Unified Control of Single-stage Z-source Grid-connected Photovoltaic System with Harmonics and Reactive Power Compensation

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Abstract—**Based on conventional single-stage grid-connected photovoltaic (PV) Z-source inverter, the unified control combining with harmonic and reactive power compensation is proposed. The grid harmonics and reactive current are measured while PV system outputting power. Then corresponding reactive power compensation is implemented to improve grid power factor. In this paper, the principle of boosting voltage for Z-source network is illustrated. Harmonic measurement method based on the theory of instantaneous reactive power is applied. Then the single-neuron PID controller was designed for maximum power point tracing (MPPT) rapidly. The unified control strategy of the whole system is proposed based on SVPWM. Simulation results revealed the grid reactive power was decreased and output distorted current was improved significantly. Besides, when irradiance suddenly changed, Z-source inverter can still trace the new maximum power point, which verified proposed unified control is accurate and feasible.**

Keywords-Z-source inverter; grid-connected PV system; reactive power compensation; harmonic current restrain; SVPWM; single-neuron PID

I. INTRODUCTION

Photovoltaic (PV) system generated power is influenced by ambient condition significantly, especially directly influenced by ambient irradiance and temperature. Two-stage grid-connected PV system has been applied. It consists Boost converter and inverter and is easy to control each part of them. However, it requires more power devices and increases energy loss of PV system[1]. Other researchers proposed single-stage inverters, which has MPPT and inverter functions synthetically. It achieves higher efficiency, but needs higher input voltage of PV array[1]. In recent decades, Z-source inverters were proposed and implemented in PV system[2,3]. Shoot-through duty of inverter bridge is utilized to boost output voltage of Z-source. Hence it has higher efficiency and stability.

Due to PV system develops towards larger capacity and generates power for local loads, harmonic and reactive power compensation have become another key technology for grid-connected PV system. The main circuit of three-phase inverter bridge conform the circuit of reactive power compensator. Hence it can output reactive power and reduce current distortion of grid via controlling inverter current[4].

This paper utilizes single-neuron PID (SNPID) controller to generate shoot-through duty to trace maximum output power of PV array. Then the shoot-through duty was combined into SVPWM to realize unified control of whole system. Simulation of proposed system was implemented for verification.

II. CONTROL OF Z-SOURCE INVERTER AND DESIGN OF SNPID CONTROLLER

A. Control Strategy of Z-Source Inverter and Reactive Power Measurement

Conventional Z-source network is shown in FIGURE. 1. It consists inductors and capacities which connect in X-type. The principle of boost voltage can be expressed by (1)[2, 3]:

$$\begin{cases} U_C = \dfrac{1-D_0}{1-2D_0} U_{PV} \\ U_Z = \dfrac{1}{1-2D_0} U_{PV} \end{cases} \tag{1}$$

where U_{PV} represents output voltage of PV array, U_C is voltage of capacitance in Z-source, U_Z is Z-source output voltage, D_0 depicts the shoot-through duty. Equation (1) indicates U_Z can be boosted via adjusting shoot-through duty. Due to the power-voltage (P-V) characteristic of PV array is influenced by ambient condition significantly, PV system should both tracing MPP and boost voltage[3]. Proposed control strategy is shown in FIGURE. 1, the principle is: the outer layer voltage loop is designed for MPPT by sampling voltage and current of PV array. Increment conductance method is utilized to seek the voltage of maximum power point, U^*_{PV}. Then a SNPID controller is designed to obtain shoot-through duty D_0 to control PV array voltage. When D_0 is increased, U_Z, the output voltage of Z-source network, would also increase. On one hand, a PI controller is used to control U_Z to reach its reference voltage U^*_Z via adjusting current of active power Δi^*_p. On the other hand, when U_Z is stable, due to shoot-through duty D_0 is increased, U_{PV} would reduce. Finally, U_{PV} can be controlled by adjusting D_0 until reaching the reference voltage U^*_{PV}.

Additionally, as FIGURE. 1 reveals, the *ip*-*iq* method is used for measuring reactive power and distorted current components[4]. Firstly, a PLL is applied to achieve sinusoidal signal $\sin\omega t$ and $-\cos\omega t$, which has the same frequency and phase with A phase grid voltage e_a. Then load current is transformed under *d*-*q* frame, i.e. i_p and i_q. The matrix C_{32} used in this transformation is:

$$C_{32} = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \tag{2}$$

And the matrix C is:

$$C = \begin{bmatrix} \sin\omega t & -\cos\omega t \\ -\cos\omega t & -\sin\omega t \end{bmatrix} \tag{3}$$

Then a low pass filter is used to achieve direct component of i_p. After summing it with output signal Δi^*_p, the combined current is transformed under static three-phase coordinates, i_{abcf}. Hence the reference current i_{abch}, which combines active current, reactive current and distorted current components, is achieved by subtracting i_{abc} from i_{abcf}[4]. Reference current under *d*-*q* frame i_d^* and i_q^* can be obtained via coordinate transformation.

B. Design of SNPID Controller

Due to the voltage of maximum power point is influenced directly by ambient condition, a SNPID controller is designed to trace maximum power point faster. SNPID controller is the combination of conventional PID controller and artificial neuron network, which produces an adaptive controller. Its advantages include strong self-learning and self-organizing abilities, and is suitable for nonlinear control. The structure of SNPID controller is shown in FIGURE. 2[5].

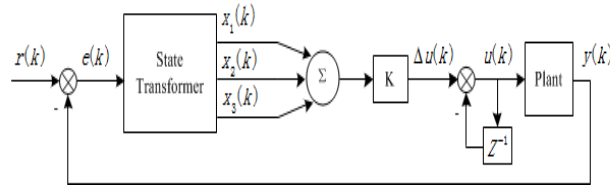


FIGURE I. STRUCTURE OF SINGLE-NEURON PID CONTROLLER

In FIGURE. 2, $r(k)$ and $y(k)$ are the actual and reference voltage of PV array, $e(k)$ is the error signal, $x_1(k)$, $x_2(k)$, $x_3(k)$ are inputs of controller, which is deduced via (4):

$$\begin{cases} x_1(k) = e(k) \\ x_2(k) = e(k) - e(k-1) \\ x_3(k) = e(k) - 2e(k-1) + e(k-2) \end{cases} \tag{4}$$

They represent the error signal, derivative and the second derivative of error signal, respectively. Output of controller is:

$$u(k) = u(k-1) + K\sum_{i=1}^{3}\frac{w_i(k)}{\sum_{i=1}^{3}|w_i(k)|}x_i(k) \tag{5}$$

K is the gain coefficient, which directly influences system stability and response speed. $w_i(k)$ is adjustable weight. In this paper, the supervisory Hebbian rule is utilized for training weights, which is expressed as follows[5]:

$$\begin{cases} w_1(k) = w_1(k-1) + \eta_P e(k)u(k)\,(e(k) - \Delta e(k)) \\ w_2(k) = w_2(k-1) + \eta_I e(k)u(k)\,(e(k) - \Delta e(k)) \\ w_3(k) = w_3(k-1) + \eta_D e(k)u(k)\,(e(k) - \Delta e(k)) \end{cases} \tag{6}$$

where η_P, η_I, η_D are learning rates for proportion, integration and derivate process. They are chosen as different constants to adjust each weight. Due to parameters are self-adaptable, D_0 can be adjusted rapidly to control the voltage of PV array.

III. UNIFIED CONTROL BASED ON SVPWM

A. SVPWM Control of Z-Source Inverter

Space vector pulse width modulation (SVPWM) has advantages of low harmonic components and high utilization of DC voltage. In this paper, SVPWM is applied in Z-source inverter. However, the shoot-through duty should be inserted into modulation to boost voltage of Z-source. Based on the conventional SVPWM, a common method is insert shoot-through time, T_{ST}, into transition of two adjacent vectors[6,7]. In order to reduce switching loss of power devices, the symmetric 5 non-shoot-through vectors are combined with shoot-through vector. For instance, in sector I, the conducting sequences of 6 power devices in FIGURE. 1, S_1 to S_6, are shown in FIGURE. 3. The shaded areas represent shoot-through time T_{ST}, and it is divided into 4 parts in one switching period.

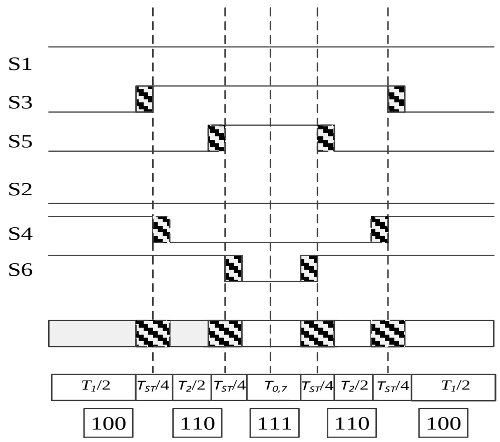


FIGURE II. SVPWM SWITCHING SIGNALS IN SECTOR I

Hence, the switch period Ts can be expressed as follows:

$$T_S = T_1 + T_2 + T_{0,7} + T_{ST} \tag{9}$$

T_1, T_2, $T_{0,7}$ are operating time of traditional space vector V_1, V_2 and V_0 or V_7 of sector I. The conducting sequences in other 5 sectors are also omitted due to the similarity.

B. Control of Inverter Current

Based on modified SVPWM mentioned above, the inverter current loop is controlled by grid voltage orientation decouple method[6], as shown in FIGURE. 1. The mathematical model of main inverter circuit can be described as follows:

$$\begin{cases} e_d = L_F \dfrac{di_d}{dt} - \omega L_F i_q + u_d \\ e_q = L_F \dfrac{di_q}{dt} + \omega L_F i_d + u_q \end{cases} \tag{10}$$

Under d-q frame, e_d and e_q are components of grid voltage, u_d and u_q are the components of voltage on the grid side, i_d and i_q are components of inverter current, respectively. L_F is reactor inductance in FIGURE. 1. So a decoupled PI controller is applied to control grid voltage:

$$\begin{cases} u_d = -(K_p + \dfrac{K_i}{s})(i_d^* - i_d) + \omega L_F i_q + e_d \\ u_q = -(K_p + \dfrac{K_i}{s})(i_q^* - i_q) - \omega L_F i_d + e_q \end{cases} \tag{11}$$

K_p and K_i are the gain and integral coefficients of PI controller, respectively. This decoupling approach realize inverter current i_d and i_q can be controlled independently to trace the reference current signal i_d^* and i_q^*, as FIGURE. 1 shows.

IV. SIMULATION AND ANALYSIS

In order to verify the accuracy and feasibility of proposed unified control of Z-source grid-connected PV system with harmonic and reactive power compensation, the simulation model of a 3kW PV system is designed in MATLAB/Simulink. Considering the voltage and current ripple of capacitors and inductors of Z-source, parameters are designed as: L_1=L_2=500μH, C_1=C_2=470μF. Besides, 13 PV modules, TSM-240W, which are produced by Trina Solar Ltd., are connected in series to form the PV array. It is modeled by model of Luft et al.[8]. Grid phase to phase voltage is 380V and the frequency is 50Hz. Nonlinear load is formed by three-phase diodes rectifier with resistors and inductors, which costs active power 7.5kW and reactive power 0.558kVar.

Firstly, ambient condition of simulation is set as standard test condition (STC). FIGURE. 4 reveals A phase inverter current I_{a_PV}, nonlinear load current I_{a_load} and grid current I_{a_grid}, when system operates under stable state. Before Z-source inverter connect to the grid, grid current curve is I_{a_load} in FIGURE. 4, THD is 7.9%, as FIGURE. 5(a) shows. After inverter connects to the grid, grid current I_{a_grid} is shown in FIGURE. 4, its THD decreases to 4.11%, as shown in FIGURE. 5(b). Besides, PV system compensates reactive power, as FIGURE. 6 shows, inverter generates active power 1kW and reactive power 0.215kVar in A phase. Grid outputs active power 1.5kW in A phase, which verifies the accuracy of unified control with harmonic and reactive power compensation. FIGURE. 7 shows the output voltage of Z-source U_Z and voltage of PV array U_{PV} in stable state. U_Z fluctuates slightly, U_{PV} is agree with reference voltage, 395V.

Additionally, in order to verify the feasibility of proposed SNPID controller, the irradiance of PV array changes from 800W/m^2 to 1200W/m^2 at 1s. Corresponding output power of PV array changes from 2.463kW to 3.819kW, as shown in Fig 8(a). FIGURE. 8(b) shows the response curves of PV array power which are controlled by conventional PID and SNPID controller, respectively. When system starts and irradiance step changes, the SNPID controller can trace the maximum power point faster than PID controller, which reveals it is much suitable for conditions that irradiance sudden changes.

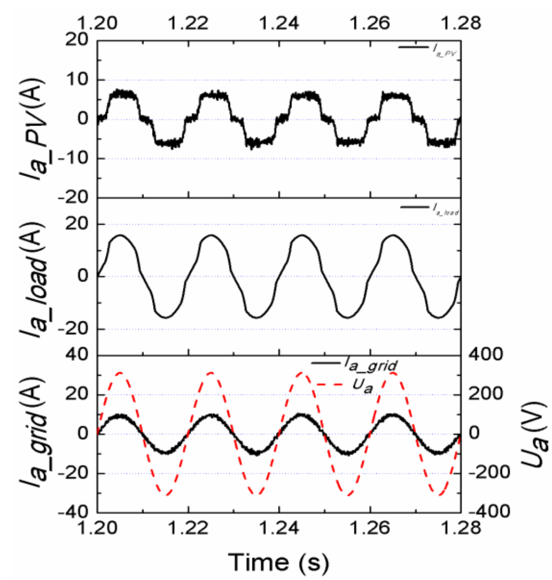
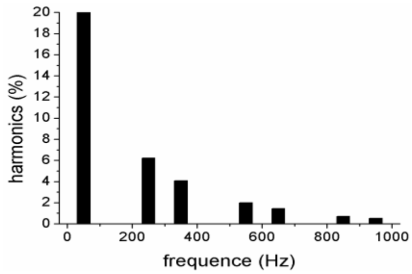
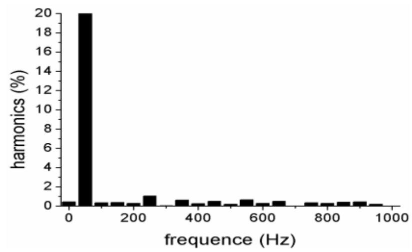


FIGURE III. CURRENT CURVES OF PROPOSED SYSTEM IN STEADY STATE

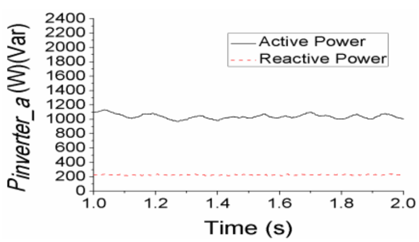


(A)

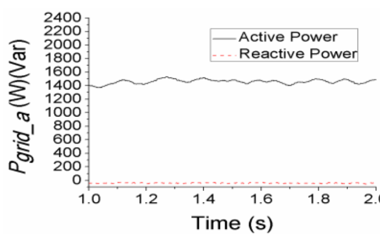


(B)

FIGURE IV. HARMONIC OF GRID CURRENT: (A) THD BEFORE COMPENSATION, (B) THD AFTER COMPENSATION



(A)



(B)

FIGURE V. ACTIVE AND REACTIVE POWER CURVES AFTER SYSTEM STARTS: (A) GENERATED POWER OF INVERTER IN A PHASE, (B) GRID POWER IN A PHASE

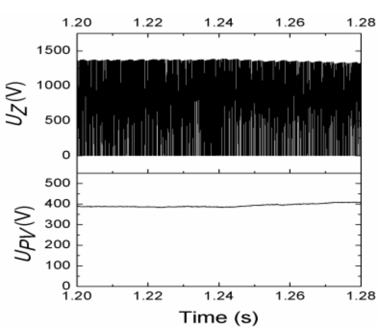
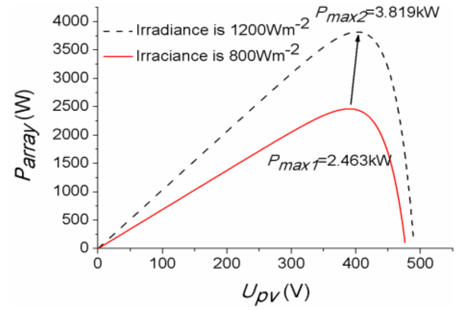
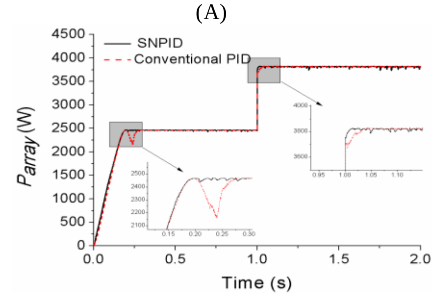


FIGURE VI. OUTPUT VOLTAGE CURVES OF Z-SOURCE AND PV ARRAY IN STEADY STATE



(A)



(B)

FIGURE VII. SIMULATION RESULTS WHEN IRRADIANCE CHANGES: (A) VARIATION OF PV ARRAY OUTPUT POWER, (B) PERFORMANCE OF SNPID AND PID CONTROLLER

V. CONCLUSIONS

It is feasible to combine conventional Z-source grid-connected PV system with harmonic and reactive power compensation. In this paper, the unified control strategy of Z-source inverter, harmonic and reactive power compensation is proposed. Simulation result shows the PV system restrains grid harmonic current and compensate reactive power. Besides, the SNPID controller has superior dynamic performance and enhances speed of MPPT. The proposed unified controlled system has compact structure and is equipped with high efficiency Z-source inverter. It can also improve power quality of grid significantly.

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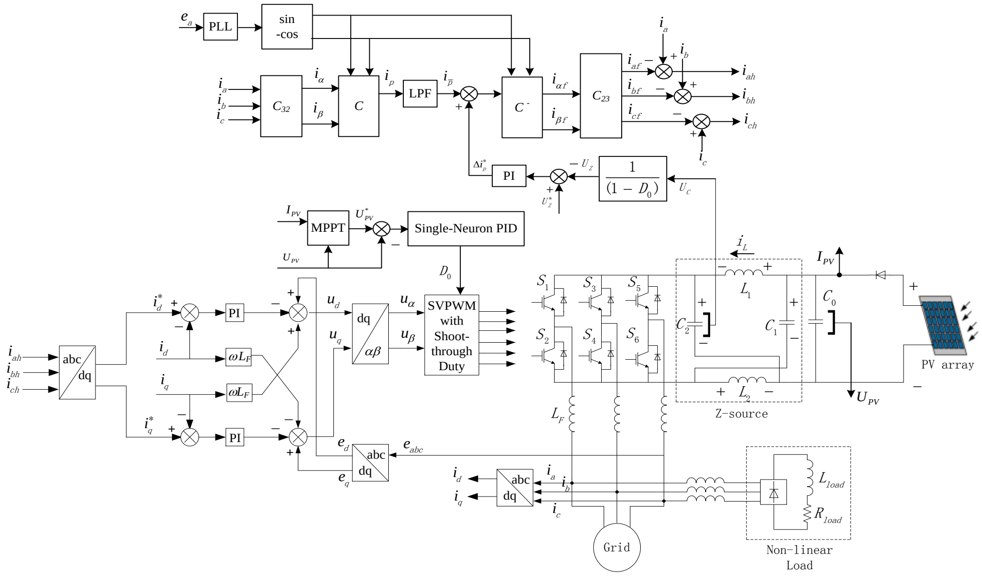

FIGURE VIII. DIAGRAM OF UNIFIED CONTROL OF SINGLE STAGE Z-SOURCE GRID-CONNECTED PV INVERTER AND REACTIVE POWER COMPENSATION.