Research on Control Method of Double-Mode Inverter with Grid-Connection and Stand-Alone

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Abstract—**Inverter system, as the interface device between the renewable energy system and grid, plays an important role in the distributed generation system. A double-mode single-phase inverter system, which can be operated in grid-connected mode or stand-alone mode with seamless transitions control, is proposed in this paper. The different control strategies applied on the system for the different modes are designed. In the grid-connected mode, the grid governs the load voltage, the inverter operates as a current source, and the grid current is directly controlled by a three-level hysteresis controller for faster dynamic responsibility and lower current ripple. In the stand-alone mode, the inverter is voltage-controlled, fuzzy controller with parameter self-adapting on-line is introduced to improve the system adaptability to the varieties of load and system parameters, so good quality of output sine-voltage can be obtained under various load conditions. In order to make the distributed generation utility-interactive, an algorithm, which controls the inverter to transfer seamlessly between grid-connected mode and stand-alone mode, is present. The DSP (TMS320LF2407A) based inverter prototype is developed to verify the analysis.**

Keywords-inverter; grid-connected; stand-alone; fuzzy control; hysteresis control; mode-transition

I. INTRODUCTION

The developments of renewable energy and distributed power generation have attracted more and more attentions because of the lack of energy sources. Distributed generation systems using renewable sources like PV or wind power offer many advantages such as compensation for power system, which can reduce tension of power supply, and standby generation which provides power to sensitive and mission-critical industrial loads during system outages until service can be restored. Both of the above advantages can be effectively utilized if the distributed generation system is utility-interactive [1].

Inverter system plays an important role as the interface device between the distributed generation system and grid. In order to implement the utility-interactive, it is necessary that the inverter system can be operated in grid-connected mode or stand-alone mode and has the ability of seamless transitions between the two modes. The PWM inverter is operated in current-control mode when it is connected to the grid, the current injected into grid should be regulated to fellow the reference. In the stand-alone mode, the PWM inverter is operated as a voltage source. The inverter is operated to regulate the voltage across the load, and steady sine-voltage is expected. In addition, the PWM inverter has to be capable of shifting between current-control mode and voltage-controlled mode, and maintain the voltage across the load in the presence of faults on grid.

The different control strategies applied on the system for the different modes are designed. When the inverter is grid-connected, it is operated in current-controlled mode with a novel three-level hysteresis control method that has double-frequency function. Compared with other controllers, it has not only the general advantages of hysteresis controller such as automatic peak-current limitation, simple implementation, a rapid dynamic response, load parameter independence and unconditional stability [2] [3], but also low switch frequency, small current ripple, low impact on DC line. When the inverter is stand-alone, it is operated in voltage-controlled mode with a self-adaptive fuzzy control scheme. An assistant fuzzy controller is induced to modify the scaling factor of primary fuzzy controller, so a fuzzy controller with parameter self-adapting on-line is used to improve the system adaptability for the varieties of load or parameters, so high quality sine-voltage can be obtained under different load conditions [4] [5].

Refer to the transition between these two modes, there may be voltage spikes or inrush currents drawn by the load due to the sudden change in the load voltage and it is harmful to the grid and inverter. In case of sensitive and mission-critical industrial load, maintaining a continuous, uninterrupted AC power is of utmost importance. It is necessary that the utility-interactive system has the ability that load is unaffected by transition from one mode to the other. The transition algorithm takes care of all the above-mentioned requirements associated with the transfer of a PWM inverter between grid-tied mode and off-grid mode. Moreover, the algorithm is completely independent of the actual realization of the current and voltage controllers.

II. CONFIGURATION OF THE INVERTER SYSTEM

A configuration of proposed grid-connecting inverter system that can be operated in stand-alone mode or grid-connected mode is shown in Fig. 1, and the circuit

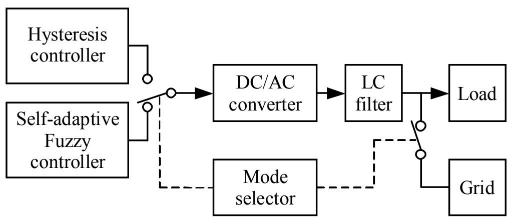

Figure 1. Configuration of the inverter system operated in stand-alone mode or grid-connection mode

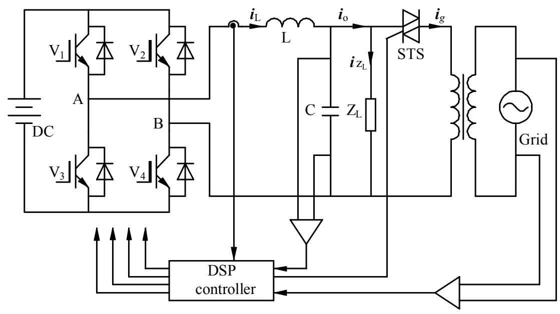

Figure 2. Single-phase grid-connection inverter system

diagram of inverter system is shown in Fig. 2. Operation of the inverter system is divided into two modes, one is grid-connected mode, and the other is stand-alone mode. The load is connected across the output of the PWM inverter. In order to disconnect from the grid in the least and exact time, a triac is used as a static transfer switch. The traic would ensure that the grid could be disconnected from load within half of a fundamental frequency cycle, in the event of a grid fault.

III. INVERTER CONTROL FOR GRID-CONNECTION

A. Equivalent Model of Grid-connection System

In many examples of grid connected inverter, the inverter is operated as a voltage source or a current source [6] [7]. When the inverter is operated as a voltage source, the grid-connection system can be equivalent to the parallel connection of two voltage sources. In this mode the inverter is controlled to generate a sine waveform voltage, the output current injected into grid depends on the grid voltage quality. If the grid voltage is distorted, the exported output current is distorted. So this scheme is not a good choice for grid-connection system.

Current-controlled mode has been chosen for this work to operate the inverter as a current source, because within the control frequency range higher output-impedance is observed from the point of view of the grid voltage. This minimizes the effect of voltage harmonics on the output current and improves the power quality. The equivalent model of the grid-connected inverter system operated in current-controlled mode is shown in Fig. 3. The grid is equivalent to a voltage source u_g in series with an equivalent resistance Z_g. The inverter is equivalent to a current source i_o. i_g is the current injected into grid, i_o is the output current of inverter, Z_L is the load impedance.

The grid is assumed to be relatively stiff and maintains the voltage across the load, so the impedance of grid is very small, that is Z_g=0. While the load is regarded as a part of the grid, u_g=u_o. So i_o is regards the current injected into grid. The Predigested mode of grid-connection system is shown as Fig. 4. Controlled by (1), the current injected into grid can match the grid voltage on frequency and phase, so the power can be injected into grid with PF=1.

$$\dot{i}_o = k\dot{u}_g \tag{1}$$

Fig. 5 shows the proposed control scheme for grid-connection system. Phase locked logic (PLL) control is employed to match the frequency and phase of grid voltage. The reference current is generated by the sine generator based on the voltage phase and the given amplitude of output current. The reference current i_{ref} subtracts the inductance current i_L for the error current i_e, which goes through the three-level hysteresis controller to obtain signals for switching full-bridge inverter.

B. Three-level Hysteresis Current Controller Design

Compared with two-level hysteresis control, three-level hysteresis control has lower inductor current ripple under the same average switching frequency. Moreover, much lower frequency and higher efficiency can be obtained with a double-frequency strategy presented in this paper.

Fig. 6 shows the sequential state machine of the three-level hysteresis current controllers. The state machine has three inputs: Q identifies the last zero state, B_1 is the logical output of hysteresis comparator #1, B_2 is the logical output of hysteresis comparator #2. A and B are the phase-leg states of the inverter. When the inverter output current is positive, u_{AB}, the output voltage of full-bridge inverter, has 1 and 0 stage. When the inverter

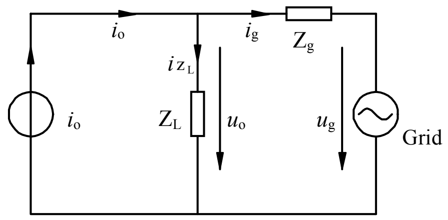

Figure 3. Equivalent model of grid-connected inverter system operated in current-controlled mode

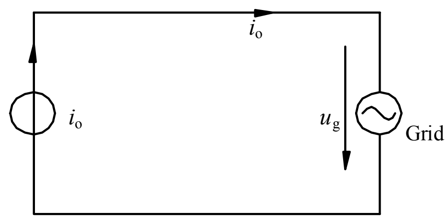

Figure 4. Predigested model of grid-connection inverter system

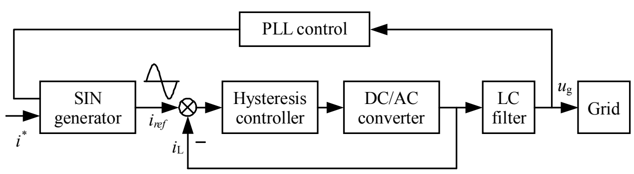

Figure 5. Control scheme for grid-connected inverter

output current is negative, u_{AB} has -1 and 0 stages. Thus, the output voltage of the inverter will be unipolar square pulse in period of half-sinusoid, under the three-level hysteresis control. The state machines can be easily implemented by DSP.

C. Experimetal Results

An experimental system has been constructed to verify the proposed current controller. The system parameters are: L=5mH, C=9.4uF. A TMS320LF2407 DSP is used to implement the control algorithms and generates PWM signals to drive the inverter. Fig. 7 shows the waveforms of drive signals of V_1 and V_3, the inductor current i_L and u_{AB}. The frequency of current ripple is twice as switches'. The output current of inverter i_o and grid voltage u_g are shown in Fig. 8.

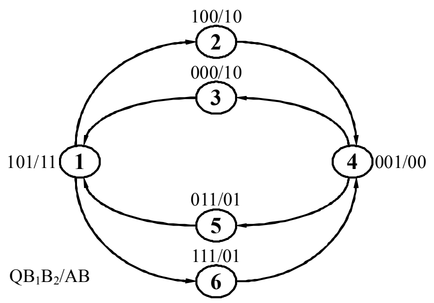

Figure 6. State-transition diagram for three-level hysteresis control

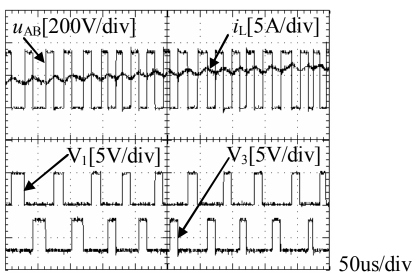

Figure 7. Experimental waveforms with three-level hysteresis control

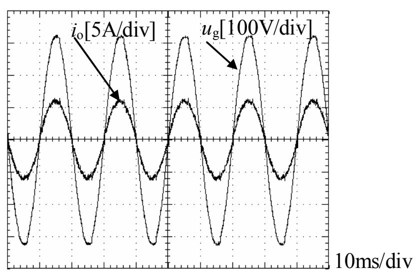

Figure 8. The output current of inverter and grid voltage

IV. INVERTER CONTROL FOR STAND-ALONE

When the inverter is stand-alone, it is operated as a voltage source. A functional block diagram of the inverter system with double-loop control is shown in Fig. 9. The current loop acts as the current reference compensated by P-regulator. For the voltage loop, a self-adaptive fuzzy control (SAFC) scheme with scaling factor self-adjusting is designed to improve the adaptive ability of inverter to the varities of inverter's parameters and different load conditions.

The structure of fuzzy control system is shown in Fig. 10. The assistant fuzzy controller is introduced to identify the system states, and then can generate a modifying signal to correct parameters of the primary fuzzy controller. In the primary fuzzy controller, the scaling factor α has relativity with the error E and the change of error EC, it can be described by (2).

$$\alpha(K) = f[E(K), EC(K)] \tag{2}$$

f is a no-linear function of E and EC. The α is decided by the instantaneous states, and has no relation with the model of system. In fact this self-adaptive controller is a no-linear controller independent of system model.

The fuzzy rules of α, output of assistant fuzzy controller, are shown in Table I. The basic rules of assistant fuzzy controller are designed to make sure that the output response of the inverter system has small overshoot and short rise-time. When error E is large and has the inverse sign with the change of error EC, it is indicated that the system response is making for the set value, so the scaling factor should be reduced for avoiding output overshoot; on the contrary, when error E is large and has the same sign with the change of error EC, it is indicated that the system is deviating from the set value, so the scaling factor should be increased for a shorting rise-time. On the other hand, when the error E is small, the scaling factor should have a big variation range.

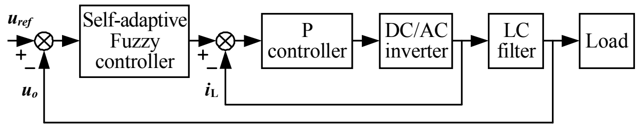

Figure 9. Block diagram of inverter system operated in stand-alone mode

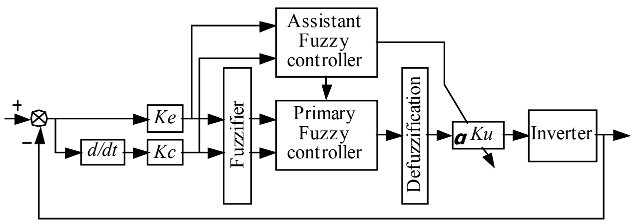

Figure 10. Block diagram of SAFC controller

TABLE I.
ASSISTANT FUZZY CONTROL RULES

EC \ E	NB	NM	NS	ZE	PS	PM	PB
NB	VB	VB	VB	B	M	SM	VS
NM	VB	VB	B	B	BM	SM	S
NS	VB	BM	NM	B	VB	S	S
ZE	SM	M	BM	VS	M	BM	SM
PS	S	SM	S	VB	B	BM	VB
PM	S	SM	BM	B	B	VB	VB
PB	VS	SM	M	B	VB	VB	VB

The experiment results in the cases of inductor load and rectifier load are given out in Fig. 11 and Fig. 12, which indicated that the inverter system with SAFC controller is relatively robust to variations of system component values and load conditions. The rationality and validity of the proposed control method are verified.

V. SEAMLESS TRANSITION BETWEEN THE GRID-CONNECTION AND STAND-ALONE MODES

The control system of grid-connection inverter can be divided into two parts with the current-controlled module and the voltage-controlled module. A mode-transition algorithm, which is completely independent of the current controller and voltage controller, is designed to control the transition between two modes.

A. Stand-alone mode to grid-connected mode

Assume that initially there is a fault on the grid and the inverter is operating in the voltage-controlled mode with the static transfer switch open. When the fault on the grid is cleared and the grid voltage comes back, the phase and amplitude of the load voltage (maintained by the PWM inverter) may not match those of grid voltage. It is necessary that both the magnitude and phases of the inverter's output voltage should be adjusted for a matching state; before the triac can be turned on to reconnect the inverter to the utility.

Thus, the steps to be performed in this phase of the algorithm can be summarized as follows:

1. Detect that the grid is normally operating.

2. Adjust the inverter's output voltage (or load voltage) to match the magnitude and phase of the grid voltage.

3. Once the load voltage is equal to the grid voltage, turn on the triac and switch inverter from voltage-controlled mode to current-controlled mode, with the reference current being equal to the load current.

4. Change the reference current slowly to the desired current (both magnitude and phase).

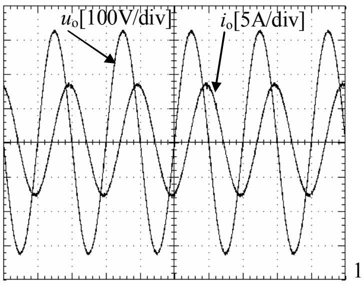

Figure 11. Waveforms of output current i_o and voltage u_o of inverter under inductor load

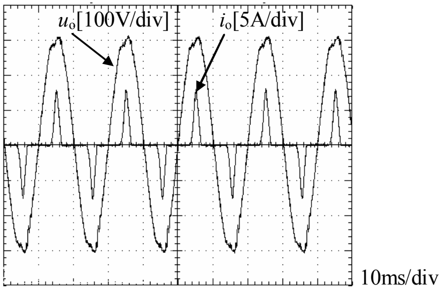

Figure 12. Waveforms of output current i_o and voltage u_o of inverter under rectifier load

B. Grid-connection mode to stand-alone mode

Assume that initially the inverter is operating in the grid-connection mode. The PWM inverter is current-controlled and the grid governs the voltage at the PCC. When there is a fault on the grid, the voltage at the PCC would drop. The fault detection circuitry turns off the triac when the grid voltage goes below a pre-set minimum value. So, the inverter is disconnected from the grid at the first zero crossing of the current. Instantly, the PWM inverter can be shifted from current controlled mode to the voltage controlled mode.

Thus, the steps to be performed in the algorithm can be summarized as follows:

1. Detect a fault on the grid and give a turn off signal to the triac.

2. Monitor the magnitude and phase of the load voltage.

3. When the triac current goes to zero, transit the inverter to a voltage-controlled mode, with the voltage reference being derived from the load voltage.

4. Ramp up the magnitude of the load voltage from its initial value to the rated value.

C. Experimetal Results

The mode-transition algorithm is tested on a hardware prototype. The details of the hardware setup are given below:

Load voltage (rms.) : 220V

Load : 50Ω

Grid current (rms.) : 5A

A solid-state relay (SSR) is used to the static transfer switch. Fig. 13 shows the progression of the phase-locking. The phase difference at start is about $\pi/2$ rad. As time progresses, the phase difference decreases to zero, as expected. Fig. 14 shows the load voltage and grid current during the progresses of shifting from voltage-controlled mode to current-controlled mode. Fig. 15 shows the progress of shifting form current-controlled mode to voltage-controlled mode. The load voltage is found to be fairly smooth during the transition.

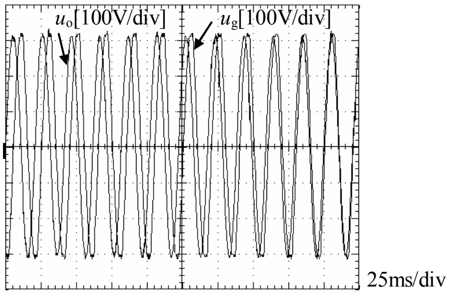

Figure 13. Load voltage and grid voltage during the phase-matching

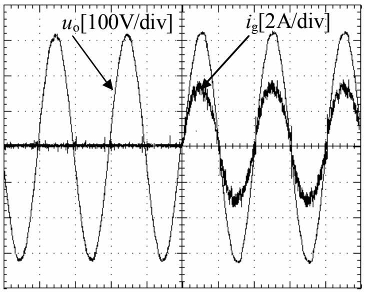

Figure 14. Load voltage and grid current during stand-alone to grid-connection

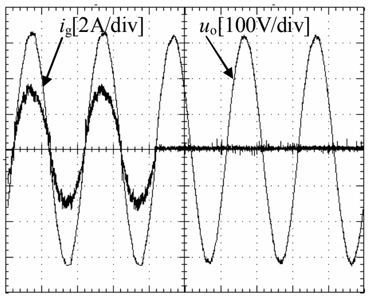

Figure 15. Load voltage and grid current during grid-connected to stand-alone

VI. CONCLUSION

The proposed inverter system not only controls the energy from renewable generations into grid, but also realizes a utility-interactive system. A continuous, uninterrupted AC power is supplied to load. The characteristics of this system are shown as follows.

The current injected into the grid is directly controlled to follow the grid voltage, with good stability performance, fast responsibility and low ripple, employing the proposed novel three-level hysteresis control when the inverter is operated in grid-connected mode.

The inverter system can obtained relatively robust to variation of system component values and load conditions, employing the self-adaptive fuzzy control (SAFC) strategy.

The proposed algorithm which can be implemented easily using digital signal processors (DSP) for the mode-transition seamlessly between grid-connected mode and stand-alone mode, so there are no inrush currents drawn by the load due to the sudden change in the load voltage.

ACKNOWLEDGMENT

This work was supported by the National Natural Science Foundation of China, NO. 50237020.

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