparse matrix converter (SSMC) is presented in this paper. The whole physical system including SSMC is modeled. Coordinate transformation, active power conservation principle and singular perturbation theory are applied to simplify the control law for SSMC. To design a global stable and robust controller, Feedback Linearization theory and H-infinity control are used. The stability of zero dynamics of the system is analyzed in detail. Based on the analysis of operation condition of SSMC, the limitations (reactive capability at both sides of SSMC) of the system are presented. It will be helpful to design the out-loop control strategy such as reactive power optimization control, maximum torque control of PMSG. The proposed generation system is not only able to realize maximum power tracking, but also reduce torque pulsation due to the distorted stator current in PMSM. At last, simulation results verify the feasibility of the proposed method.**

I. INTRODUCTION

Recently, energy resource and environment problems have attracted much attention all over the world. The research on renewable energy resources without pollution pressure is very essential. Wind energy is such a kind of renewable energy resources [1~4]. With the development of power electronics, variable-speed generation mode which can realize maximum power point tracking (MPPT) [2~5] has became the mainstream. Due to the decreased cost of magnetic materials and improved performance of magnetic material characteristic, permanent magnet is used to replace the field winding of synchronous motor [1, 6]. The application of permanent magnet synchronous generator for wind power generation has become a research hotspot.

Usually, the power electronics devices applied in WECS (wind energy conversion system) include the converters based diode-rectifier and inverter (DRI), DRI with additional cascaded DC/DC circuit [2, 5], active front-end converter [1] and other topologies. The DRI is known for simple structure, low cost. But it is inevitable to result in serious harmonics current in stator of PMSM, consequently, to result in serious torque pulsation. Although the DRI with additional circuit possesses the ability of MPPT, the disadvantages similar to DRI still exist. The active front-end converter is a popular power converter device with many advantages, but the cost is relatively high. Matrix converter [8~9], known as “the green frequency converter”, has lots of advantages such as bidirectional energy flow, sinusoidal input and output current, as well as no large energy storage components. It is an alternative which has a chance to replace active front-end converter in the near future. Especially, the matrix converter’s derivative topology—two stage matrix converter which has almost the same function with conventional matrix converter and moreover has the possibility to simplify its topology according to its specific application, reduce its cost and improve its reliability [10].

In the past decades, many attempts have been made to apply matrix converter to WECS. Ref [12] applied matrix converter to WECS based on doubly-fed induction generator. In this paper the matrix converter just replaced the active front-end converter without considering the special issues related with matrix converter. Ref [13] made full use of the function of frequency conversion of matrix converter, and much effort was paid to research on modulation strategy. Some other works [14] are almost similar to ref [12] without too much improvement.

Consider the characteristic of high power factor of PMSG and the requirement of unidirectional power flow in such application, a novel generation scheme is proposed in this study. The system topology as shown in fig.1, compared to WECS based on active front-end converter, this circuit is much simpler, less active power switches. Therefore, this scheme is more cost effective and reliable. Compared to DRI with additional DC/DC circuit, the cost is almost the same, but its steady performance of torque is improved greatly.

In additional to the new topology, much work is concentrated on analysis and design of control system. because of the nonlinearity of the proposed system, the time-scale separation principle and feedback linearization technique [15] are implemented to simplify the system. In order to design a controller which is insensitive to disturbance, H-infinity technique is applied to the design.

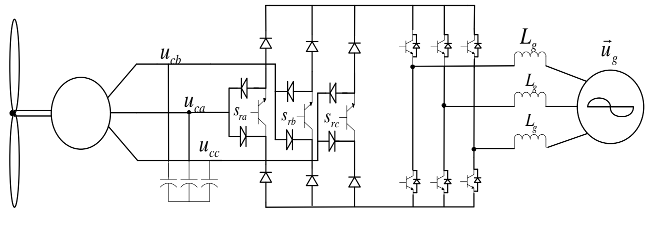

Fig.1. Proposed schematic diagram for WECS.

II. MODELING

A. the model of PMSG

The mathematical model of Surface-Mounted permanent magnet synchronous generator in the stationary reference frame can be expressed in complex vector as follows.

$$J\frac{d\omega_m}{dt} = T - T_e \tag{1}$$

$$\frac{d\vec{\psi}_s}{dt} = -R_s\vec{i}_s + \vec{u}_c \tag{2}$$

$$\vec{\psi}_s = L\vec{i}_s + \psi_{PM}e^{j\theta} \tag{3}$$

$$T_e = 3n_p/2\, im[\vec{\psi}_s \times \vec{i}_s] \tag{4}$$

Where $\vec{\psi}_s$ is stator flux, ψ_{PM} is the amplitude of rotor flux, θ is the spatial electrical position of rotor flux, $\vec{i}_s$ is stator current, $\vec{u}_c$ is the stator voltage, J, n_P represents moment of inertia, the number of pole pairs, respectively. Take noting that the variable with arrowhead denotes vector in this paper.

B. the mathematical model of matrix converter

Because matrix converter without input filter has no any dynamic component such as inductance and capacitance, the relation between input and output can be expressed by algebraic equation only. In reality, the input filter must be installed to filter harmonics injecting into power grid, therefore, the matrix converter should be represented by using a group of differential equation and algebraic equation together. Then the matrix converter system is stated as follows.

$$C_s\frac{d\vec{u}_c}{dt} = -\vec{i}_s - i_{dc}\vec{d}_r \tag{5}$$

$$u_{dc} = \frac{3}{2}\vec{u}_c \bullet \vec{d}_r \tag{6}$$

$$i_{dc} = \frac{3}{2}\vec{d}_i \bullet \vec{i} \tag{7}$$

Where $\vec{d}_i, \vec{d}_r, \vec{i}, u_{dc}$ and i_{dc} represent inverter modulation vector, rectifier modulation vector, the current vector injecting into power grid, average voltage in dc link and current, respectively. The operator $\bullet$ denotes dot product.

C. the model in the grid side

The proposed WECS is connected to power supply through a filter inductance. The model on side of power grid can be expressed as

$$L_g\frac{d\vec{i}}{dt} = u_{dc}\vec{d}_i - \vec{u}_g \tag{8}$$

Where L_g, $\vec{u}_g$ represents inductance of output filter and power grid voltage, respectively. Consider the physical limitations, modulation vector for rectifier and inverter should meet the following inequality constraints.

$$\begin{cases} \left|\vec{d}_r\right| \le 1 \\ \left|\vec{d}_i\right| \le \sqrt{3}/3 \end{cases} \tag{9}$$

D. D-Q model of the system

In order to obtain high dynamic performance, it is used to modeling the system in the rotor synchronous reference frame. Separating (2~7) into d-q components yields

$$L\frac{di_{sd}}{dt} = -R_s i_{sd} + L\omega i_{sq} + u_{cd} \tag{10}$$

$$L\frac{di_{sq}}{dt} = -R_s i_{sq} - L\omega i_{sd} - \omega\psi_{PM} + u_{cq} \tag{11}$$

$$T_e = 3n_p/2\psi_{PM}\, i_{sq} \tag{12}$$

$$C_s\frac{du_{cd}}{dt} = -i_{sd} + C_s\omega u_{cq} - 1.5(i_d d_{id} + i_q d_{iq})d_{rd} \tag{13}$$

$$C_s\frac{du_{cq}}{dt} = -i_{sq} + C_s\omega u_{cd} - 1.5(i_d d_{id} + i_q d_{iq})d_{rq} \tag{14}$$

Let the system equations on the side of power grid be expressed in power grid voltage synchronous reference frame, and d-axis of reference frame be fixed to voltage vector of power grid. Separating (8) into d-q components yields.

$$L_g\frac{di_d}{dt} = 1.5(u_{cd}d_{rd} + u_{cq}d_{rq})d_{id} + L_g\omega_g i_q - u_g \tag{15}$$

$$L_g\frac{di_q}{dt} = 1.5(u_{cd}d_{rd} + u_{cq}d_{rq})d_{iq} - L_g\omega_g i_d \tag{16}$$

Up to now, the most modeling work has been completed. To provide more insights into the system, the equivalent circuit of the whole system in the d-q coordinate is shown in fig.2.

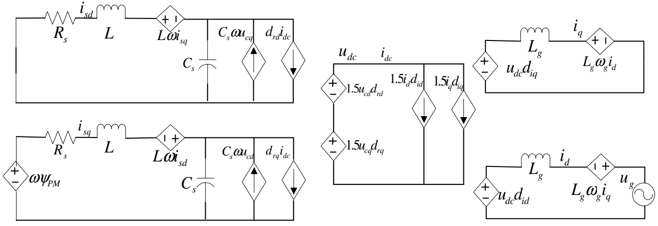

Fig.2 the equivalent circuit of the proposed WECS.

III. CONTROL STRATEGY

According to the modeling and analysis mentioned above, it is obvious that there are two degrees of freedom, namely, rectifier modulation vector and inverter modulation vector, for the purpose of realizing the variable speed constant frequency generation. In order to simplify the design, we just disable the degree of freedom of rectifier modulation vector, i.e. let it be zero to make the input current vector in phase with the voltage vector of power grid. Such operations can be expressed as follows.

$$\begin{cases}\vec{d}_r \otimes \vec{u}_c = 0 \\ \left|\vec{d}_r\right| = 1\end{cases} \qquad (17)$$

In addition to the operation's simplicity, the other advantages are the reduced cost and higher voltage transfer ratio. However, the possibility of optimization of PMSG operation is dim.

As the stability of system is important, the stability analysis about matrix converter system under the constant power condition is studied intensively in literature [11]. For Most of them, small signal stability analysis method is used only. In this paper, we propose a novel robust stable control law which is based on the feedback linearization theory.

A. robust control based on feedback linearization

Before going on this section, some basic concepts related to the design should be introduced. Feedback linearization is an approach to nonlinear control design that has attracted lots of researchers in recent years. The central idea is to algebraically transform nonlinear systems dynamics into (fully or partly) linear ones, so that linear control techniques can be applied. For more details, people who are interested can refer to [15]. Singular perturbation method may be used to reduce the order of dynamic system. For PMSG, the time scale of mechanical subsystem is much larger than that of Electro-magnetic subsystem. Therefore, it is reasonable to regard the angular velocity ω_m as almost constant compared to other variables, i.e. the derivative of ω_m can be negligible.

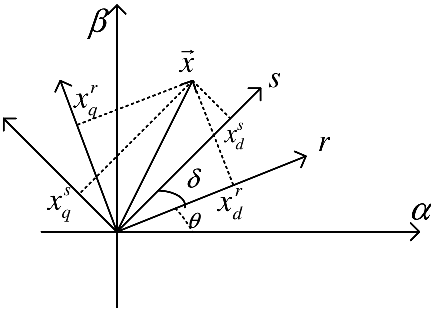

Fig. 3 the diagram on coordinate transformation.

Refer to (14~16), it is found that it is not easy to design a control law convenient to use in the original form of (14~16), consider the active power balance principle on both sides of matrix converter, the problem may be simplified greatly. However, if the feedback linearization is applied immediately, it is still difficult to go on the next steps. Therefore, some coordinate transforms are used.

In the concrete, the Equation (5) is transformed into rotating reference frame, with the d-axis of reference frame fixed to the stator voltage vector, as shown in (18). The other equations of the system are written as follows.

$$\begin{cases}C_s \dfrac{du_{cd}^s}{dt} = -i_{sd}^s - 1.5u_g i_d \big/ u_{cd}^s \\ 0 = i_{sq}^s + C_s \omega u_{cd}^s\end{cases} \qquad (18)$$

$$J\frac{d\omega_m}{dt} = 3n_p \big/ 2\psi_{PM}\, i_{sq}^r - T \qquad (19)$$

$$\begin{cases}L\dfrac{di_{sd}^r}{dt} = -R_s i_{sd}^r + L\omega i_{sq}^r + u_{cd}^r \\ L\dfrac{di_{sq}^r}{dt} = -R_s i_{sq}^r - L\omega i_{sd}^r - \omega\psi_{PM} + u_{cq}^r\end{cases} \qquad (20)$$

$$\begin{cases}i_{sd}^s = i_{sd}^r \cos(\delta) - i_{sq}^r \sin(\delta) \\ i_{sq}^s = i_{sq}^r \cos(\delta) + i_{sd}^r \sin(\delta)\end{cases} \qquad (21)$$

$$\begin{cases}u_{cd}^s = u_{cd}^r \cos(\delta) - u_{cq}^r \sin(\delta) \\ 0 = u_{cq}^r \cos(\delta) + u_{cd}^r \sin(\delta)\end{cases} \qquad (22)$$

$$\begin{cases}L_g \dfrac{di_d}{dt} = u_c d_{id} + L_g \omega_g i_q - u_g \\ L_g \dfrac{di_q}{dt} = u_c d_{iq} - L_g \omega_g i_d\end{cases} \qquad (23)$$

Where, the variables with superscript r and s mean that the variables are on rotor synchronous rotating coordinate and stator voltage synchronous rotating coordinate, respectively. Equation (20) represents model of PMSG in rotor synchronous rotating coordinate. Equation (21) and (22) represent coordinate transformations which are depicted in fig.3. Equation (23) denotes system on grid side in the grid voltage synchronous rotating coordinate.

Denote velocity error of PMSG as

$$e_1 = \omega_m - \omega_m^* \qquad (24)$$

In order to assure no steady error, an additional expansion state variable is defined as

$$e_0 = \int e_1 d\tau \qquad (25)$$

Then

$$\begin{cases}\dot{e}_0 = e_1 \\ \dot{e}_1 = e_2 \\ \dot{e}_2 = e_3 \\ \dot{e}_3 = f(\alpha, i_{sd}^r, i_{sq}^r, u_{cd}^s, i_d, i_q) + g d_{id}\end{cases} \qquad (26)$$

Introducing a auxiliary control input u with $u = d_{id} + f(\cdot)/g$ Where $f(\cdot)$ is shown in appendix.

Then

$$\dot{e}_3 = gu \qquad (27)$$

Taking in account the inevitable uncertainties such as parameter variation, switches loss and other un-modelled error, Equation (26) can be written in more compact form as

$$\dot{x} = Ax + b(u + w) \qquad (28)$$

$$z = cx \qquad (29)$$

Where $A = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 \end{bmatrix}, b = \begin{bmatrix} 0 \\ 0 \\ 0 \\ g \end{bmatrix}, \ c = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix}^T$, w represents the disturbance.

To get a robust control law, the state feedback ($u = kx$) is applied, the feedback gain k can be obtained by solving the following optimization problem in linear matrix inequality [16].

$$\min \ \gamma$$
$$s.t. \begin{bmatrix} XA^T + Q^T b^T + AX + bQ & b & Xc \\ b^T & -\gamma^2 & 0 \\ cX & 0 & -1 \end{bmatrix} \qquad (30)$$
$$X > 0$$

Where $k = QX^{-1}$, and the final control law can be written

$$d_{id} = kx - f(\cdot)/g \qquad (31)$$

For the system (23-2), its control law can be achieved by similar way as stated above. Due to the limitation of space, its detailed procedure is omitted here.

B. *Zero dynamic stability analysis*

Stability analysis of Zero dynamic [15] is of importance in the feedback linearization design. Referring to (20-1), an energy function for it can be found easily which satisfies

$$\dot{v}(\chi, w) \le -\alpha(|\chi|) + r(|u|) \qquad (32)$$

Where $\alpha(), r() \in K_\infty$. Therefore, the system of (20-1) is input-state-stable, then, the whole system is stable.

IV. THE LIMITATIONS OF OPERATION

Because the conditions of normal operation of the system are: 1) the DC loop $u_{PN} \ge 0$, for the reason avoiding resulting in short circuit in the side of power supply; the condition can be described in the way of power factor: i.e. $PF_r > \sqrt{3}/2$. 2) The power factor must be greater than $\sqrt{3}/2$ in the side of inverter, otherwise the Dc current is blocked by diodes on the side of rectifier; consequently, the basic principle of operation can not meet. The limitations list above is not so obvious, especially, from the point of view of equivalent circuit, because they exist in the form of instant not the form of average.

Based on the previous analysis about the limits of system's operation, we could get the reactive reference current by solving (23). Refer to (23) and calculate the steady state of them, then

$$u_{sd} = L_g \omega_g i_q \qquad (33)$$
$$u_{sq} = u_g - L_g \omega_g i_d \qquad (34)$$
$$Q = u_{sd} i_q - u_{sq} i_d \qquad (35)$$

Substitute (33) and (34) into (35), then

$$i_q = \sqrt{\frac{Q + u_g i_d - L_g \omega_g i_d^2}{L_g \omega_g}} \qquad (36)$$

Where i_d, Q should meet the following constraints

$$i_d = 1.5 \frac{P}{u_g} \qquad (37)$$
$$\frac{Q}{P} \le \frac{\sqrt{3}}{3} \qquad (38)$$

Where P is the active power injected to grid. From (36) to (38), we could get the feasible range of required reactive power which is shown in fig.4.

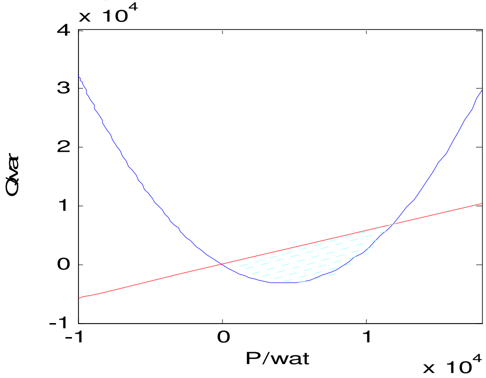

Fig.4 the range of reactive power reference (shaded parts)

V. SIMULATION RESULTS

The simulation evaluation has been conducted on the system shown in Fig.1 using MATLAB/SIMULINK, the setup for simulation consists of wind turbine, PMSG, SSMC, power grid and some filters. All the parameters related are listed in table I.

Table I

PARAMETER LIST

device	parameters	
Power grid	$V_g(RMS)/V$	220
	$\omega_g/(rad \cdot s^{-1})$	120π
Input filter	$C_s/\mu F$	30
Output filter	L_g/mh	1
PMSG	R_s/Ω	0.815
	$L_d, L_q/mh$	8.5
	ψ_{PM}/wb	0.35
	$J/(kg.m^{\wedge 2})$	$1.6e^{-3}$
	n_p	8

The PMSG is rated at 4.7kw, and the switch frequency used in simulation is selected to be 5 kHz. The main task is to verify the feasibility of the proposed power generation scheme.

Figure 5 shows the currents in d-q coordinate and the response of speed tracking of the proposed control strategy. A t the instant of 0.4s, the wind velocity changes suddenly, in less than 0.1s, the system restores its new steady state. Therefore, it is safe to say the dynamic response of the proposed controller is very fast. As can be seen from fig.6, the torque pulsation is small in steady state. Figure 7 demonstrates the currents injected into power supply in a-b-c coordinate and the voltages in stator terminal of PMSG from 0.35s to 0.5s. Figure 8 illustrates the output line-line voltage of matrix converter.

All the simulation results validate the correctness of the proposed approach for wind power generation.

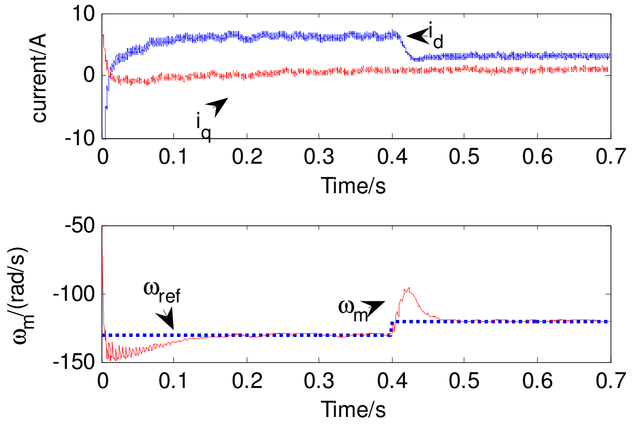

Fig.5 current in d-q coordinate and reference rotor angular velocity.

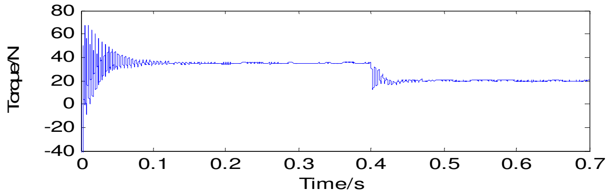

Fig.6 the Electromagnetic torque of the PMSG.

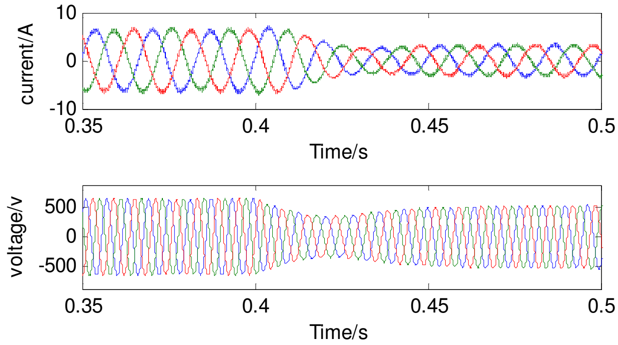

Fig.7 the current injected into power grid and voltage in the stator of PMSG.

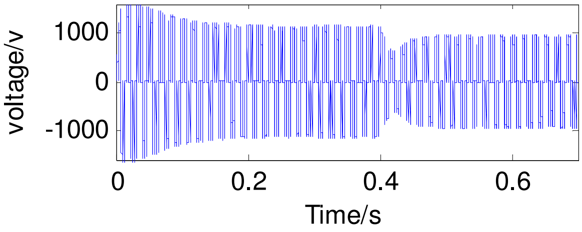

Fig.8 output line-line voltage of matrix converter.

VI. CONCLUSION

A novel cost effective WECS based on super sparse matrix converter is proposed. Its basic principle of operation and limitations are studied in detail. For such a strong coupled nonlinear system, to design a controller being robust against uncertainty, feedback linearization and H-infinity control approach are applied. To simplify the design task, two-time-scale property and coordinate transformation are applied. Because only one control degree of freedom is used efficiently, the reactive regulation on the side of PMSG can not controlled independently and its optimal operation can not achieved. In the next step, the second control freedom may be used fully to improve the performance of the proposed WECS further more.

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APPENDIX

$$g = 1.5m \cdot u_g \big/ (a \cdot L_g \cdot C_s)$$

Where $f(\cdot) = m(\xi_1 i_{sq}^r + \xi_2 i_{sd}^r + \xi_3 u_{cd}^s + \varphi)$

$$m = 1.5 n_p \psi_{PM} \big/ (L \cdot J)$$

$$\xi_1 = [LC_s a_2 \omega - a_1 R_s C_s + \sin(\delta)(R_s \sin(\delta) - L\omega\cos(\delta))] \big/ LC_s - 1.5 u_g i_d \sin(\delta) \big/ [a \cdot C_s (u_{cd}^s)^2]$$

$$\xi_2 = [-LC_s a_1 \omega - a_2 R_s C_s + \cos(\delta)(R_s \sin(\delta) - L\omega\cos(\delta))] \big/ LC_s + 1.5 u_g i_d \cos(\delta) \big/ [a \cdot C_s (u_{cd}^s)^2]$$

$$\xi_3 = [a_2 \cos(\delta) - a_1 \sin(\delta)] \big/ L$$

$$\varphi = \frac{1.5 u_g}{u_{cd}^s L_g a C_s} [-a L_g i_d (R_s \sin(\delta)/L - \omega\cos(\delta)) + L_g \omega_g i_q - u_g + \frac{1.5 u_g L_g i_d^2}{C_s (u_{cd}^s)^2}]$$

$$a_1 = \frac{R_s^2 - (L\omega)^2}{L} + \frac{\sin(\delta)}{a \cdot C_s}$$

$$a_2 = 2R_s\omega - \frac{\cos(\delta)}{a \cdot C_s}$$

$$a = -c\tan(\delta) - \sin(\delta)$$