Fuzzy Tuning and Power Reaching Law-Based Discrete Sliding Mode Control for Solar Photovoltaic Inverters

En-Chih Chang, Hung-Liang Cheng and Chun-An Cheng

Department of Electrical Engineering, I-Shou University, Taiwan, R.O.C.
E-mail: enchihchang@isu.edu.tw

Abstract. This paper develops a digital signal processor (DSP)-controlled solar photovoltaic inverter that is well realized to prove the proposed controller. The discrete sliding mode control (DSMC) with power reaching law (PRL) not only suits for digital implementation because of its finite sampling frequency but permits faster convergence speed. However, the chattering around PRL-based DSMC exists and may cause excessive power losses. A fuzzy tuning technology is employed to handle the problem of the chattering so that the robustness of the system can be increased. Simulation results display that the proposed solar photovoltaic inverter can generate low total harmonic distortion (THD) under rectifier-type load circumstances and fast transient response under step load changes. Experimental results on a solar photovoltaic inverter laboratory prototype controlled by a digital controller are provided to substantiate both theoretical analysis and simulation results.

1. Introduction

With the raising indispensability for high-quality AC power supplies, solar photovoltaic inverters have been adopted as an important part for sustainable energy systems [1], [2]. Solar photovoltaic inverters are demanded to keep high performance sine output voltage of low harmonic distortion and fast transience even feeding highly nonlinear loads that can be achieved by employing feedback controller. With the availability of high-frequency switching devices and the popularity of the DSP, numerous digital control methods have been applied in solar photovoltaic inverters [3-5] and one of them is sliding mode control (SMC) because of its insensitivity against system uncertainties [6-8]. The SMC methodology is initially developed from a continuous-time perspective. If it is implemented on a digital computer, the limited sampling rate, sample/hold effects and discrete errors will worsen system performance. Thereby we present a power reaching law (PRL)-based discrete sliding mode control (DSMC) to carry out digital implementation and simultaneously accelerates convergence rate in the design of solar photovoltaic inverters [9-12]. But, high frequency oscillations called chattering that may lead to the excitation of unmodeled dynamics and even damage the plant. A fuzzy tuning technology has been effectively used in various science and engineering fields and possesses many advantages, such as model-free, universal approximation theorem and rules-based algorithm. It relies on the human capability to understand the behaviour of the system, and provides qualitative control rules which do neither request an exact mathematical modelling of the system nor complicated computations [13-15]. The FL is thus incorporated in PRL-based DSMC to eliminate the effect of the chattering. By using the association of the FL and PRL-based DSMC, simulations and experiments on a solar photovoltaic inverter prototype have proved the achievement of very low THD under nonlinear loading and fast dynamic response under transient loading.
2. System Modelling and Controller Design

Fig. 1 depicts a generally utilized solar photovoltaic inverter, which is composed of an LC filter and switching component with MOSFET transistors. By applying KVL and KCL, the state space equations of solar photovoltaic inverter can be formulated as

$$L \frac{di_L}{dt} + v_c = K_{\text{pwm}}v_{\text{con}}$$  \hspace{1cm} (1)$$

$$i_L = C \frac{dv_c}{dt} + \frac{v_c}{R}$$  \hspace{1cm} (2)$$

where $K_{\text{pwm}} = V_d/\hat{v}_{\text{tri}}$ the equivalent gain of the inverter, $V_d$ = the dc supply voltage, $\hat{v}_{\text{tri}}$ = the amplitude of the triangular wave of the PWM, and $v_{\text{con}}$ = the control signal.

Substituting (2) into (1), the differential equation is expressed as follows.

$$\frac{\ddot{v}_c}{RC} = -\frac{1}{LC}v_c - \frac{1}{LC}v_c - \frac{K_{\text{pwm}}}{LC}\frac{v_c}{R}$$  \hspace{1cm} (3)$$

where $x = [v_c, \dot{v}_c]^T$, and $u = v_{\text{con}}$, the (3) can be rewritten as

$$\begin{pmatrix}
\dot{x}_1 \\
\dot{x}_2
\end{pmatrix} =
\begin{bmatrix}
0 & 1 & -1 \\
-\frac{1}{LC} & -\frac{1}{RC} & 0
\end{bmatrix}
\begin{pmatrix}
x_1 \\
x_2
\end{pmatrix} +
\begin{bmatrix}
0 \\
\frac{K_{\text{pwm}}}{LC}
\end{bmatrix}u$$  \hspace{1cm} (4)$$

The fuzzy SMC with PRL is now employed to make controlled solar photovoltaic inverter resist the prescribed load uncertainty while keeping low distorted output-voltage and achieving robust performance.

For digital implementation purpose, the discrete-time equation can be stated as

$$x_z(k + 1) = \Phi x_z(k) + \Gamma u(k) + w(k)$$  \hspace{1cm} (5)$$

where $x_z(k) = [v_c, \dot{v}_c]^T$, $\Phi = e^{AT}$, $\Gamma = \begin{bmatrix} T_s & e^{AT}d_T \end{bmatrix}B$, and $T_s$ is the sampling period, $w(k) = i_o(k)$.

In order to enforce the output $x_z(k)$ to $x_{\text{ref}}(k)$. Therefore, a tracking error $x_{ze}(k)$ can be expressed as

$$x_{ze}(k) = x_z(k) - x_{\text{ref}}(k)$$  \hspace{1cm} (6)$$

where $x_{\text{ref}}(k)$ stands for reference sinusoidal voltage.

From (5) and (6), the error dynamics yields
\( x_{ze}(k+1) = \Phi x_{ze}(k) + \Gamma u(k) + \psi(k) \) \tag{7}

where \( \psi(k) = \Phi x_{ref}(k) - x_{ref}(k+1) + w(k) \).

The following discrete sliding surface \( s(k) \) can be constructed by
\[
s(k) = cx_{ze}(k)
\] \tag{8}

where \( c \) is a matrix.

Then,
\[
s(k+1) = cx_{ze}(k+1) = c\Phi x_{ze}(k) + c\Gamma u(k) + c\Phi x_{ref}(k) - cx_{ref}(k+1) + cw(k)
\] \tag{9}

The power reaching law can be introduced as
\[
s(k+1) = s(k) - \varepsilon T_s [s(k)]^\gamma \text{sgn}(s(k))
\] \tag{10}

where \( 0 < \varepsilon T_s < 1 \) and \( 0 < \gamma < 1 \).

From (9) and (10), we have
\[
u(k) = -(c\Gamma)^{-1}\left[c\Phi x_{ze}(k) + c\Phi x_{ref}(k) - cx_{ref}(k+1) - s(k) + \varepsilon T_s [s(k)]^\gamma \text{sgn}(s(k)) + cw(k)\right]
\] \tag{11}

The sgn function is shown in (11) and it frequently has the chattering in practice. Thus, the sgn function and sliding surface are fuzzified, so that the chattering can be eliminated. The sliding surface is a particular fuzzy case and its membership function can be defined below.

\[
\Lambda_{s=0} = \begin{cases} 1, & s = 0 \\ 0, & \text{otherwise} \end{cases}
\] \tag{12}

Then, the human experience is fixed as linguistic rules in the following.

3. Simulation and Experimental Results

The parameters of the solar photovoltaic inverter used for the proposed controller are listed in Table 1. In order to test the performance of the transience further, Fig. 2(a) shows the simulated output voltage and the load current obtained using the proposed controller under step load change from no load to full load at a 90 degree firing angle. As can be seen, the proposed controller shows slight instant voltage droop and fast recovery of the steady-state response. Similarly, the transience with linear resistive load is explored and Fig. 2(b) displays the experimental result with step load change from no load to full load at a 90 degree firing angle. The transient behaviour is satisfactory and the output-voltage droop with fast retrieval is also tiny. Figure 3(a) shows the simulated output voltage and the load current waveforms of the solar photovoltaic inverter controlled by the proposed controller under rectifier load (parallel resistor, 40 Ω and capacitor filter, 200 μF). A very low output-voltage distortion (%THD is 0.91%) appears at the output voltage while the current ascends suddenly. The experimental performance of the proposed controller with rectifier load (capacitive filter 200μF and 40 Ω resistive load) is reported, too. Fig. 3(b) represents that the experimental output voltage is almost sine wave and produces low distortion (%THD of output-voltage is 1.92%), which exceeds the industrial standard. In the phase planes, the classic SMC shown in Fig. 4(a) with a chatter vibration converges to the origin. The transient response and steady-state errors are unsatisfactory. However, the state trajectory of the proposed controller plotted in Fig. 4(b) provides fast and smooth convergence to zero. Thereby, the proposed controller does effectively eliminate the chattering and decrease steady-state errors.

| Table 1. System parameters |
|---------------------------|
| **DC-link voltage** | \( V_d = 200 \text{ V} \) |
| **Filter inductor** | \( L = 0.2 \text{ mH} \) |
| **Filter capacitor** | \( C = 5 \mu \text{F} \) |
| **Resistive load** | \( R = 12 \Omega \) |
| **Output voltage and frequency** | \( V_c = 110 \text{ V}_{\text{rms}}, f = 60 \text{ Hz} \) |
| **Switching frequency** | \( f_s = 18 \text{ kHz} \) |
4. Conclusions
A combination of the Fuzzy tuning technology and the PRL-based DSMC for solar photovoltaic inverters is proposed to maintain low distorted output-voltage even under non-linear loading. As compared to continuous-time SMC, the DSMC can speed up the convergence rate and is more suitable for digital implementation, while the Fuzzy tuning devotes to eliminate the chatter phenomenon. Experimental and simulation results corroborate the applicability and efficacy of the proposed controller.

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References

[1] P. Breeze, Solar Power Generation, Academic Press, 2016.
[2] R. Teodorescu, M. Liserre, and P. Rodriguez, Grid Converters for Photovoltaic and Wind Power Systems, Wiley, New York, USA, 2010.
[3] M. Gangavarapu, “Perturb and Observe MPPT Algorithm Implementation for PV Applications,” International Journal of Computer Science and Information Technologies, vol. 6, no. 2, pp. 1884-1887, 2015.
[4] I. P. Ratna, W. Sapto, and R. Muhamad, “Maximum Power Point Tracking for Photovoltaic Using Incremental Conductance Method,” Energy Procedia, vol. 68, pp. 22-30, 2015.
[5] R. J. Wai, C. Y. Lin, Y. C. Huang, and Y. R. Chang, “Design of High-Performance Stand-Alone and Grid-Connected Inverter for Distributed Generation Applications,” IEEE Trans. Ind. Electron., vol. 60, no. 4, pp. 1542-1555, 2013.
[6] X. Hao, X. Yang, T. Liu, L. Huang, and W. J. Chen, “A Sliding-Mode Controller With Multiresonant Sliding Surface for Single-Phase Grid-Connected VSI With an LCL Filter,” IEEE Trans. Power Electron., vol. 27, no. 5, pp. 2507-2514, 2012.
[7] A. Abrishamifar, A. A. Ahmad, and M. Mohamadian, “Fixed Switching Frequency Sliding Mode Control for Single-Phase Unipolar Inverters,” IEEE Trans. Power Electron., vol. 28, no. 5, pp. 2259-2268, 2013.
[8] R. Aghatehrani, and R. Kavasseri, “Sensitivity-Analysis-Based Sliding Mode Control for Voltage Regulation in Microgrids,” IEEE Trans. on Sustainable Energy, vol. 4, no. 1, pp. 50-57, 2013.
[9] W. Gao and J. C. Hung, “Variable structure control of nonlinear systems: A new approach,” IEEE transactions on Industrial Electronics, vol. 40, no. 1, pp. 45–5, February 1993.
[10] V. K. Thakar, “Power rate reaching law based discrete sliding mode control,” Annual Progress Seminar 2005.
[11] W. Gao, Y. Wang, and A. Homaifa, “Discrete-time variable structure control systems,” IEEE transactions on Industrial Electronics, vol. 42, no. 2, pp. 117–122, April 1995.
[12] S. C. Tan, Y. M. Lai, and C. K. Tse, Sliding Mode Control of Switching Power Converters: Techniques and Implementation, CRC Press, Boca Raton, FL, USA, 2012.
[13] X. S. Yang, Nature-Inspired Algorithms and Applied Optimization, Springer, New York, 2018.
[14] Y. Y. Tzou, and R. S. Ou, “DSP-Based Feedforward Fuzzy Control of a PWM Inverter for AC Voltage Regulation,” Journal of Control Systems and Technology, vol. 2, No. 4, pp. 231-238, 1994.
[15] A. Syropoulos, Theory of Fuzzy Computation, Springer-Verlag, New York, 2014.