Research on Shoot-Through Zero Vector of Impedance Source Linearization Control Strategy

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Abstract: Z-source inverter takes advantage of a distinctive impedance source network and modulation method of shoot-through vector, and achieves the function of buck/boost DC - AC inverter in the single stage system at the same time, which is suitable for grid-connected PV systems with large input voltage variations. The purpose of this study is to draw a unified method of shoot-through vector and grid inverter of the z-source inverter, apply the method of state-space averaging for the modeling analysis of the z-source inverter and give a complete mathematical model. Based on which and according to the nonlinear control theory and making use of the linearization of affine nonlinear model of the z-source inverter, we can get the specific derivation of equation. The results of the simulation and experiment show that according to the linearization of the shoot-through vector with affine nonlinear model for the z-source, we can make the system have the characteristics of fast and accurate tracking, small overshoot, small DC voltage, AC current ripple and small THD, and it has a certain practical value.

Keywords: Z-source inverter, state-space averaging method, linearization control, shoot-through vector.

1. INTRODUCTION

As the key equipment in the photovoltaic generation system, grid-connected inverter can transform direct current produced by solar cells into alternating current. The requirement about inverter's output waveform quality mainly includes two aspects: one is high accuracy of steady-state, and the other is well dynamic performance. Therefore, research on the development of high-performance inverter has been a key point in the photovoltaic electric generation field [1, 2]. The traditional inverter mainly has two kinds of topology structure: voltage source and current source type, that must have access to a buck-boost DC-DC converter through the input terminal, so that it is weak in anti-EMI.Z-source inverter which is also called impedance source inverter. It is a kind of practical and applicable inverter which not only realizes the function of voltage adjusting, but also overcomes the deadband time by introducing shoot-through state, so that it can make two bridge legs of the same switch tube turn on together instead of destroying the switch tube. Most traditional power electronic converters use PI regulating error technique [3, 4], which is not dependent on mathematical models but establish mathematical models with nonlinear systems which consist of fixed parameters and structure. Then, it will make small-signal linear perturbation approximation in steady operating points that will turn the original nonlinear system into a linear model. After that, it will do PI compensation design on the controlled variable, that will work by dynamically adjusting the percentage of the duty ratio of the switch. What's more, this control program only works accurately when the actual operating point of the system is very stable and more close to the steady operating points.

However, with the increasing widely application of power electronic equipment, request on the scope of work and the dynamic and static performance of the system of the power electronic switching converters is becoming higher. Considering the nonlinear characteristics of power electronic switching converters, unstable factors that the z-source inverters' particular non minimum phase property have, especially the stability and dynamic response when the system is in the large disturbance, and nonlinear contains all sorts of uncertainty information control model is urgent [5-7]. This paper deeply studies the z-source inverter of shoot-through vector linearization control strategy.

2. WORKING PRINCIPLE

Single-phase z-source inverter's shoot-through state consists of single bridge arm shoot-through and double arm shoot-through. Double arm straight will increase switching losses but ensure the steady DC voltage, so this text takes the latter one as the subject[8, 9]. Fig. (**1**) is a single-phase z-source inverter for grid-connected system. We make voltage source v_s and internal resistance R_{mpp} series equivalent because of the panels influenced by environmental factors. The output voltage is v_{pv} .

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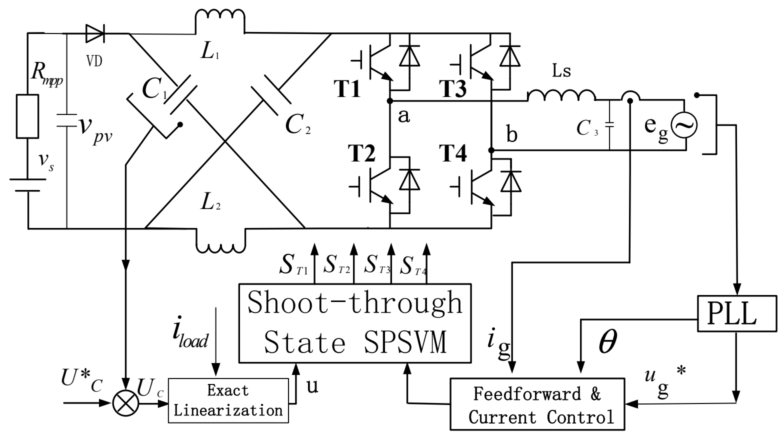

Fig. (1). Single-phase Z-source inverter for grid-connected system.

Considering that the inductor volt second remain unchanged in the shoot-through state and non-shoot-through state and the average voltage u_L across the inductor is zero in a switching period, we can get the relationship between $u_o = u_c$ and u_s :

$$u_L = \frac{t_o u_c + t_1(u_s - u_c)}{T} = 0 \tag{1}$$

$$\frac{u_c}{u_s} = \frac{1-D}{1-2D} \tag{2}$$

In the equation above, shoot-through duty cycle (D-voltage up factor) is: $D = \frac{t_0}{T}$, $T = t_0 + t_1$.

AC voltage peak point of the inverter is:

$$u_{ab} = M\frac{u_{pv}}{2} = M\,B\frac{u_{pv}}{2} \tag{3}$$

In the equation above, M is the modulation ratio, and B is coefficient of pressure, and $M \le 1$, $B \ge 1$.

By adjusting the duty ratio and modulation ratio, the inverter AC value can be controlled, so that the z-source is a topological structure of lifting pressure which is very suitable for photovoltaic inverter input voltage fluctuation larger.

3. LINEARIZATION OF AFFINE NONLINEAR MODEL OF THE Z-SOURCE

We analyzed the stability of the dynamic system under the condition of considering the capacitor voltage and inductor current of the z-source as feedback quantity and turn out to find that there will be dynamic instability in the system if considering the former one as feedback quantity [10]. Therefore, this paper takes the inductor current as feedback control scheme to control output voltage.

$$\dot{x} = Ax + Bu \tag{4}$$

In the equation above, $x = [\,i_L \quad v_C \quad v_{pv}\,]^T$ is state variable, $u = [\,v_s \quad i_{load}\,]^T$ is input variable, i_L is z-source inductor current, v_C is z-source network capacitor voltage, i_{load} is load current. The equation of shoot-through is:

$$\dot{x} = A_1 x + B_1 u = \begin{bmatrix} 0 & -\frac{1}{L} & 0 \\ -\frac{1}{C} & 0 & 0 \\ 0 & 0 & -\frac{1}{C_{pv}R_{mpp}} \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C} \\ \frac{1}{C_{PV}R_{mpp}} & \frac{1}{C_{pv}} \end{bmatrix} u \tag{5}$$

The equation of non-shoot-through state is:

$$\dot{x} = A_2 x + B_2 u = \begin{bmatrix} 0 & -\frac{1}{L} & \frac{1}{L} \\ \frac{1}{C} & 0 & 0 \\ -\frac{2}{C_{pv}} & 0 & \frac{1}{C_{pv}R_{mpp}} \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 0 & -\frac{1}{C} \\ \frac{1}{C_{PV}R_{mpp}} & \frac{1}{C_{pv}} \end{bmatrix} u \tag{6}$$

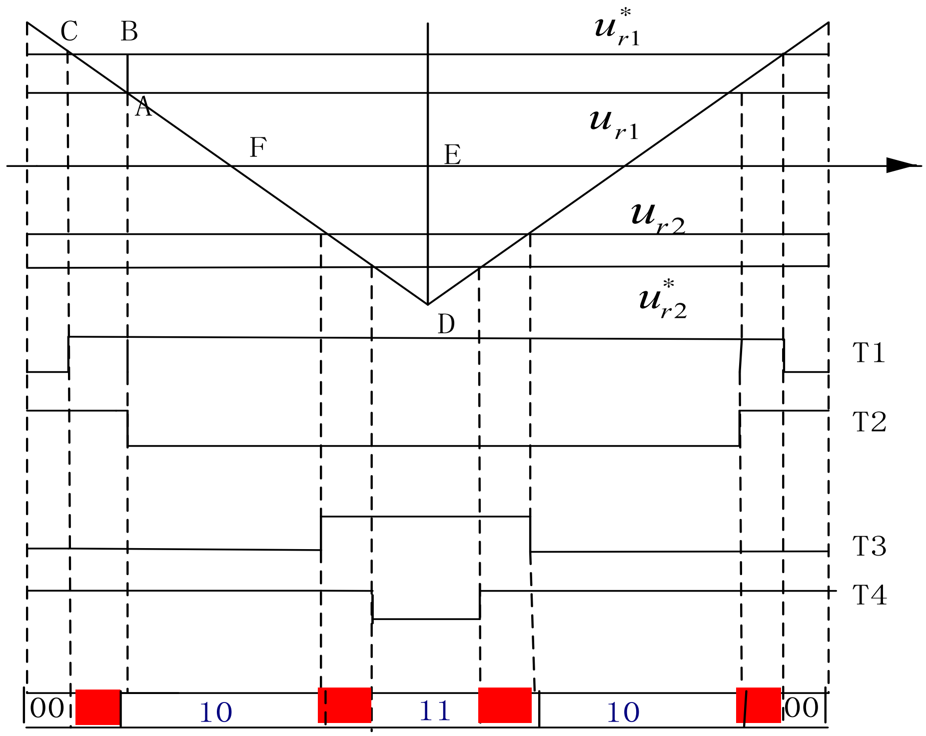

Fig. (2). The control principle of single-phase grid connected inverter with zero vector.

According to the state-space averaging method, we can get state space average model of the z-source inverter system. D is shoot-through zero vector duty ratio and 1-D is non-shoot-through duty ratio (Fig. **2**).

$$\dot{x}=\left[DA_1+(1-\mathrm{D})A_2\right]x+\left[DB_1+(1-D)B_2\right]u \tag{7}$$

$$A=DA_1+(1-\mathrm{D})A_2=\begin{bmatrix} 0 & -\frac{1-2D}{L} & \frac{1-D}{L} \\ \frac{1-2D}{C} & 0 & 0 \\ -\frac{2(1-2D)}{C_{PV}} & 0 & -\frac{1-D}{C_{pv}} \end{bmatrix}$$

$$B=DB_1+(1-D)B_2=\begin{bmatrix} 0 & 0 \\ 0 & -\frac{1-D}{C} \\ \frac{1}{C_{PV}R_{mpp}} & \frac{1-D}{C_{pv}} \end{bmatrix}$$

With the nonlinear control of photovoltaic array to output voltage, we choose the feedback control of photovoltaic array's output voltage v_{pv} as the output variable. D, which is shoot-through duty ratio is input variable and expressed by u, which is the reference value of output voltage where the photovoltaic array denotes the maximum power point. This way we can transform eq. 7 to affine nonlinear one like Eq. (12).

$$\begin{cases} \dot{x}=f(x)+g(x)u \\ y=h(x)=x_3-V_{mpp} \end{cases} \tag{12}$$

$$f(x)=\begin{bmatrix} \frac{x_3-x_2}{L} \\ \frac{x_1-i_{load}}{C} \\ \frac{i_{load}-2x_1}{C_{PV}}+\frac{v_s-x_3}{C_{PV}R_{mpp}} \end{bmatrix} \quad g(x)=\begin{bmatrix} \frac{2x_2-x_3}{L} \\ \frac{i_{load}-2x_1}{C} \\ \frac{2x_1-i_{load}}{C_{PV}} \end{bmatrix} \tag{13}$$

$$x=\left[x_1 \quad x_2 \quad x_3\right]^T=\left[i_L \quad v_C \quad v_{pv}\right]^T$$

According to Eq. (12), this system is a single input single output affine nonlinear system which is nonlinear for state variable x and linear for controlled variable u, and we use the feedback of the exact linearization state to linearize.

4. PART OF THE EXACT LINEARIZATION FOR Z-SOURCE INVERTER

When x is equal to 0, the rank of matrix $\left[g(x) \;\; ad_f g(x) \;\; ad_f^2 g(x)\right]$ is 3, which is also equal to the dimension of the system. The system has an output function called $\omega(x)$ that will make relative degree $r=n=3$. However, we can't achieve complete linearization via state feedback from equation 12 but to partly realize the linearization of the system. What we should do next is to find the output function $\omega(x)$ to make:

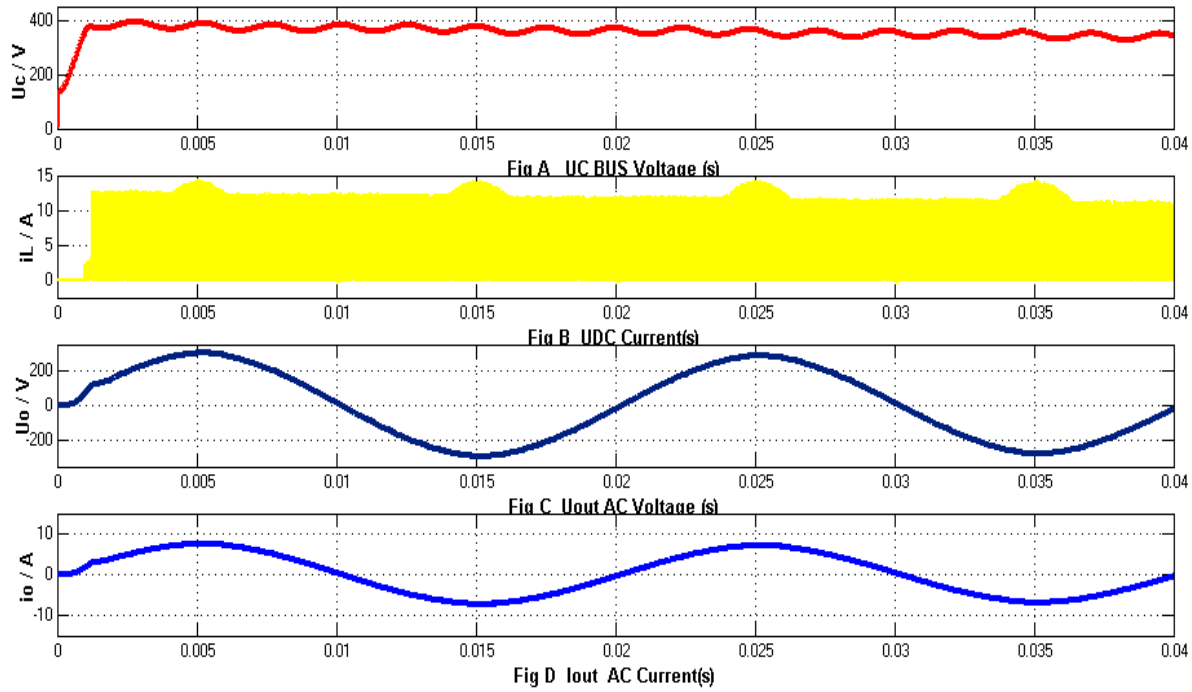

Fig. (3). Traditional algorithm of controlling the the waveforms with shoot-through zero vector.

$$\begin{aligned} &L_g\omega(x)=0 \\ &L_gL_f\omega(x)=0 \\ &L_gL_f^2\omega(x)=0 \end{aligned} \tag{14}$$

Since it is difficult to solve the partial differential equations above, we use the zero dynamics method to make the state equation of the system partially linearized. Because of the zero dynamics' stability of the system, we need to take internal dynamics of the system into consideration and make the system partially linearized via reasonable coordinate conversion.

$$z_1=\varphi_1(x)=h(x)=x_3-v_{mpp} \tag{15}$$

The coordinate transformation must meet the following criteria : $L_g\varphi_2(x)=L_g\varphi_3(x)=0$. The solution is:

$$\begin{aligned} &z_1=\varphi_1(x)=h(x)=x_3-v_{mpp} \\ &z_2=\varphi_2(x)=Cx_2+C_{pv}x_3 \\ &z_3=\varphi_3(x)=L(x_1^2-x_1i_{load})+Cx_2^2+\frac{C_{pv}}{2}x_3^2 \end{aligned} \tag{16}$$

Its inverse mapping is:

$$\begin{aligned} &x_1=\frac{Li_{load}+\sqrt{L^2i_{load}^2+4L\left[z_3-\frac{2z_2^2-\Delta}{2C}\right]}}{2L} \\ &\Delta=4C_{pv}z_2(z_1+v_{mpp})+(2C_{pv}^2+C_{pv}C)(z_1+v_{mpp})^2 \\ &x_2=\frac{1}{C}\left[z_1-C_{pv}(z_1+v_{mpp})\right] \\ &x_3=z_1+v_{mpp} \end{aligned} \tag{17}$$

Based on this coordinate transformation, we can get the following equation:

$$\dot{z}_1=L_fh(x)+L_gh(x)u=\frac{i_{load}-2x_1}{C_{pv}}+\frac{v_s-x_3}{C_{pv}R_{mpp}}+\frac{2x_1-i_{load}}{C_{pv}}u \tag{18}$$

The zero dynamics:

$$\begin{aligned} &L_f\varphi_2(x)=-x_1+\frac{v_s-x_3}{R_{mpp}} \\ &L_f\varphi_3(x)=-x_2i_{load}+\frac{x_3(v_s-x_3)}{R_{mpp}} \end{aligned} \tag{19}$$

Then we can get the control law of state feedback according to $z=\dot{z}=0$.

$$u=-\frac{L_fh(x)}{L_gh(x)}=1+\frac{x_3-v_s}{(2x_1-i_{load})R_{mpp}} \tag{20}$$

After that, we will make no assignment (or for zero) for the deadband register of TMS320F28335 by utilizing the

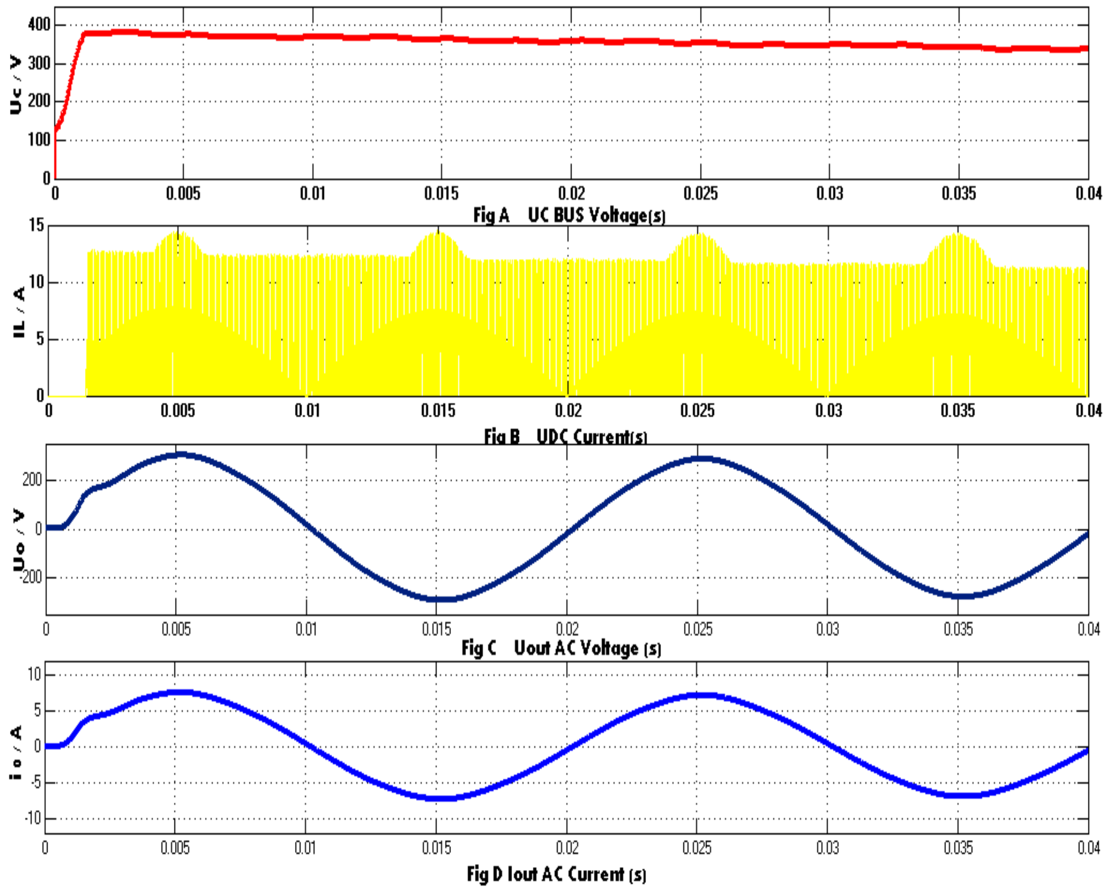

Fig. (4). Linearization algorithm of controlling the waveforms with shoot-through zero vector.

feedback. Next, we can make the value of shoot-through zero vector plus the grid connected current given value and AC voltage feed forward value, and assign them to the registers called CMPR1, CMPR2, CMPR3, so that the zero vector will be generated by CMPR3 based on the linearized results of real-time state equations, and realize the adjustment of DC voltage at last.

5. SIMULATION AND EXPERIMENT

5.1. Simulation by MATLAB

In order to verify the correctness and validity of control strategy, we use Matlab/Simulink to simulate the control strategy of the z-source inverter. The simulation parameters are the following ones: inverter power is 1.5KW, $L1$=$L2$=8 mH, R_{mpp} =0.03 Ω, $C1$=$C2$=470 μF , Lac=8.7mH, $C1$=3uF , V_{in} =200 V, f_s =20 kHz. Simulation waveforms are shown in Fig. (**3**) and Fig. (**4**).

There are respectively 4 pictures in Fig. (**3**) and Fig. (**4**) which are numbered as Fig **A**, Fig **B**, Fig **C** and Fig **D**. They are respectively DC capacitor voltage, DC inductor current, AC voltage and AC current. Fig. (**3**) expresses traditional no model PI control mode. Fig. (**4**) expresses linearization control strategy by using shoot-through vectors. There is a lot of improvement in the DC voltage ripple and the stability for traditional control strategies, which can depress the system response and the overshoot well.

5.2. Experimental Verification

In order to further validate the proposed control method above, we built the three-phase grid connected inverter with TMS320F28335 as the core of the unbalance test platform. The grid-connected inverter which has the experimental capacity of 100KW has the following experimental parameters: grid simulation of AC power called WPAP330150 and Simulation of 150KW DC power supply; Its maximum DC power and AC power are all150KW that can simulate all kings of unbalanced voltage; The open circuit voltage is 1000V DC; YOKOGAWADL850 oscillographic recorder for 100MS/s, high resolution of 16 bit and isolation of 1KV.

Fig. (**5**) expresses the DC voltage, AC voltage and current waveform of grid connected inverter. During the grid load changes and power waveform changes, DC can maintain the ideal waveform.

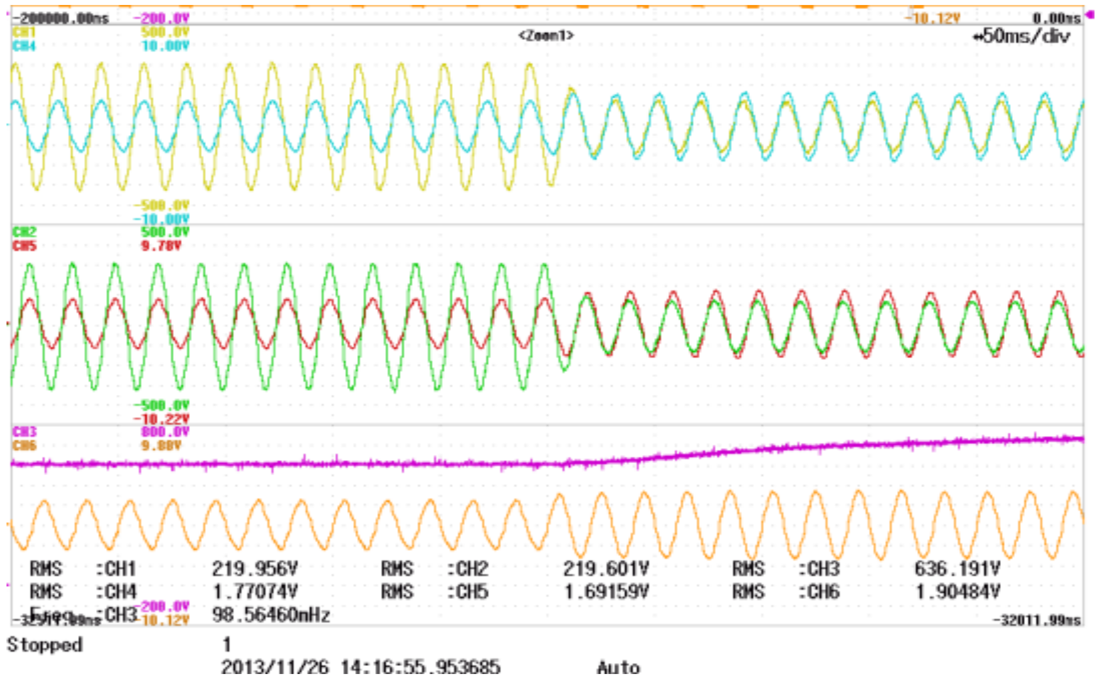

Fig. (5). Control principle of single-phase grid-connected inverter with shoot-through vector.

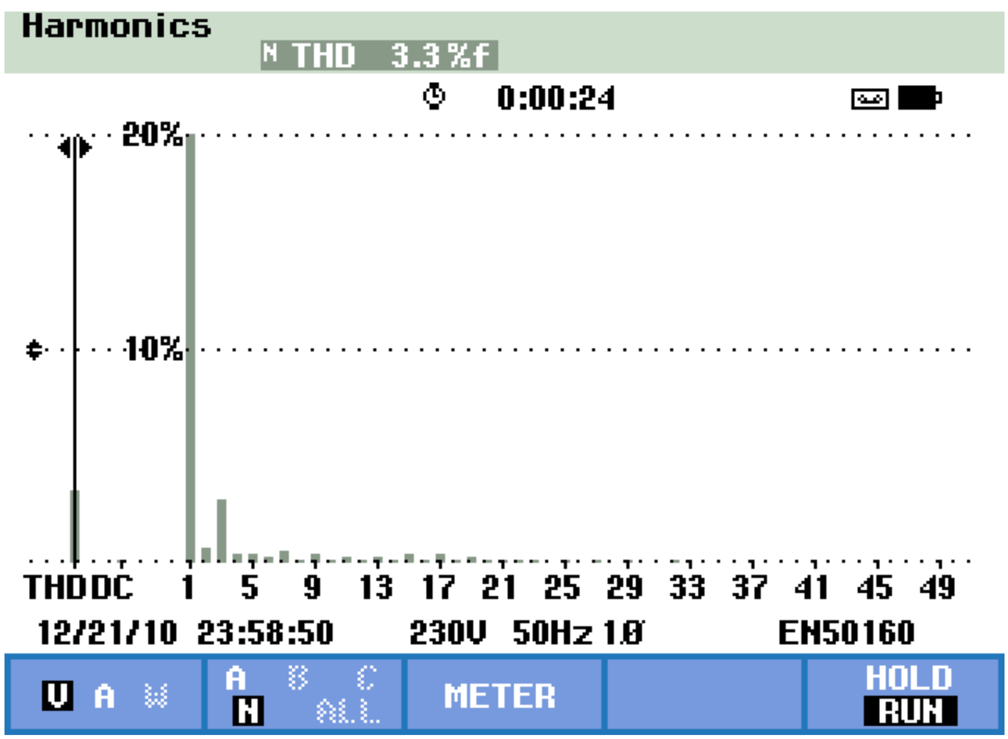

Fig. (6). Traditional control algorithm of the grid-connected current harmonic wave.

Z-source inverter allows the arm straight up and down the bridge that reduces the impact of current system and reduces the harmonic so as to improve the current waveform.

Compared with Fig. (**6**) and Fig. (**7**), we found that THD grid current waveform was improved obviously and the THD value decreased from 10% to 3%.

CONCLUSION

Photovoltaic grid-connected system based on a z-source has the following characteristic. Firstly, it can neatly adjust the voltage to meet the demand of photovoltaic grid connected in a large range fluctuation of inverter. Secondly, the single-stage energy conversion systems minimize the number

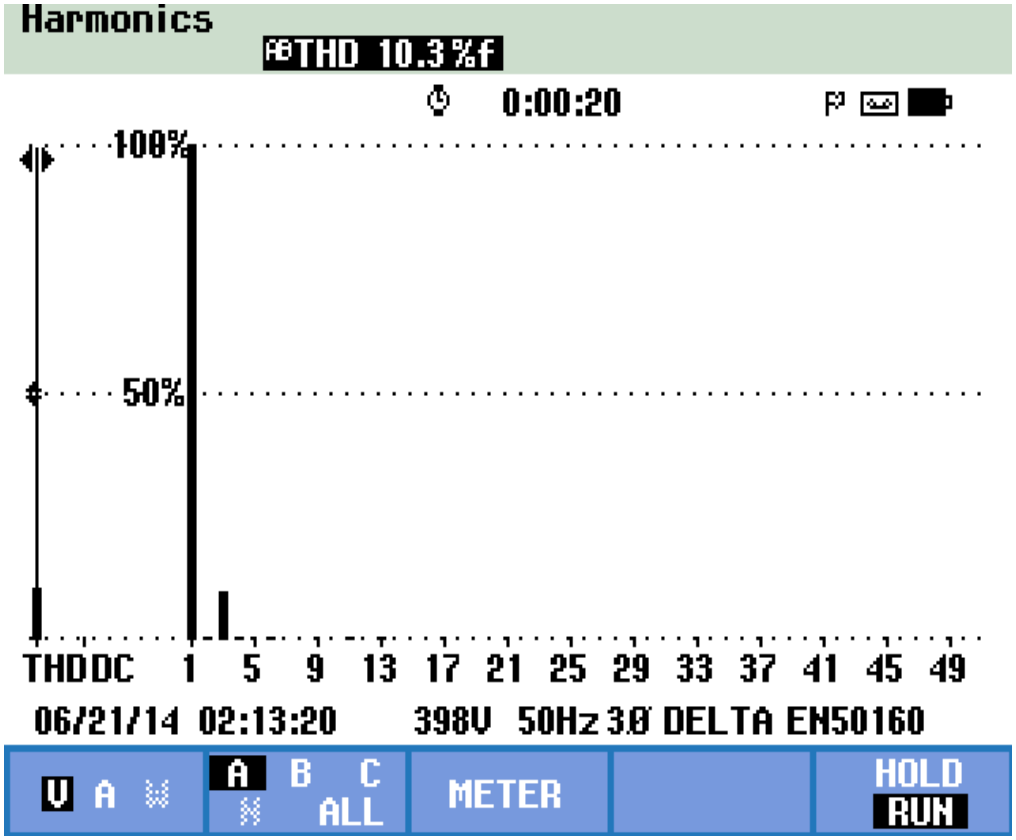

Fig. (7). Traditional control algorithm of the grid-connected current harmonic wave.

of active devices and decease the problems of system complexity, cost and the increased volume caused by switching device driver, heat and other aspects. Moreover, the system allows shoot-through, which means that the circuit cannot be damaged even it suffers strong electromagnetic interference (EMI) and incorrectly triggers switching device. So, the system reliability is greatly improved and we don't need to set the deadband, and the output waveform distortion decreases obviously.

Keeping these problems comprising of nonlinear characteristics of z-source inverter, DC voltage ripple and the harmonic of grid-connected inverter, this paper proposes that we can control the output voltage ring of the photovoltaic array by using nonlinear zero dynamics according to the impedance source theory and the characteristics of the z-source inverter. The paper introduces the design process of shoot-through zero vector with z-source zero dynamic and introduces the relative formula of the parameters design. On this basis, we carried on the algorithm simulation and experiment, and the experimental results show that the control strategy can effectively reduce the harmonic of grid current and achieve a stable DC bus voltage.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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