Fuzzy-Based Nonlinear Variable Structure Control of DC-AC Inverters for Wind Energy Systems

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***Abstract*—This paper presents a fuzzy-based nonlinear variable structure controlled DC-AC inverter, and is suitable for the application of wind energy systems. The Nonlinear Variable Structure Control (NVSC) can provide zero tracking error and achieves system behavior with high accuracy. But, the chatter problem still exists in switching manifold of NVSC. The chatter incurs steady-state errors and high voltage harmonics in DC-AC inverter output, thus deteriorating the performance of the Wind Energy System (WES). To remove the chatter, the NVSC's switching manifold can be smoothed by Fuzzy Logic (FL). By combining NVSC with FL, a closed-loop wind energy DC-AC inverter system will yield low total harmonic distortion, zero tracking error, and fast dynamic response. Experimental results are given to conform that the proposed control method can obtain good performance under different kinds of loading. Because the proposed control method is simpler to realize than prior control methods and provides zero tracking error, this paper will be of interest to designers of related green energy.**

***Index Terms*—DC-AC inverter, Nonlinear Variable Structure Control (NVSC), chatter, Wind Energy System (WES), Fuzzy Logic (FL)**

I. INTRODUCTION

The DC-AC inverters have been widely used in wind energy systems [1]. The DC-AC inverter of WES is demanded to provide high-quality AC output voltage of low Total Harmonic Distortion (THD), zero steady-state errors and fast dynamic response, and these can be achieved by employing control method. Traditionally, if a linear loading is applied to the DC-AC inverter, a PID control can improve the system performance. However, the PID control can not provide good performance while the controlled plant is highly nonlinear and uncertain [2]-[6]. Some control technologies derived for DC-AC inverter systems are also reported in the literature, such as, deadbeat control, H-infinity control, multi-loop control, and so on. However, these technologies are difficult to implement and complicated in algorithms [7]-[9]. Variable Structure Control (VSC) is proposed in the 1950's, and it is a robust method for handling nonlinear system where occurs parameter variations and external disturbance [10], [11]. The VSC uses a switching control law to force the system to reach and maintain in the switching manifold. To design the variable structure controller, the following steps should be done:

1) The trajectory of the state error is forced toward the switching manifold.
2) Once the state error hits the switching manifold, the trajectory of the state error must slide along the manifold to the origin.

The inverters with VSC are usually employed, and have been recognized as an effective robust control. Malesani *et al*. developed a three level PWM inverter with fixed frequency. Though the steady-state response is good, the proposed method is complex and the dynamic response is unsatisfactory under nonlinear loading [12]. Chan *et al*. presents a discrete variable structure controlled servo systems. However, such system still has chatter problem [13]. A fixed switching frequency sliding mode control for the application of the inverters is proposed by Abrishamifar *et al*. The dynamic response is good, but a poor steady-state response is obtained [14]. By combining the optimal technique and the feedforward control, a discrete-time SMC methodology is developed for inverters. The performance of the inverter is good under linear loading, but the inverter's output has a noticeable distortion under nonlinear loading [15]. As above-mentioned these methods [12]-[15], linear switching manifolds exist and result in inaccurate tracking control. For high-accuracy tracking control, the NVSC can be developed for DC-AC inverters. Unfortunately, the NVSC with a chatter problem still happens, and may cause steady-state errors and serious voltage harmonics, even deteriorates the performance of the WES [16]-[18]. Fuzzy Logic (FL) is proposed in 1970s, and has been applied to the inverter related control due to its simplicity of structure, and ease of use [19]-[21]. Thus, to remove the chatter problem, a mathematically simple FL can be introduced around the switching manifold. The control design of the VSC will select both the membership functions and fuzzy inference rules, and then the switching manifold can be fuzzified, thus achieving zero tracking error. By combining a NVSC with FL, a closed-loop DC-AC inverter will yield good

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performance under different loading. The proposed control method has been realized for the actual DC-AC inverters controlled by a DSP and CPLD. Experiments are presented to illustrate good performance of the proposed controlled DC-AC inverter, thus suiting for the application of the WES. The organization of this paper is as follows: Section II describes the dynamic model of the DC-AC inverter. The proposed fuzzy-based nonlinear variable structure control is designed in Section III. Section IV shows the experimental results. Section V concludes this paper.

II. DYNAMIC MODEL OF DC-AC INVERTER

Fig. 1 briefly shows the block diagram of a single-phase DC-AC inverter, which consists of an LC filter and switching component with MOSFET transistors. The LC filter and connected loading can be regarded as the plant of a closed-loop feedback system. The load may be resistive loading, step load change with linear resistive loading, or full-wave diode rectifier load followed by an electrolytic capacitor in parallel with a load resistor.

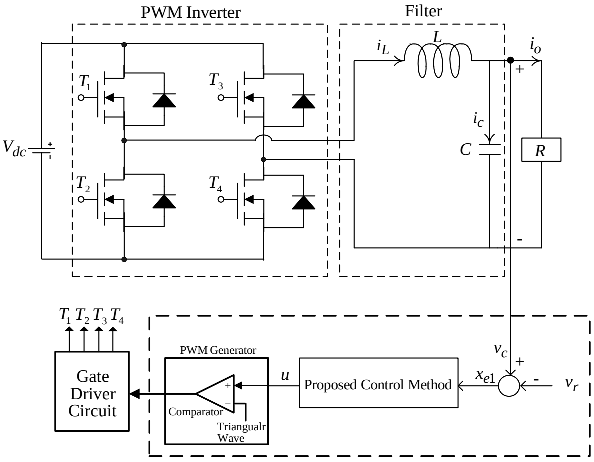


Figure 1. Digital controlled DC-AC inverter.

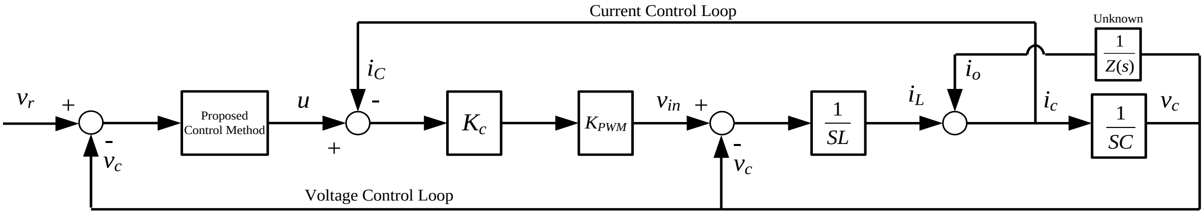


Figure 2. Closed-Loop with the proposed control method.

In Fig. 2, the output voltage and the capacitor current are sensed as feedback variables. The control objective is to make the output voltage equal a sinusoidal reference input, and a fast dynamic response is obtained by the use of the current control loop once an abrupt load change occurs. The control loop with the proposed method is completely shown in Fig. 2., where K_c is the compensated gain of the current loop, and K_{PWM} is the equivalent gain of the single-phase DC-AC inverter.

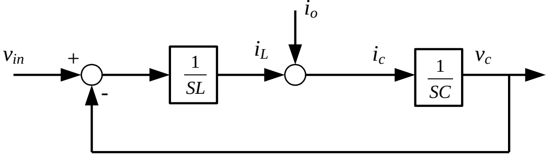


Figure 3. Block diagram of the LC filter.

Also, the block diagram of the LC filter is represented as Fig. 3. The state space equation of the LC filter can be expressed as the following state space form:

$$\begin{bmatrix}\dot{v}_c\\ \dot{i}_L\end{bmatrix}=\begin{bmatrix}0 & \frac{1}{C}\\ -\frac{1}{L} & 0\end{bmatrix}\begin{bmatrix}v_c\\ i_L\end{bmatrix}+\begin{bmatrix}0\\ \frac{1}{L}\end{bmatrix}v_{in}+\begin{bmatrix}1\\ 0\end{bmatrix}\left(\frac{1}{C}\dot{i}_o\right) \quad (1)$$

Then, the state vector $\begin{bmatrix}\dot{v}_c & \ddot{v}_c\end{bmatrix}$ can be substituted for the state vector $\begin{bmatrix}\dot{v}_c & \dot{i}_L\end{bmatrix}$, and the state space equation is rewritten as:

$$\begin{bmatrix}\dot{v}_c\\ \ddot{v}_c\end{bmatrix}=\begin{bmatrix}1 & 0\\ -\frac{1}{LC} & 0\end{bmatrix}\begin{bmatrix}v_c\\ \dot{v}_c\end{bmatrix}+\begin{bmatrix}0\\ \frac{1}{LC}\end{bmatrix}v_{in}+\begin{bmatrix}0\\ 1\end{bmatrix}\left(-\frac{1}{C}\dot{i}_o\right) \quad (2)$$

From Fig. 2, the output voltage v_c should track a sinusoidal reference AC voltage v_r. When the output voltage v_o completely tracks sinusoidal reference AC voltage v_r, the difference between v_c and v_c will be converged to zero. Therefore, we define $e_1 = v_r - v_c$ and $e_2 = \dot{e}_1$, then the error state space equation can be derived as:

$$\begin{bmatrix}\dot{e}_1\\ \dot{e}_2\end{bmatrix}=\begin{bmatrix}0 & 1\\ -a_2 & -a_1\end{bmatrix}\begin{bmatrix}e_1\\ e_2\end{bmatrix}+\begin{bmatrix}0\\ b\end{bmatrix}u+\begin{bmatrix}0\\ w\end{bmatrix} \quad (3)$$

where $a_1 = \frac{K_c K_{PWM}}{L}$, $a_2 = \frac{1}{LC}$, $b = -\frac{K_c K_{PWM}}{LC}$, and $w = a_1 v_r + a_2 \dot{v} + \ddot{v}_r + \frac{1}{C}\dot{i}_o$ is the disturbance. The error e_1 is a difference measure between v_c and v_r. If the control signal u is designed well, the e_1 will converge to zero and the output of the inverter remain the same as what is desired v_r.

III. CONTROL DESIGN

The designed u is partitioned into two terms:

$$u = u_e + u_n \tag{4}$$

where the equivalent control term u_e is valid only on the switching manifold, and the second term u_n guarantees the existence of the switching manifold mode.

For computer implementation, a nonlinear VSC with a hyperbolic tangent function is constructed as:

$$\sigma(k) = x_{e2}(k) + \rho \tanh(\eta x_{e1}(k)) \tag{5}$$

where ρ and η are constants.

From (5), we have:

$$\sigma(k+1) = x_{e2}(k+1) + \rho \tanh(\eta x_{e1}(k+1) \tag{6}$$

The equivalent control by the use of the invariance condition can be obtained as:

$$\Delta\sigma(k+1)\big|_{w=0,\, u=u_e} = \sigma(k+1) - \sigma(k) = 0 \tag{7}$$

The existence of the switching mode is expressed by:

$$\sigma(k+1)\sigma(k)\big|_{u=u_e+u_n} < 0 \tag{8}$$

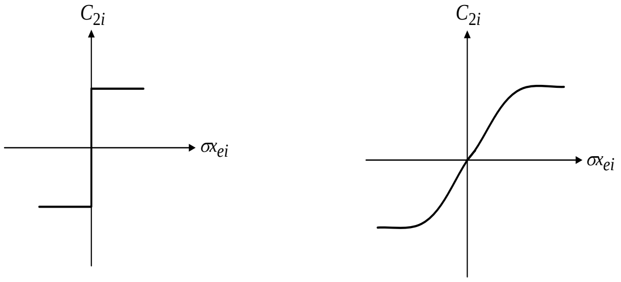
Then, the switching control yields:

$$u_n = -C_2 sign(\sigma(k)x_e),\ C_2 > 0 \tag{9}$$

It is worth noting that the (9) implies the sign function across the manifold $\sigma(k)$, and thus causes a chatter problem. A solution to this problem is to smooth the discontinuous control by the use of the fuzzy logic. Fuzzy logic is a direct methodology for governing a system without the requirement of a mathematical model. FL gains crisp data from various sensors, and such data are transferred to fuzzy membership functions by the fuzzification operation. Then, they go through a set of fuzzy "IF-THEN" rules in an inference engine and lead to fuzzy outputs. These fuzzy outputs are transferred back to crisp values by the defuzzification operation. Because NVSC is implemented via a digital computer, the switching action with the chatter exists. It is a crisp representation for fuzzy logic, thus its membership function can be written as:

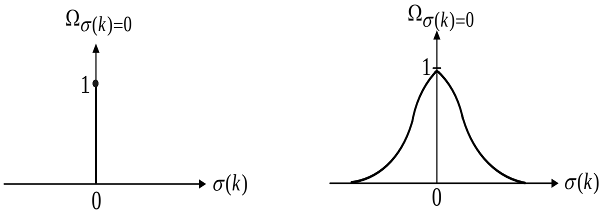
$$\Omega_{\sigma(k)=0} = \begin{cases} 1 & ,\ \ \sigma(k) = 0 \\ 0 & ,\ \ \text{otherwise} \end{cases} \tag{10}$$

For the elimination of the chatter, fuzziness of the sign function and switching manifold are shown as Fig. 4 and Fig. 5, respectively.



(a) (b)

Figure 4. (a) Switching criteria with the sign function, and (b) fuzziness of the sign function.



(a) (b)

Figure 5. (a) Switching manifold as a special fuzzy case, and (b) fuzziness of the switching manifold.

Then the human experience is fixed as linguistic rules with the help of in the following statements:

IF farther from the switching manifold
THEN greater feedback gain (11)

The design steps are described in the following.

Step 1: Defining two inputs, σx_{ei} and $\Delta\sigma x_{ei}$ (the change of σx_{ei}) for controlling system dynamic.

Step 2: Defining a crisp switching manifold, $\sigma = x_{e2} + \rho \tanh(\eta x_{e1})$ for deciding the system dynamic.

Step 3: As shown in Fig. 6, the fuzzy linguistics and the membership functions of the fuzzy input and output variables *S*, *DS*, *KD* must be designated.

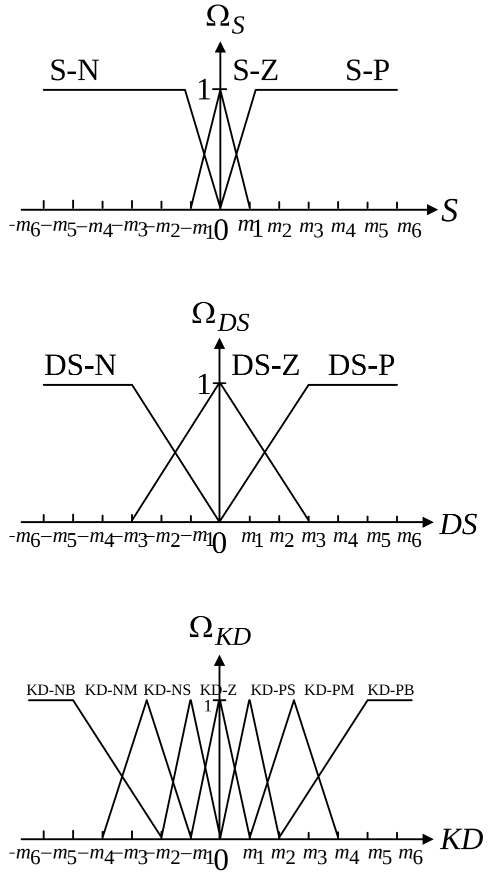


Figure 6. Fuzzy membership functions of *S*, *DS* and *KD*

Step 4: The output of each rule can be expressed by the use of the inference method as follows:

IF S-P and DS-P THEN KD-PB
IF S-P and DS-Z THEN KD-PM

IF S-P and DS-N THEN KD-PS
IF S-Z and DS-P THEN KD-PS
IF S-Z and DS-Z THEN KD-Z
IF S-.Z and DS-N THEN KD-NS
IF S-N and DS-P THEN KD-NS
IF S-N and DS-Z THEN KD-NM
IF S-N and DS-N THEN KD-NB

where:

S-P: S is positive
S-Z: S is zero
S-N: S is negative
DS-P: DS is positive
DS-Z: DS is zero
DS-N: DS is negative
KD-PB: KD is positive big
KD-PM: KD is positive medium
KD-PS: KD is positive small
KD-NS: KD is negative small
KD-NM: KD is negative medium
KD-NB: KD is negative big

Step 5: Quantifying crisp input variables σx_{ei} and $\Delta\sigma x_{ei}$ through multiplying the scaling factors *GS* and *GDS*, respectively, that is $\sigma x_{ei} \times GS$ and $\Delta\sigma x_{ei} \times GDS$.

$$C_{2i} = \Im(\cdot) \times GKS \tag{12}$$

where $\Im(\cdot)$ is the fuzzy rules, and *GKS* denotes the scaling factor of C_{2i}.

Step 6: The control input u can be represented as:

$$u = -\sum_{i=1}^{2} (c_{1i} + c_{2i}) x_{ei} \tag{13}$$

where c_{1i} and c_{2i} are the elements of equivalent control gain and switching control gain, respectively.

IV. EXPERIMENTAL RESULTS

The proposed system parameters are listed in Table I. Firstly, to test the steady-state behavior of the DC-AC inverter using the proposed control method, the values of *L* and *C* filter parameters are assumed in suffering from 20% ~ 300% of nominal values while the DC-AC inverter system is under 10Ω resistive loading. Fig. 7 and Fig. 8 show output-voltage waveforms of the DC-AC inverter controlled by the proposed control method and the classic VSC. The proposed control method is more insensitive to the parameter variations than the classic VSC. Then, to test the transient behavior of the DC-AC inverter using the proposed control method, Fig. 9 shows the output voltage and the load current under TRIAC load. As can be seen, a fast recovery of the steady-state response is obtained. However, waveforms obtained using the classic VSC under the same loading is shown in Fig. 10, and a significant voltage drop occurs at the 90^0 firing angle. In final summary, the proposed control method provides the elimination of the chatter and achieves zero tracking error so that the good performance can be obtained as Fig. 7 and Fig. 9. Table II lists experimental output-voltage %THD under LC parameter variation and TRIAC load.

TABLE I. SYSTEM PARAMETERS

DC-bus Voltage V_{dc}	230V
Output Voltage v_c	$110V_{rms}$
Output Frequency *f*	60Hz
Filter Inductor *L*	1.5mH
Filter Capacitor *C*	20μF
Switching Frequency f_s	15kHz
Rated Load *R*	10Ω

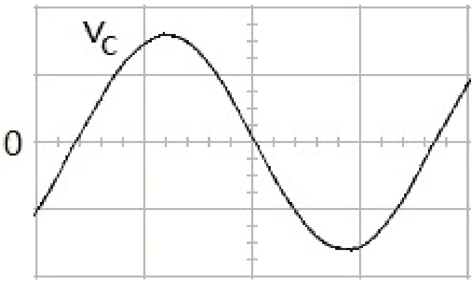


Figure 7. Wind energy inverter output voltage under LC parameter variation with the proposed control method (100V/div; 5ms/div).

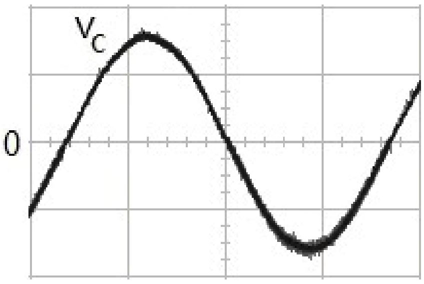


Figure 8. Wind energy inverter output voltage under LC parameter variation with the classic VSC (100V/div; 5ms/div).

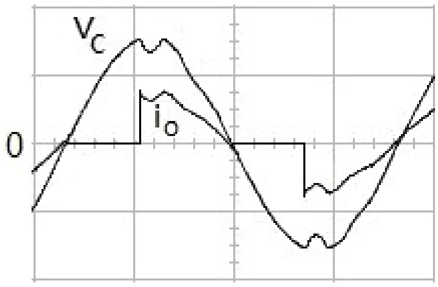


Figure 9. Wind energy inverter output waveforms under TRIAC load with the proposed control method (100V/div; 20A/div; 5ms/div).

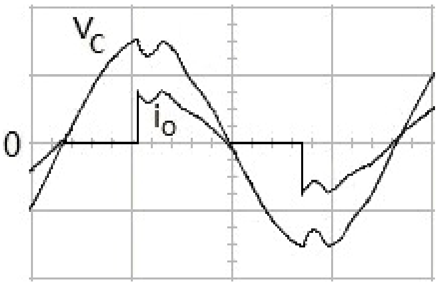


Figure 10. Wind energy inverter output waveforms under TRIAC load with the classic VSC (100V/div; 20A/div; 5ms/div).

TABLE II. EXPERIMENTAL OUTPUT-VOLTAGE %THD UNDER LC PARAMETER VARIATION AND TRIAC LOAD

	Proposed Method		Classic VSC	
Loading	LC Variation	TRIAC Load	LC Variation	TRIAC Load
%THD	1.24%	1.71%	10.87%	9.62%

V. CONCLUSIONS

In this paper, a high performance DC-AC inverter by the use of a fuzzy-based NVSC is proposed. The NVSC not only is capable of making a control system robust with regards to plant parameter variations and external load disturbances but also allows the system converge to the origin in finite time. However, the chatter still exists in switching manifold of NVSC. Thus, by the addition of FL, the switching manifold of the NVSC is smoothed, and the chatter can be eliminated. Experimental results are performed in support of the proposed control method.

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