AMSE JOURNALS-2016-Series: Modelling A; Vol. 89; N°1; pp 143-155
Submitted July 2016; Revised Oct. 15, 2016, Accepted Dec. 10, 2016

Modeling and Simulation of Grid-connected Inverter based on Out-loop Power Control and Experimental Verification

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Abstract

Aim at photovoltaic system or wind power system outputting constant DC voltage, research on the control strategy of grid-connected inverter suitable for such system is put forward in this paper. A novel dual-loop control structure that consists of power outer-loop and current inner-loop is proposed. The reference value of the outer-loop is provided by maximum power point tracking and integrative system operation status, and the active current component is given by the power outer-loop regulator. Finally, the stable operation under different power factor of the grid-connected inverter is realized by the current inter-loop regulator. Modeling and simulation research work based on MATLAB 7.1 is carried out in the paper. A prototype of 30kW rated grid-connected inverter is tested on developed wind simulation operation platform in the laboratory. Simulation and experimental results verified correctness and effectiveness of control structure and strategy of grid-connected inverter.

Key words

Grid-connected inverter, outer-loop power control, modeling and simulation, power factor

1 Introduction

Along with the continued consumption of fossil energy and fast growth of economy and population, the renewable-energy generation technology has received extensive attention worldwide [1]. As a result, various renewable-energy power generation systems [2] and their designs [3] emerge accordingly. The grid-connected inverter is the interface between power generation system and power grid, and thus it is of great significance to achieve high performance and special control strategy for it [4].

The grid-connected inverter used in new energy grid-connected power generation systems are mostly three-phase voltage-source inverters with pulse width modulation (PWM) technology and have advantages such as sine current output, low harmonic content and adjustable power factor [5]. The grid-connected inverter using such control technology generally come with outer voltage loop and inner current loop, where the output of voltage loop serves as the active current reference of inner loop to control the output active power. It maintains the power factor to be 1 during proper operation, and regulates demand of reactive power during grid fault so that it runs in reactive compensation status. The research of grid-connected inverter with such control structure is very extensive and in-depth presently, particularly in the field of application in photovoltaic and wind power system scenarios [6], output current control [7], LCL filter design [8], operation against grid fault [9] and reactive compensation, harmonic suppression [10]. However, the grid-connected inverter with such control structure should have a certain fluctuation on the part of voltage outer loop, and otherwise adjustment of the active current is impossible. If the system has completed the close-loop regulation of DC-side bus voltage in the pre-stage of grid-connected inverter, and the constant DC voltage is sent to the DC-side of inverter, then grid-connected inverter with such control structure is no longer applicable and will cause system instability. Though DC-side voltage can keep stable during actual operation, DC-side current will present substantial fluctuation, causing failure of grid-connected inverter in outputting specified active power. Therefore, research on control strategy for grid-connected inverter without outer voltage loop control is of great significance.

For photovoltaic or wind power system of outputting constant voltage in the front device, an applicable grid-connected inverter control scheme is proposed in this paper. A new double-loop control structure with outer power loop and inner current loop is used and modelling and simulation are realized. With the simulation and operation platforms of wind power generation in laboratory, the experiment on a prototype of 30 kW for grid-connected inverter is developed to verify the correctness and feasibility of such control scheme for grid-connected inverter.

2. Circuit topology of the Grid-connected Inverter and Working Principle

The topology of the grid-connected inverter with outer power loop and inner current loop is shown in Fig. 1. The hardware of the grid-connected inverter is not changed. The DC input side is stable DC voltage since the pre-stage of power generation system has finished the close-loop regulation over the DC-side voltage. The task of grid-connected inverter is still to convert DC input power into AC power. By use of current modulation technology, the maximum power output of unit power factor operation is realized so as to provide certain reactive compensation to the grid side during power grid failure. The difference from general outer voltage loop structure lies in the output active current component is given by the outer power loop.

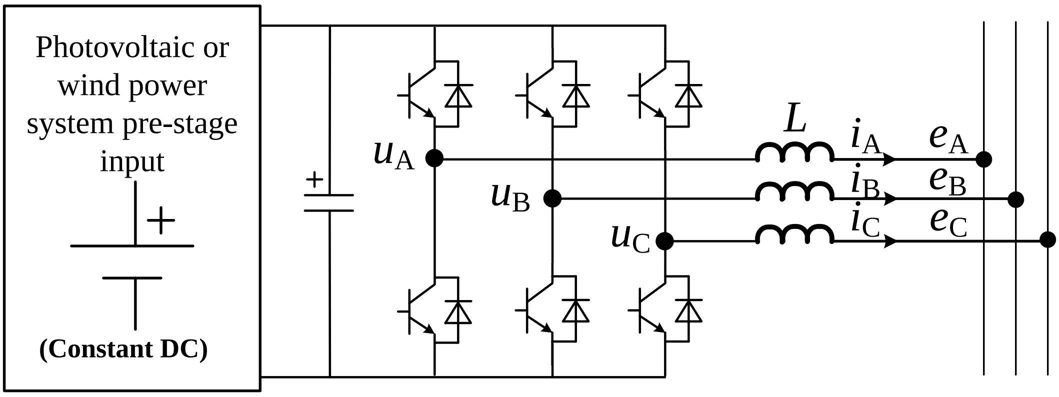


Fig.1. The main circuit topology of the grid-connected inverter with power outer-loop and current inner-loop

3. Mathematic Model and Control Strategy of Grid-connected Inverter

In the three-phase voltage type grid-connected inverter structure shown in Fig. 1, e_A, e_B and e_C are instantaneous values of the grid-side phase voltage; u_A, u_B, u_C and i_A, i_B, i_C are respectively the three- phase output voltage and three-phase output current of grid-connected inverter; and L is the output filtering inductance. Suppose the equation for three-phase symmetric power grid voltage is as follows,

$$\begin{cases} e_A = \sqrt{2}E_0\cos(\omega t) \\ e_B = \sqrt{2}E_0\cos(\omega t - \frac{2}{3}\pi) \\ e_C = \sqrt{2}E_0\cos(\omega t - \frac{4}{3}\pi) \end{cases} \tag{1}$$

where E_0 is the valid value of grid-side voltage and ω is the grid-side voltage fundamental wave angular frequency.

Suppose R is the equivalent resistance of each phase at output side of grid-connected inverter. According to Fig. 1, the following equation can be obtained based on Kirchhoff's voltage equation,

$$\begin{cases} u_{\mathrm{A}} = Ri_{\mathrm{A}} + L\dfrac{\mathrm{d}i_{\mathrm{A}}}{\mathrm{dt}} + e_{\mathrm{A}} \\ u_{\mathrm{B}} = Ri_{\mathrm{B}} + L\dfrac{\mathrm{d}i_{\mathrm{B}}}{\mathrm{dt}} + e_{\mathrm{B}} \\ u_{\mathrm{C}} = Ri_{\mathrm{C}} + L\dfrac{\mathrm{d}i_{\mathrm{C}}}{\mathrm{dt}} + e_{\mathrm{C}} \end{cases} \tag{2}$$

Based on Clark conversion, the mathematic model in two-phase static coordinate system is obtained as

$$\begin{bmatrix} u_{\alpha} \\ u_{\beta} \end{bmatrix} = \begin{bmatrix} Ri_{\alpha} + L\,\mathrm{d}i_{\alpha}/\mathrm{dt} + e_{\alpha} \\ Ri_{\beta} + L\,\mathrm{d}i_{\beta}/\mathrm{dt} + e_{\beta} \end{bmatrix} \tag{3}$$

where u_{α} and u_{β} are the grid-side voltage in two-phase static coordinate system respectively; e_{α} and e_{β} are the grid-connected inverter output voltage in two-phase static coordinate system; and i_{α} and i_{β} are the grid-connected inverter current in two-phase static coordinate system.

Using park conversion to convert the mathematic model in two-phase static coordinate into the one in two-phase rotating coordinate, the power grid voltage in rotating coordinate is obtained as

$$\begin{bmatrix} u_{\mathrm{d}} \\ u_{\mathrm{q}} \end{bmatrix} = L\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix} i_{\mathrm{d}} \\ i_{\mathrm{q}} \end{bmatrix} + R\begin{bmatrix} i_{\mathrm{d}} \\ i_{\mathrm{q}} \end{bmatrix} + \begin{bmatrix} e_{\mathrm{d}} \\ e_{\mathrm{q}} \end{bmatrix} + L\begin{bmatrix} -\omega i_{\mathrm{q}} \\ \omega i_{\mathrm{d}} \end{bmatrix} \tag{4}$$

Equation (4) shows that d-q parameters on the axis are still coupled with each other. In order to realize complete active and reactive decoupling while enabling output current of grid-connected inverters to track given value quickly, PI regulator can be used to realize close-loop regulation of active and reactive current. Let

$$\begin{cases} \Delta u_{\mathrm{d}} = L\dfrac{\mathrm{d}i_{\mathrm{d}}}{\mathrm{d}t} + Ri_{\mathrm{d}} = \mathrm{PI}(i_{\mathrm{d}}^{*}, i_{\mathrm{d}}) \\ \Delta u_{\mathrm{q}} = L\dfrac{\mathrm{d}i_{\mathrm{q}}}{\mathrm{d}t} + R\mathrm{i}_{\mathrm{q}} = \mathrm{PI}(i_{\mathrm{q}}^{*}, i_{\mathrm{q}}) \end{cases} \tag{5}$$

Plugging equation (5) into equation (4) gives

$$\begin{cases} u_{\mathrm{d}}^{*} = \Delta u_{\mathrm{d}} - L\omega i_{\mathrm{q}} + e_{\mathrm{d}} \\ u_{\mathrm{q}}^{*} = \Delta u_{\mathrm{q}} + L\omega i_{\mathrm{d}} + e_{\mathrm{q}} \end{cases} \tag{6}$$

Equation (6) shows that the system realizes complete decoupling at this moment. By way of PWM strategy for space voltage vector, driving signals of all bridge arm switch tubes in grid-connected inverters are obtained, and by changing the active current and the reactive current, the purpose of changing active and reactive power input by grid-connected inverters into power grid is reached, thus eventually realizing reliable operation in various conditions.

For control strategy, the grid-connected inverter with outer power loop and inner current loop control structure differs from the general grid-connected inverters with outer voltage loop in the reference value of specific active current given by the regulator of power outer loop. On the other hand, the reference input of outer power loop regulator depends on the pre-stage input of system. Photovoltaic or wind power system is subject to track the maximum power, and operation state of current system is also taken into account, and thus eventually produces the reference input for outer power loop regulator. It is compared with the actually detected power outputted from grid-connected inverters to power grid, and the given active current component is eventually obtained.

The control strategy for grid-connected inverters with outer power loop control structure is shown in Fig. 2. The digital phase-locked loop method is used to realize voltage orientation in power grid. In consideration of grid-connected inverters operating under unbalance failure of grid-side power voltage, positive and negative sequence components of power grid voltage should be separated before phase locking. During proper operation of grid-connected inverters, the component of reactive current is 0, and unit power factor operation is realized. In case of power grid failure, demand of reactive current component is obtained by way of reactive power calculation process based on demand of reactive compensation.

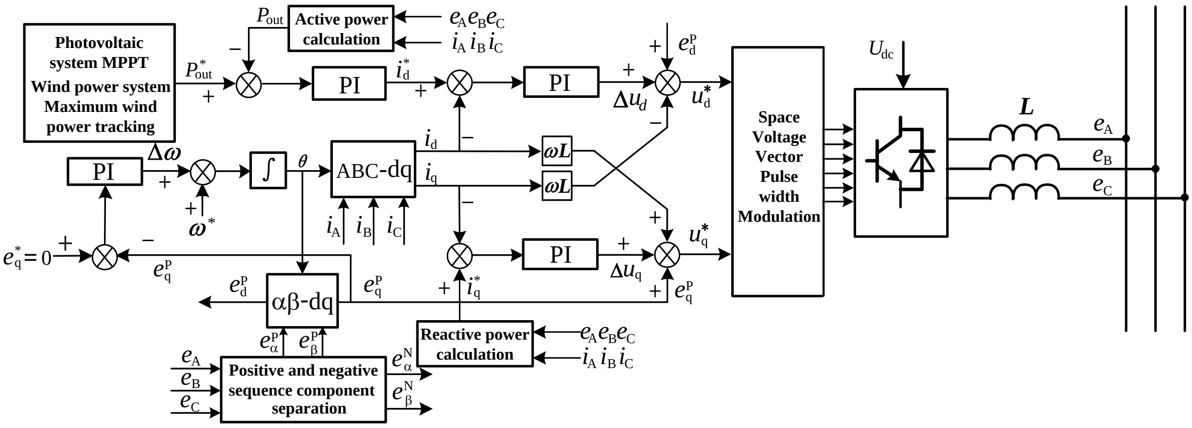


Fig.2. Block diagram of control strategic of grid-connected inverters controlled by voltage outer loop

4. Modeling and Simulation

In order to verify the correctness of the proposed control strategy of grid-connected inverter, modeling and simulation of the proposed control strategy and the whole system in MATLAB 7.1 is carried out. According to above mathematic model and control strategy of grid-connected inverter shown in Fig. 2, the specific SIMULINK simulation model is established as Fig. 3. The space vector pulse width modulation (SVPWM) is employed to obtain the drive signal of power electronic devices. The inner current loop regulators give the required voltage vector for SVPWM scheme, which is supplied by the voltage components in two-phase rotating coordinate. The reference input of outer power loop is provided by an integrated MPPT simulated module, which is realized by programming MPPT algorithm of photovoltaic system or wind power system. Some simulation parameters of grid-connected inverter are given in Tab. 1.

Tab.1. Simulation parameters of grid-connected inverter

Rated power	30kW	Control cycle	1e-5s
DC voltage	600V	Grid voltage	Phase voltage 155V
Filter inductance	4mH	Filter capacitor	17mF/900V

In order to simulate and verify the proposed control strategy of grid-connected inverter comprehensively, the stable operation of two different power levels, suddenly step load and step unload, and reactive power compensation are all demonstrated by the SIMULINK simulation model.

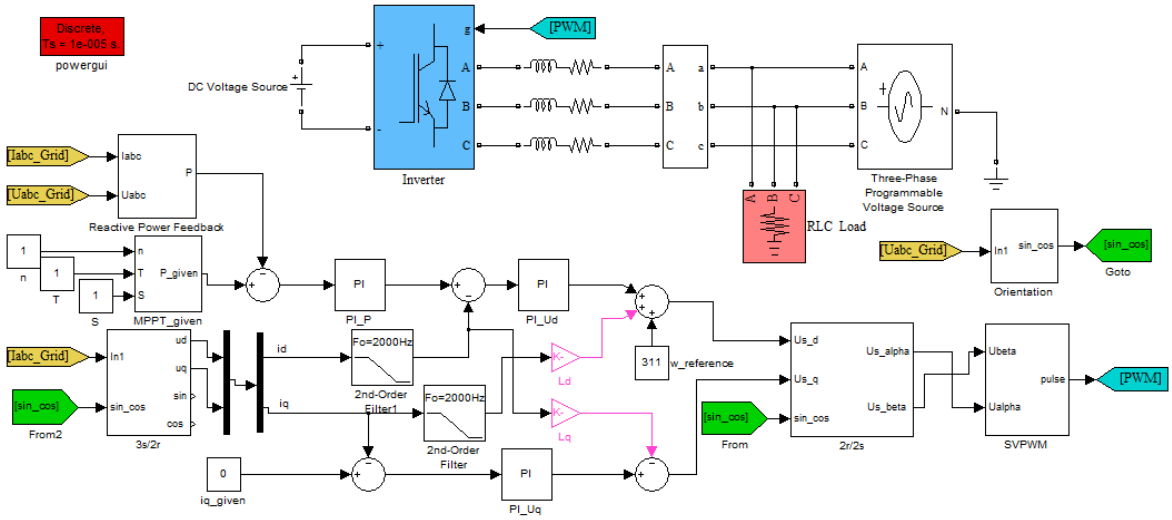


Fig.3. SIMULINK simulation model of grid-connected inverter using proposed outer-loop power control

Fig. 4 and Fig. 5 display the output three-phase current waveform and the single-phase current and voltage waveforms comparison of grid-connected inverter respectively at 10kW and 30kW, which demonstrates the stable operation at different power levels. Obviously, simulation results especially three-phase current at 30kW are superior to those at 10kW because the filtering effect is better when the output power is bigger. Simulation results during sharp load and unload are shown in Fig. 6. Although the output power increases suddenly, the output current can be regulated to reach target value rapidly after a short transient change process. All of these simulation results are carried out under the unity power factor. If the reactive power regulation is necessary, the grid-connected inverter should possess this ability. So, the corresponding simulation results are also attained and displayed in Fig. 7, where the active current is set as 45A and the reactive current is 20A. The proposed control strategy with the outer power loop helps the grid-connected inverter to provide the required reactive power.

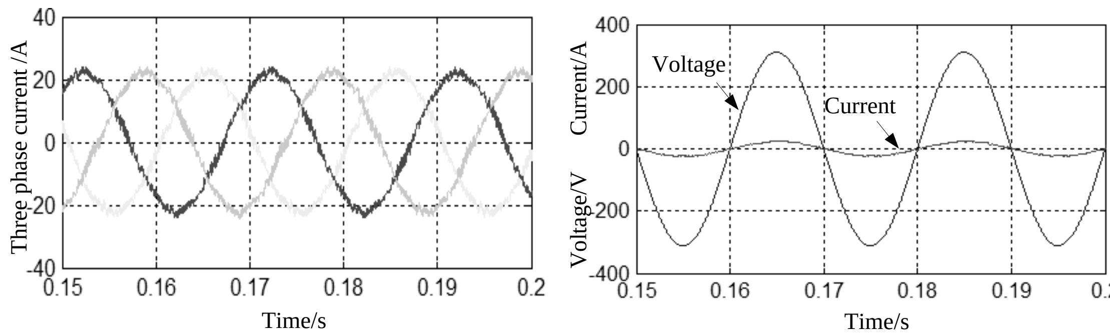


Fig.4. Simulation results of output current and voltage waveforms of grid-connected inverters at 10 kW

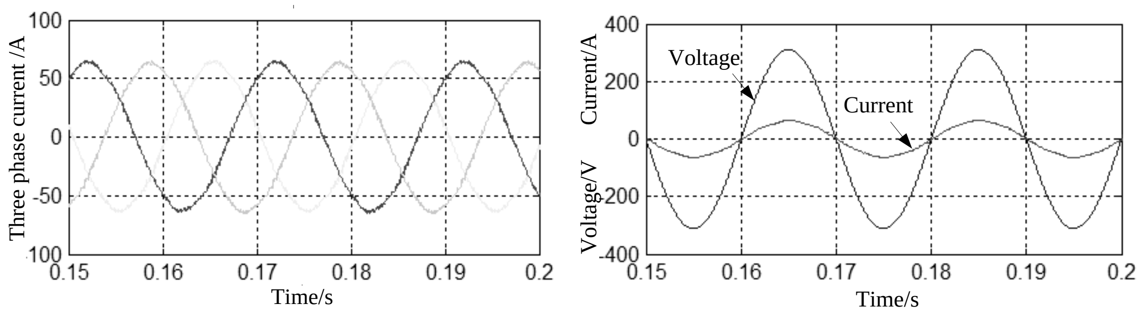


Fig.5. Simulation results of output current and voltage waveforms of grid-connected inverters at 30 kW

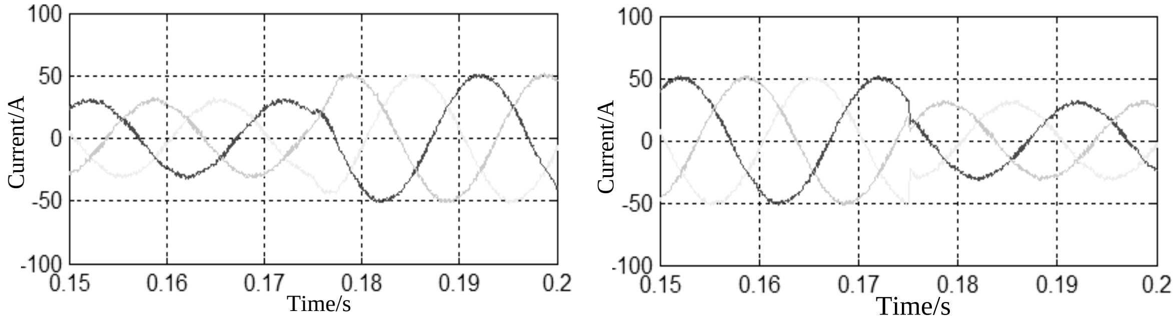


Fig.6. Simulation results at sharp output power rise or drop of grid-connected inverters

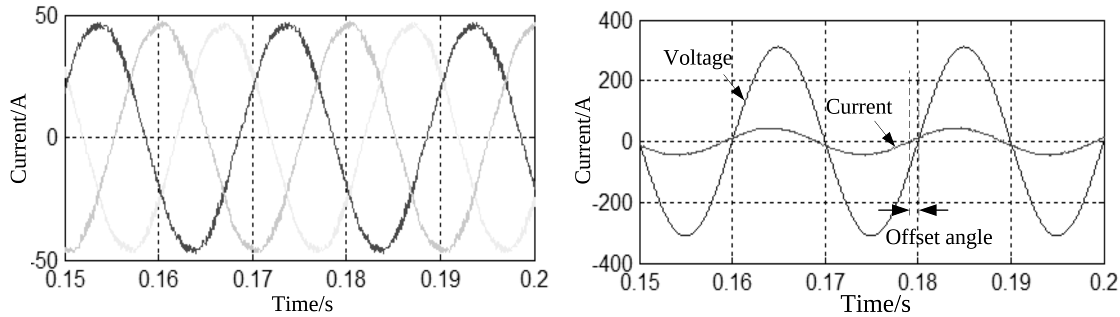


Fig.7. Simulation results when grid-connected inverters provides reactive power regulation

5. Experimental Verification

The simulation and operation platform of the wind power constructed in the laboratory is used for verifying the grid-connected inverters control strategy of outer voltage loop and inner current loop. The structural schematics are shown in Fig. 8. Made up of industrial control computer and data collection card, LabVIEW simulation device system works along with rotating speed torque sensing tester to control and adjust output torque characteristics of asynchronous motor, thus simulating wind turbine [11]. To meet experimental conditions that the input DC voltage should be constant, output of wind turbine is adjusted by DSP controller so that the DC-side voltage input to grid-connected inverters is constant 600 V DC. Rated power of grid-connected inverters is 30 kW. As the experiment aims to verify correctness and effectiveness of control strategy, L-type filter is used with inductance 4 mH instead of LCL filter. As the DC side voltage is only 600 V, which does not meet the voltage demand of full-power operation of grid-connected inverters, the isolation transformer with voltage ratio 1:1.42 is added to the grid side in this experiment. The capacitor array on the DC bus of grid-connected inverter is 17 mF/900 V. Controllers of both wind turbine and grid-connected inverters are all NXP MC56F8346-type DSP assisted by Lattice CPLD M4A5-128/64 realizing the control strategy together. Main circuit of grid-connected inverters is Mitsubishi PM450CLA120 IPM with 8 kHz working frequency.

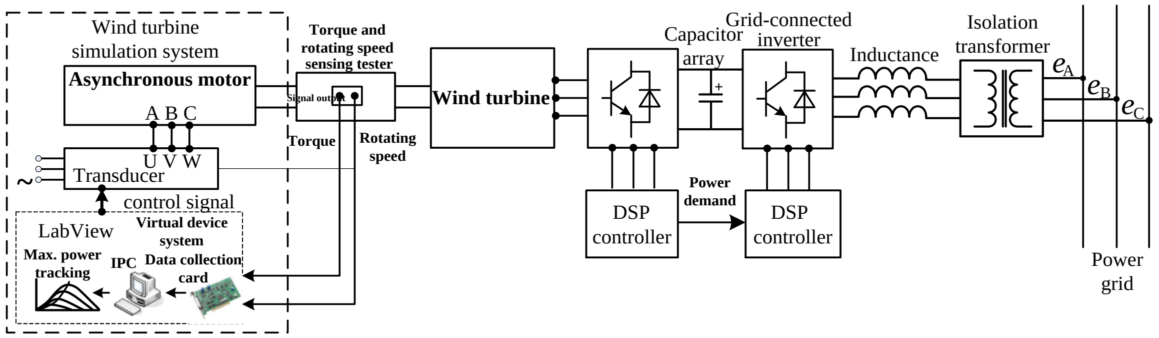
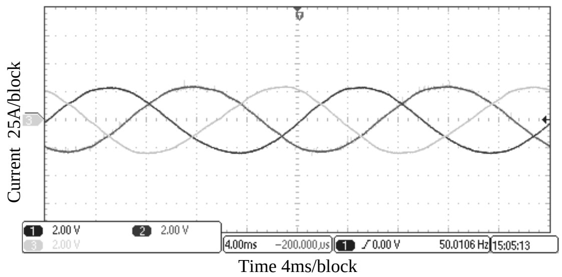
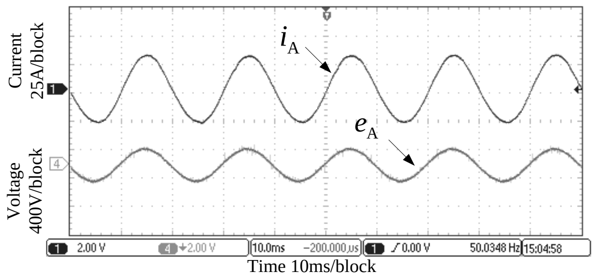


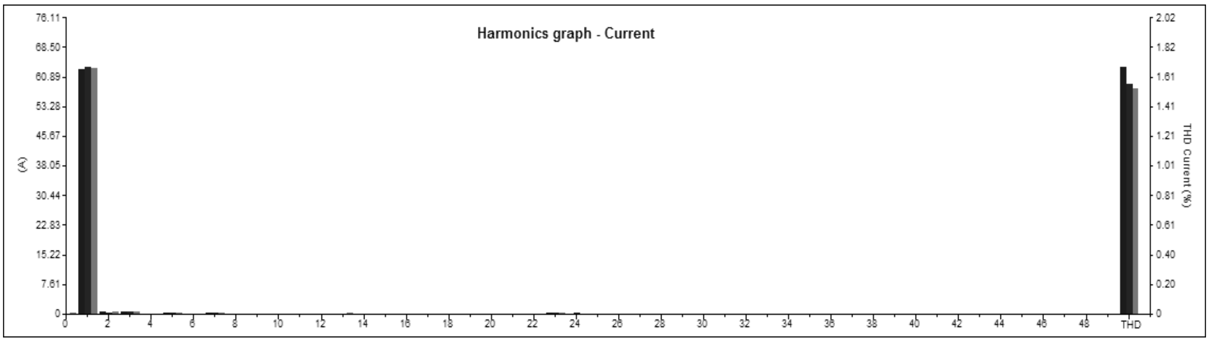
Fig.8. Verification platform for testing the grid-connected inverter with power outer loop



(a) Three-phase current

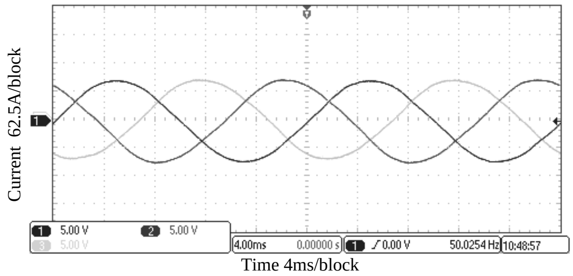


(b) Single-phase voltage and current

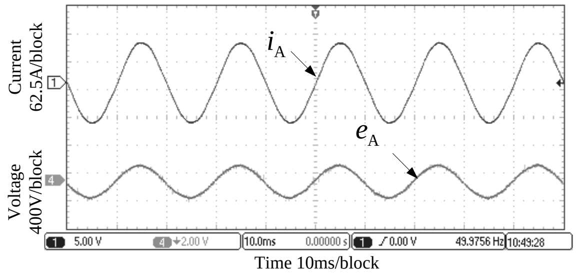


(c) THD test diagram

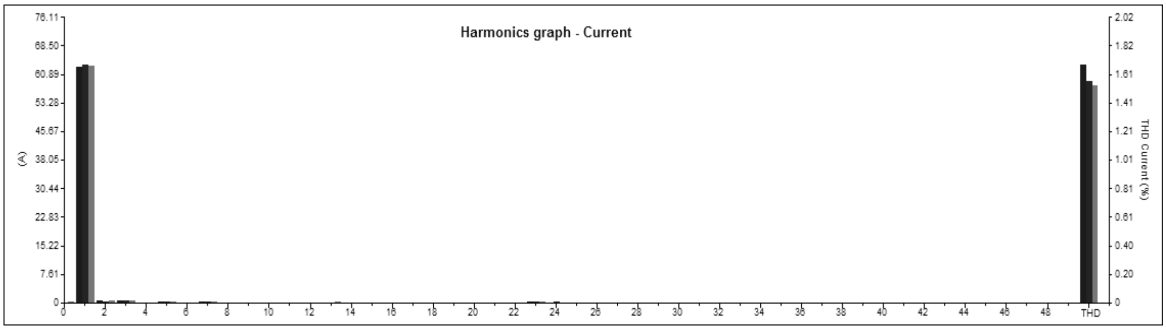
Fig.9. Output current and voltage waveform of grid-connected inverters at 10 kW



(a) Three-phase current

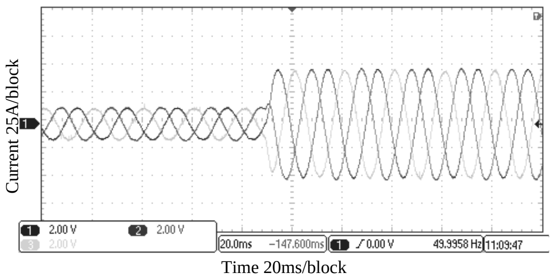


(b) Single-phase voltage and current

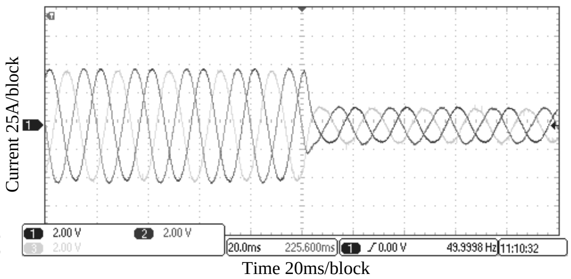


(c) THD test diagram

Fig.10. Output current and voltage waveforms of grid-connected inverters at 30 kW

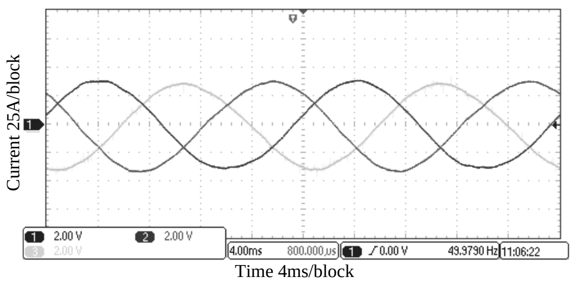


(a) From 15 A to 45 A

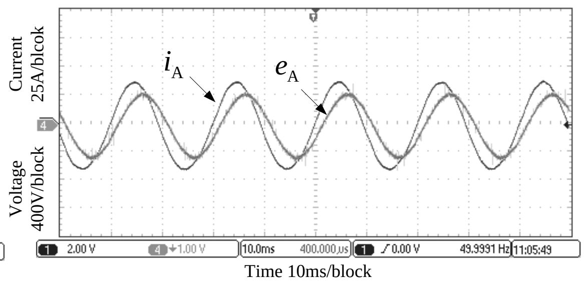


(b) From 45 A to 15 A

Fig.11. Current waveforms with sudden load and unload of grid-connected inverters



(a) Three-phase current



(b) Single-phase voltage and current

Fig.12. Voltage and current waveforms when grid-connected inverters provide reactive regulation

Firstly, the grid-connected inverters operation performance at unit power factor is tested. The wind turbine simulation system controls asynchronous motor to run on specified wind turbine characteristic curve, and thus change of wind speed and rotating speed will change its output power. The reference input of outer power loop regulator is given by integrating the pre-stage maximum tracking algorithm. Fig. 9 and Fig. 10 are voltage and current waveforms of grid-connected inverters respectively when it outputs 10 kW and 30 kW active power, specifically including three-phase output current waveform, single-phase output current and grid-side voltage comparison waveform, and THD test diagram. The waveforms and data in these figures show that three-phase output current waveform features high sine degree, few harmonic content, accurate phase locking and high power factor and that use of L-type filter can meet the demand to have THD go below 5% with varied power.

To verify whether grid-connected inverters has the ability to output power with sharp increase or decrease in a short time, Fig. 11 show the three-phase current waveforms respectively corresponding to sudden rise of active current component from 15 A to 45 A and sudden drop of it from 45 A to 15 A. The waveform diagrams show that the system presents sound and complete current waveform, and that the inverter works steadily at sudden increase and decrease of load. Considering this, the grid-connected inverters with outer power loop control structure is perfectly adaptive to sudden rise or drop in load during operation. Good dynamic performance helps acceptance of direction and coordination for realizing the maximum tracking control of photovoltaic or wind power system.

Full-power grid-connected inverters should be able to inject reactive power to power grid in case of power grid failure, i.e. enabling steady operation in a state without proper unit power factor. Fig. 12 shows the experiment waveforms for active current component 25 A and reactive current component 20 A respectively. The waveforms show that the waveform sine degree is high, and that grid-connected inverter control runs well. Thus, the function of reactive compensation for power grid is realized.

The above experiment results show that, the grid-connected inverter with outer power loop and inner current loop control structure can realize stable operation in various states and present excellent operation performance.

6. Discussion

The control strategy of grid-connected inverter based on outer power loop is proposed and verified in this paper. But the application of the proposed control strategy is only employed in grid-connected inverter with a stable DC voltage input, which means the system can provide the DC bus voltage through the pre-stage voltage or other control strategy. Otherwise, the large fluctuation of DC voltage is not conducive to stable operation of the grid-connected inverter.

The digital phase-locked loop is employed to attain the grid voltage orientation angle. If the grid voltage is asymmetry or a fault takes place in grid network, this orientation method will be unsuitable for the system and must be redesigned.

Compare to the general control strategy of grid-connected inverter based on outer voltage loop, the proposed control strategy in the paper is more conducive to track the maximum power point. One other thing to note is the coordination control between the pre-stage system control and the inverter control, which is the key to stable operation of the whole system.

7. Conclusion

With the consideration that photovoltaic and wind power system may output constant DC voltage, the grid-connected inverter control strategy suitable for such system operation is presented. The control structure of outer power loop and inner current loops is applied, and maximum power tracking algorithm is combined with system operation state to provide the reference input for power outer loop. The output of outer power loop regulator serves as the demand of active current component, and the inner current loop control is used to realize stable operation of grid-connected inverter in various states. The simulation and experiment results show that grid-connected inverters with such control structure also boasts excellent operation performance, and it can meet the application requirement of new energy power generation systems and boasts very good application prospect.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Award No. 51407085, the Postdoctoral Science Foundation of China under Award No. 2015M571685, the Fundamental Research Funds for the Central Universities under Grant NJ20160046, the grant from the Priority Academic Program Development of Jiangsu Higher Education Institution and Jiangsu University Senior Talents Special Project under award 13JDG111.

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