

Fuzzy Variable Structure Control for PWM Inverters

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Abstract—This paper proposes the practical realization of a fuzzy variable structure control applied to a PWM inverter. Variable structure Control (VSC) is a robust control method for handling nonlinear systems where occur parameter variations and external disturbances. However, control input chattering round sliding surface exists, and may deteriorate the system performance. To reduce the chattering, a fuzzy logic for VSC is applied to overcome the problem. By composing the advantages of both VSC and fuzzy logic (FL), the PWM Inverter system can be designed and produces low total harmonic distortion (THD) output voltage and fast dynamic response under different types of load. Experimental results on a single-phase PWM inverter laboratory prototype controlled by a dSPACE-based DSP controller are presented to illustrate the improved performance, particularly under severe rectifier load. Moreover, for comparison purposes, a conventional variable structure controlled single-phase PWM inverter is also tested on the same experimental system.

Keywords—Variable structure Control (VSC), chattering, fuzzy logic (FL), total harmonic distortion (THD), PWM Inverter

I. INTRODUCTION

With the increasing demands for high-quality power sources, a pulse-width modulated PWM inverter has been used as a key element for a high-performance power conversion system for critical loads, like data processing systems, telephone switching systems, and life support equipment in hospitals. In that kind of applications it is necessary that the inverter generates by itself the voltage waveform. That kind of inverters, named voltage source inverters, are becoming more and more popular in standalone applications like Microgrids, being able to operate in parallel by using droop method or virtual inertias.

The critical point of these inverters is its performance that generally lies on the following criteria: (1) output voltage waveform with low harmonic distortion (THD) for linear and nonlinear loads; (2) fast transient response for load step changes; and (3) the steady-state error as small as possible. In order to achieve above criteria, proportional-integral (PI) controllers perform reasonably well under constant load conditions. However, the consistent regulation performance is not achieved when the process is subject to fluctuating load disturbances [1], [2], [3]. Also, various control schemes can

be found in literature, such as the multi-loop control [4], the deadbeat control [5], the fourier transform (DFT)-based harmonic elimination technique [6], and so on. However, these methods require complex mathematical models or large computation time.

Variable structure control has been recognized as a powerful device capable of exhibiting good robustness, even invariant under certain condition, with respect to system parameter variations and external disturbances [7], [8]. Many VSC applications to PWM inverter systems have been reported. In [9], a control strategy for DC/AC inverter is proposed in which an inverter is controlled by a double-loop regulation scheme. However, the control design uses a typical VSC and cumbersome analog implementation, and thus incurs distorted output voltage during steady-state operation when supplying a nonlinear load. Reference [10] utilizes two sliding control laws to achieve DC/AC converter tracking control. This method has a complicated hardware design and an undesirable chattering phenomenon. In the earlier works of [11] and [12], they adopt conventional VSC for PWM inverters, resulting in problems of chattering and steady-state errors. However, as mentioned above [9-12], owing to the sampling action of digital implementation and delay of switch device, the chattering exists in a VSC system is fearful to control system; In case of these inverter applications, chattering has caused serious voltage harmonics.

FL was developed in 1970s [13], and further developed in inverter applications, since its operation principle does not require precise knowledge of the load parameters, FL controllers have the potential of operating successfully under a wide range of load variation [14], [15]. Thus, in this paper, we will use a simple FL to reduce the chattering effect. By incorporating a VSC with FL, not only the sliding surface is fuzzified by FL, thus reducing the chattering, but also VSC accomplishes the rejection of system uncertainties. This proposed algorithm is then applied to the control of a PWM inverter system in which the control law is realized on a dSPACE DSP and will show the effectiveness of low output voltage distortion, fast dynamic response, and insensitive to load variation even under rectifier loads. Experimental results are finally shown to validate the performance of this proposed controller.

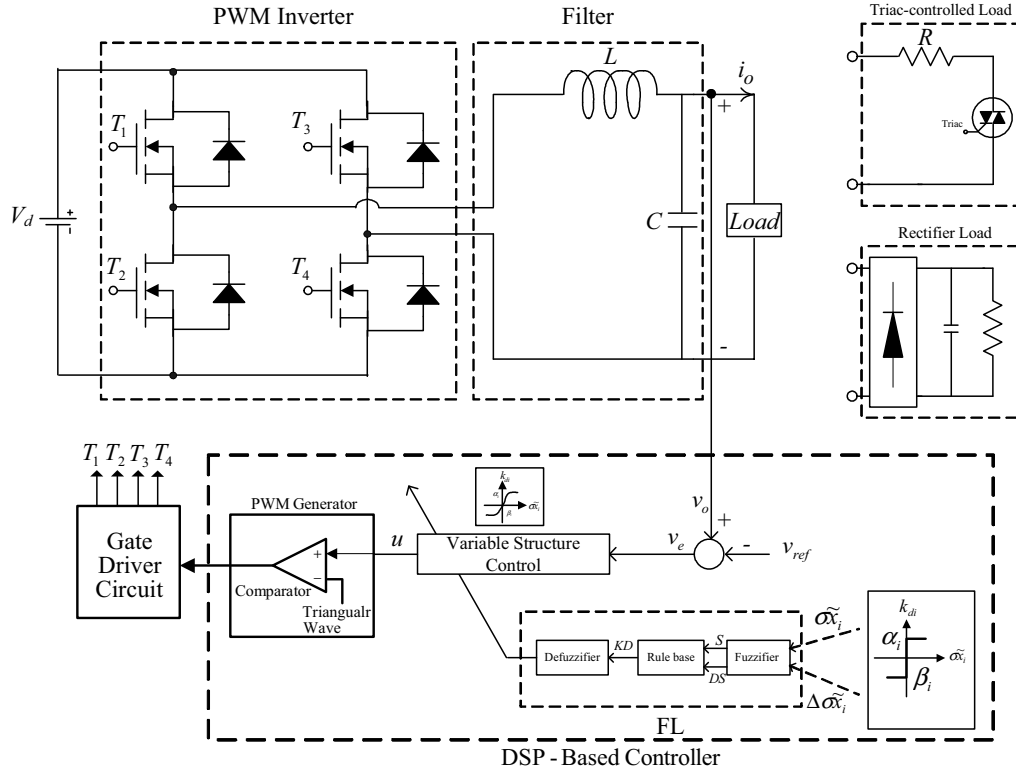


Fig. 1 Block diagram of PWM inverter system.

II. MATHEMATICAL MODELING

The system block diagram of PWM Inverter is shown in Fig. 1 [16]. Let v_o be the load voltage, v_{ref} be the desired sinusoidal waveform, and $v_e = v_o - v_{ref}$ be the voltage error. Assuming that the switching frequency is high enough, PWM inverter can be regarded as a constant gain, K_{pwm} . Choosing $\tilde{x}_1 = v_e$ and $\dot{\tilde{x}}_1 = \tilde{x}_2$, the resulting error dynamic state equation can be derived as

$$\begin{bmatrix} \dot{\tilde{x}}_1 \\ \dot{\tilde{x}}_2 \end{bmatrix} = \underbrace{\begin{bmatrix} 0 & 1 \\ -\frac{1}{LC} & -\frac{1}{RC} \end{bmatrix}}_A \begin{bmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{bmatrix} + \underbrace{\begin{bmatrix} 0 \\ \frac{K_{pwm}}{LC} \end{bmatrix}}_B u + \underbrace{\begin{bmatrix} 0 \\ -\frac{1}{LC}v_{ref} - \frac{1}{RC}\dot{v}_{ref} - \ddot{v}_{ref} \end{bmatrix}}_f \quad (1)$$

The control objective is to make the output voltage be equal to a reference input. The above system takes the following form

$$\dot{\tilde{x}} = A\tilde{x} + Bu + f \quad (2)$$

where $\tilde{x}$ is the error state vector, u is the control input, A is the system matrix, B is the control matrix, and f is the disturbance.

Then the sliding function is given by

$$\sigma = c_1\tilde{x}_1 + \tilde{x}_2 = c^T\tilde{x} \quad (3)$$

where c is the sliding surface coefficient vector.

The control input u is chosen as

$$u = -K^T\tilde{x} \quad (4)$$

where K is the feedback gain vector.

The dynamics in sliding motion can be written as

$$\dot{\sigma} = 0 \quad (5)$$

Then, for $\det(cB) \neq 0$, the equivalent control u_{eq} is derived as follows

$$\dot{\sigma}|_{u=u_{eq}, f=0} = c^T\dot{\tilde{x}} = c^T(A\tilde{x} + Bu_{eq}) = 0 \quad (6)$$

Therefore, the equivalent control can be expressed as

$$u_{eq} = -K_{eq}^T\tilde{x} \quad (7)$$

where K_{eq}^T is the equivalent feedback gain vector.

From (6) and (7), it yields obtains

$$K_{eq}^T = (c^TB)^{-1}c^TA \quad (8)$$

The hitting control law guarantees a system trajectory that moves toward the sliding surface from any initial condition if the following condition occurs:

$$\lim_{\sigma \rightarrow 0} \sigma \dot{\sigma} < 0 \quad (9)$$

Let system control u be composed by K_{eq}^T and $K_s^T \text{sign}(\sigma\tilde{x})$, that is,

$$u = -K_{eq}^T\tilde{x} - K_s^T \text{sign}(\sigma\tilde{x}) \quad (10)$$

For two-order system case, K_s^T can be written as

$$K_s^T = \begin{bmatrix} k_{s1} \\ k_{s2} \end{bmatrix} \quad (11)$$

and k_{si} , $i = 1$ to 2 is given by

$$k_{si} = \begin{cases} \alpha_i & \text{if } \tilde{\alpha}_i > 0 \\ 0 & \text{if } \tilde{\alpha}_i = 0 \\ \beta_i & \text{if } \tilde{\alpha}_i < 0 \end{cases} \quad (12)$$

Thus, the condition in (12) is represented to satisfy the inequality (9) and the system state (2) will be transferred on the sliding surface (5). Obviously, (12) uses a sign function and often causes chattering problem in practice. To solve such a problem, fuzzy logic is introduced, and the design is described in detail in Section III.

III. DESIGN OF FUZZY VARIABLE STRUCTURE CONTROL

FL is a direct method for controlling a system without the need of a mathematical model. FL gets crisp data from various sensors. These data are changed to linguistic or fuzzy membership functions via the fuzzification process. After that, they go through a set of fuzzy “IF-THEN” rules in an inference engine and result in fuzzy outputs. These fuzzy outputs are then changed back to crisp values by the defuzzification.

If the VSC is implemented by means of a digital signal processor (DSP), the switching actions with chattering will occur in (12), which is a crisp version. In other words, the sliding surface is a particular fuzzy case, and its membership function is defined as

$$\mu_{\sigma=0} = \begin{cases} 1 & , \sigma = 0 \\ 0 & , \text{otherwise} \end{cases} \quad (13)$$

To alleviate the chattering, fuzziness of the sign function and sliding surface are shown as Fig. 2 and Fig. 3, respectively.

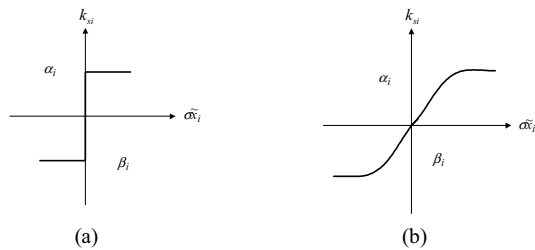


Fig. 2 (a) Switching criteria with the sign function, and (b) fuzziness of the sign function.

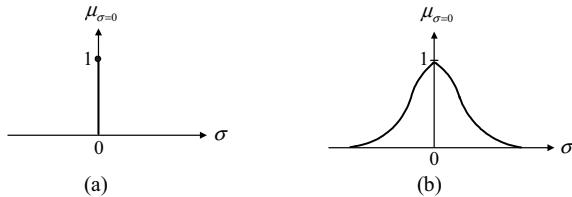


Fig. 3 (a) Sliding surface as a special fuzzy case, and (b) fuzziness of the sliding surface.

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

IF farther from the sliding surface
THEN larger feedback gain

(14)

The design steps are described as follows:

Step 1: To govern system dynamic, define two inputs, $\tilde{\alpha}_i$ and $\Delta\tilde{\alpha}_i$ (the change of $\tilde{\alpha}_i$).

Step2: To determine the system dynamic behavior, we define a crisp sliding surface, $\sigma = c^T \tilde{x}$.

Step3: The fuzzy linguistics and the membership functions of the fuzzy input and output variables S , DS , KD are nominated as shown in Fig. 4.

Step 4: The output of each rule is determined by inference method as follows:

IF S.P and DS.P THEN KD.PB
IF S.P and DS.ZO THEN KD.PM
IF S.P and DS.N THEN KD.PS
IF S.ZO and DS.P THEN KD.PS
IF S.ZO and DS.ZO THEN KD.ZO
IF S.ZO and DS.N THEN KD.NS
IF S.N and DS.P THEN KD.NS
IF S.N and DS.ZO THEN KD.NM
IF S.N and DS.N THEN KD.NB

where

S.P: S is positive
S.ZO: S is zero
S.N: S is negative
DS.P: DS is positive
DS.ZO: 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: Quantification of the crisp input variables $\tilde{\alpha}_i$ and $\Delta\tilde{\alpha}_i$ is carried out by multiplying the scaling factors GS and GDS , respectively, i.e., $\tilde{\alpha}_i \times GS$, and $\Delta\tilde{\alpha}_i \times GDS$.

$$k_{si} = T(\bullet) \times GKS \quad (15)$$

where $T(\bullet)$ indicates the fuzzy rules, and GKS is the scaling factor of k_{si} .

Step 6: The control input u is written as

$$u = - \sum_{i=1}^2 (k_{eqi} + k_{di}) \tilde{x}_i \quad (16)$$

where k_{eqi} are the elements of equivalent feedback gain, K_{eq}^T .

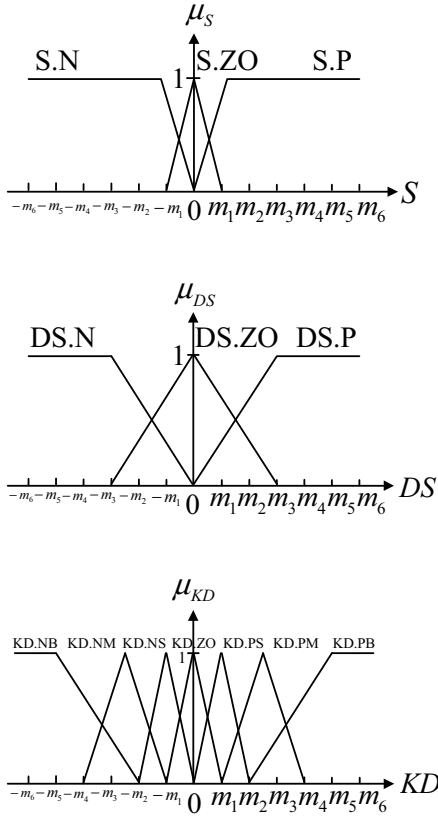


Fig. 4 Fuzzy membership functions of S , DS and KD .

IV. EXPERIMENTAL RESULTS

In order to confirm the effective performance of the PWM inverter, key experiment under rectifier load were done. The controller is validated with a hardware setup. The control algorithms are designed and implemented using MATLAB/Simulink and the codes are then compiled and loaded to a dSPACE DS1102 controller board implement the controller. The system parameters are summarized in Table I.

Table I System parameters

DC-bus Voltage V_d	250V
Output Voltage V_o	110V _{rms}
Output Frequency f	60 Hz
Filter Inductor L	2 mH
Filter Capacitor C	30 μ F
Switching Frequency f_s	18 kHz
Rated Load R	20 Ω

In order to test the transient performance, the load-step change response is shown in Fig. 5 when the rated load is suddenly connected. We found that the proposed controller exhibits small voltage sag and fast recover time under load-step changes. On the contrary, the waveform shown in Fig. 6 with conventional VSC exhibits worst voltage compensation at the firing angle. The rectifier load consists of a full wave rectified with a parallel resistor, a 55 Ω resistance and 100 μ F filter capacitor. A comparison of the performance by using the proposed controller and the conventional VSC are shown in

Fig. 7 and Fig. 8, respectively. Fig. 7 depicts the output voltage waveform which is nearly sinusoidal and has low distortion (%THD of 2.89%), which is under the industrial standard of 5%. Fig. 8 exhibits a noticeable distortion (%THD of 8.15%). Indeed, the chattering is alleviated by the proposed controller, and thus the inverter output voltage can obtain a significant improvement reducing the voltage THD under rectifier-type load condition.

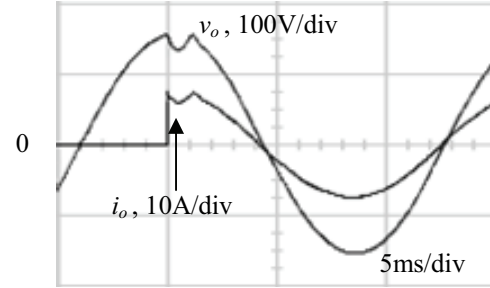


Fig. 5 Load step changes (from full load to no load at 90°) with fuzzy VSC.

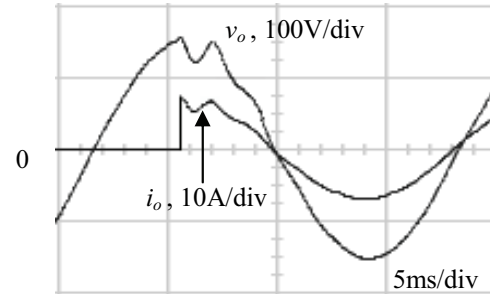


Fig. 6 Load step changes (from full load to no load at 90°) with conventional VSC.

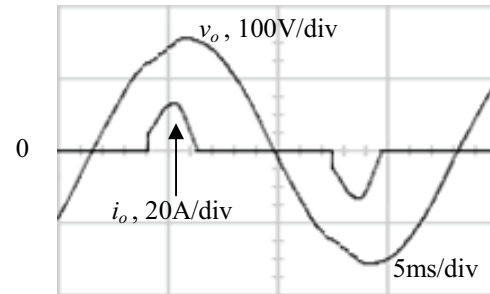


Fig. 7 Voltage and current waveforms when supplying a rectifier load, using fuzzy VSC

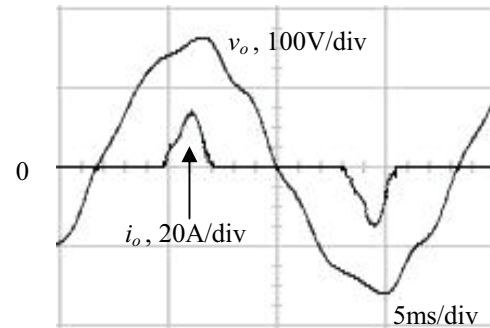


Fig. 8 Voltage and current waveforms when supplying a rectifier load, using conventional VSC

V. CONCLUSIONS

This paper proposes a fuzzy VSC applied to PWM inverter in order to achieve the following features: fast dynamic response, chattering reduction, and low THD output voltage. The proposed controller not only has the merits of the conventional VSC but also reduces the chattering problem by using fuzzy logic. The system's performance has been verified by means of experimental tests on a laboratory inverter prototype, confirming the proposed methodology. Compared to the conventional VSC under the same operating conditions, the proposed controller exhibits better inverter performance.

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