Indirect Current Control Algorithm for Utility Interactive Inverters in Distributed Generation Systems

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***Abstract*—Distributed generation (DG) systems should go into intentional islanding operation to back up private emergency loads when the main grid is out of electric power. Conventional utility interactive inverters which are normally operated in current mode must change their operation into voltage mode to ensure stable supply voltage for emergency loads when intentional islanding operation occurs in DG systems. During the transition between current mode and voltage mode, a serious transient problem may occur on the output terminal voltage of utility interactive inverters. This paper proposes a new inverter system and its control algorithm for seamless transfer during intentional islanding operation in DG systems. Filter design guidelines and data for LCL filters that is appropriate for the proposed control algorithm are also presented.**

***Index Terms*—Distributed generation (DG) systems, indirect current control, line interactive inverters, seamless transfer.**

I. Introduction

MODERN society widely depends on fossil energy that speeds up glove warming by emitting environmental pollutants such as CO_2, NO_X, SO_X gases, etc. Renewable energy is a good remedy to decrease environmental problems resulting from fossil energy. Renewable energy generation systems range from 1 kW to several hundred MW level which are normally connected to a main power grid as a distributed generation (DG) system [1].

DG systems fall in islanding operation if they are still in operation even when the main grid is out of order. If this condition sustains, the secondary winding of the distribution transformer may be inversely excited by the DG system which results in danger to people. Moreover, when the grid power is restored, the phase difference between the grid voltage and the DG voltage may result in voltage shock to utility equipment. Further more, the voltage and frequency of the DG system may become unstable during the islanding operation which brings customers' equipment in malfunction or break down. This situation is called unintentional islanding operation that should be cleared by so called anti-islanding method [2]–[4].

Manuscript received July 6, 2006; revised March 20, 2007. Recommended for publication by Associate Editor Z. Chen.

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Digital Object Identifier 10.1109/TPEL.2008.920879

While, some DG systems have private emergency load for which the DG system should continuously supply stable electric power even when the main grid is out of power. This situation is called intentional islanding operation. When intentional islanding operation occurs, the DG system should be disconnected from main grid for safety, while it continuously supplies stable voltage to emergency load seamlessly.

Conventional utility interactive inverters in a DG system are normally operated by current control mode to inject power to main grids. When intentional islanding operation occurs, the utility interactive inverter should change its operation mode into voltage control mode to ensure supplying continuous power to private emergency loads. During the mode change, the output voltage of the DG system may become unstable because of transient phenomena.

The voltage stability will be worsen when the main grid is tripped by abrupt faults such as voltage sags/swells or black out. When islanding detection is delayed by such factors as non-detection zone (NDZ), communications between sensors and controllers, or signal processing of controllers, etc, the DG system will lost control on its output terminal voltage during the delay time.

This paper presents a new inverter system and control algorithm for intentional islanding operation in DG systems. Even the islanding detection is delayed comparatively long time, proposed utility interactive inverters can supply seamless stable voltage on its output terminal without transient. Proposed theory is proved by simulation and experiment.

II. Indirect Current Control Algorithm

A. Power Circuit Topology

Fig. 1 shows inverter circuit topology based on the proposed current control algorithm. The utility protection switch S_u is governed by a local utility, while the inverter interactive switch S_i is governed by the proposed utility interactive inverter system. When the grid power is normal, the utility protection switch S_u and the inverter interactive switch S_i are all in ON state. In this case, proposed inverter indirectly regulates the grid injection current I_o by controlling the applied voltage on the line inductor. If we assume that the emergency load consumes 25% of the inverter rated power, the injected current to the grid is restricted to 75%.

When the grid is in fault condition, the utility protection switch S_u is tripped by the utility instantly. After that the fault is assumed to be reported to the utility interactive inverter with in 3/4 cycle. By acknowledging the main power fault, proposed inverter stops current injection into the grid by switching off

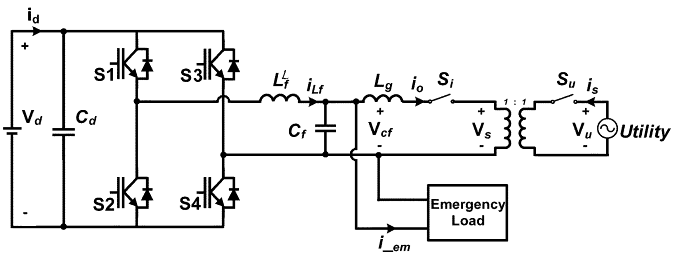


Fig. 1. Single-phase DG system using proposed utility interactive inverter.

TABLE I
ELECTRICAL SPECIFICATION OF THE PROPOSED DG SYSTEM

Rated power(P)	10kW
Nominal voltage(V)	220V
Nominal line frequency(f)	60Hz
Switching frequency(f_{sw})	15kHz

the inverter interactive switch S_i, while seamlessly supplying power to the emergency load by entering into intentional islanding operation.

Table I shows the electrical specifications of the proposed utility interactive inverter system. Although the power rating of the proposed system is 10 kW for home applications, the proposed indirect current control algorithm can be extended to larger scaled DG systems including three-phase inverters without much difference.

LCL filter configuration is considered for the grid interface of the proposed utility interactive inverter. In conventional direct current regulation type utility interactive inverter systems, L-type filter is used for regulating the injection current into the grid, and CL-type filter is additionally installed for attenuating the injection current ripple that is resulted from the inverter switching [5], [6].

However, the filter topology presented in this paper is based on LC-type filter that attenuates the voltage ripples from the inverter switching. Thus by controlling the filter capacitor voltage, the injection current can be regulated indirectly by applying proper voltage to the line inductor L_g that is located in grid side.

B. LCL Filter Design

Design procedure for the LCL filter of the proposed indirect current controlled utility interactive inverter is proposed as follows [7].

1) Calculate R_{base}

$$R_{\text{base}} = \frac{V^2}{P} = \frac{220^2}{10000} = 4.84\,\Omega. \quad (1)$$

2) Determine LC filter bank by filter cut off frequency

$$f_c = \frac{1}{10} \times f_{\text{sw}} = 1500 \text{ Hz} \quad (2)$$

$$L_f C_f = \left(\frac{1}{2\pi f_c}\right)^2. \quad (3)$$

TABLE II
DESIGN DATA FOR THE LCL FILTER

L_f	514μH
C_f	22μF
L_g	1.28mH

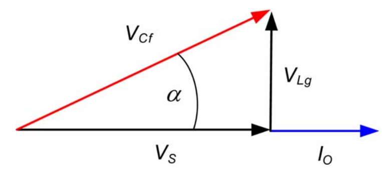


Fig. 2. Phasor diagram for proposed indirect current control algorithm.

3) Decide L/C ratio that guarantees good transient characteristics on filter inductor current

$$\frac{L_f}{C_f} < \left(\frac{R_{\text{base}}}{\zeta_c}\right). \quad (4)$$

4) Calculate L and C

$$L_f = \left(\frac{1}{2\pi f_c}\right) \cdot \left(\frac{R_{\text{base}}}{\zeta_c}\right) = 514\,\mu\text{H} \quad (5)$$

$$C_f = \left(\frac{1}{2\pi f_c}\right) / \left(\frac{R_{\text{base}}}{\zeta_c}\right) = 22\,\mu\text{F}. \quad (6)$$

5) Calculate $L_g(0.1\text{pu})$

$$L_g = 0.1 R_{\text{base}}/2\pi f = 1.28 \text{ mH}. \quad (7)$$

Table II shows the LCL filter data designed by proposed design procedure.

C. Control System

Conventional direct current regulation method has good performance on injection current in utility interactive operation mode, while transient problem is expected during operation mode change from current regulation to voltage regulation when intentional islanding operation occurs. However, proposed indirect current regulation method has no transient problem during the operation mode change.

Proposed indirect current control algorithm regulates the injection current indirectly by controlling the applied voltage on the line inductor L_g during utility interactive operation. When the active power to be injected into grid is assumed P_{av}, the required injection current I_o through the line inductor can be calculated as

$$I_o = \frac{P_{\text{av}}}{V_s}. \quad (8)$$

Then, the required voltage applied on the line inductor L_g should be equal to

$$V_{Lg} = 2\pi \cdot f \cdot L_g \cdot I_o. \quad (9)$$

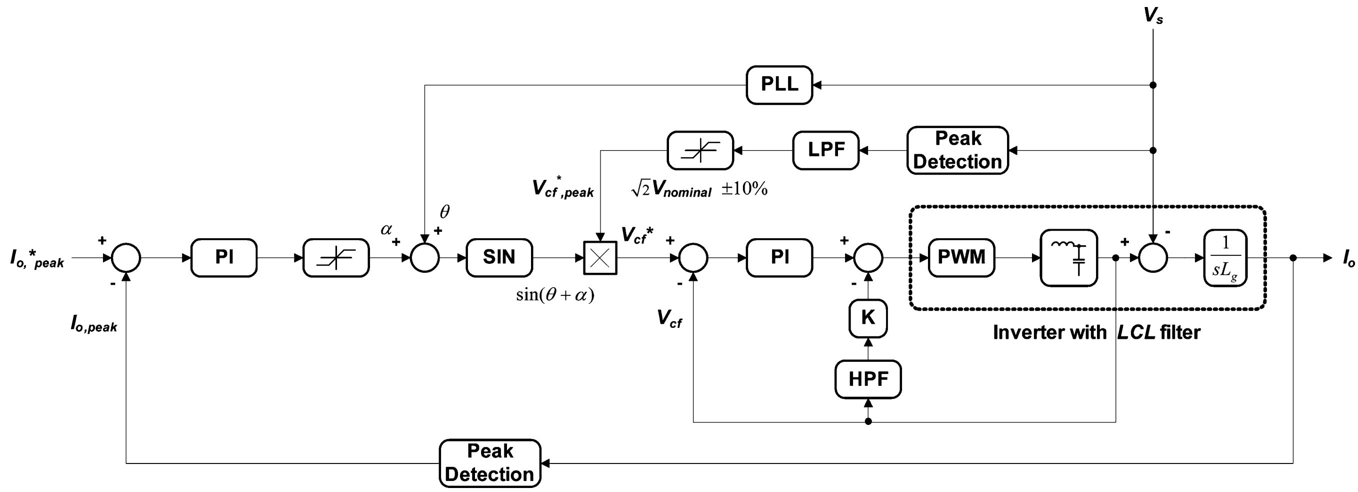


Fig. 3. Control system block diagram for the proposed indirect current control algorithm.

Fig. 2 describes phasor diagram among the grid voltage V_s, target injection current I_o, filter capacitor voltage $V_{\rm Cf}$, and the required voltage on the line inductor V_{Lg}.

Therefore, the required magnitude and control angle for the filter capacitor voltage to inject current I_o into grid can be calculated as follows:

$$V_{\rm cf} = \sqrt{V_s^2 + V_{\rm Lg}^2} \tag{10}$$

$$\alpha = \tan^{-1}\frac{V_{\rm Lg}}{\sqrt{V_s^2 + V_{\rm Lg}^2}}. \tag{11}$$

Equations (10) and (11) will be the references to control the proposed utility interactive inverter. The magnitude of the filter capacitor voltage can be controlled by a simple feedforward controller since it is not necessarily controlled accurately. However, the control angle α should be controlled precisely.

Fig. 3 describes control system block diagram for the proposed indirect current control method. The outer control loop regulates the injection current I_o slowly in the frequency domain, while the inner control loop instantaneously controls the filter capacitor voltage of the output LC filter ($V_{\rm Cf}$) in the time domain.

Parallel inner compensation loop of the filter capacitor voltage via high pass filter (HPF) is added to dampen the resonance resulted from the LC output filter [8].

Reference for the outer control loop is calculated by (8) multiplied by $\sqrt{2}$. Since the injection current I_o is assumed to be sinusoidal, only its peak value is sensed and fedback to outer control loop. The outer PI controller slowly minimizes the injection current error by regulating the control angle α that is added to the synchronized phase angle of the main voltage $\theta(= \omega_s t)$ generated by a PLL circuit. Here, ω_s is angular frequency of the main voltage. The resultant phase angle summation $(\alpha + \theta)$ is sent to the augment for a sine function.

The output of the sine function is multiplied by the peak value of the filter capacitor voltage ($V_{\rm Cf,peak}^*$) resulting in the reference for the nested inner voltage control loop ($V_{\rm Cf}^*$). The peak value of the filter capacitor voltage ($V_{\rm Cf,peak}^*$) is fed forward from the peak value of the main voltage via the limiter of $\sqrt{2} \cdot V_{\rm nominal} \pm 10\%$ in which the window width depends on local utility standards. When the peak value of the grid is out of the limiter range, the proposed inverter system stops utility interactive operation mode, but goes into intentional islanding operation mode without transient problems.

The inner PI controller instantaneously controls the filter capacitor voltage to the reference value ($V_{\rm Cf}^*$). If the inner PI control gains are properly designed, the filter capacitor voltage will be controlled sinusoidal according to the reference magnitude of $V_{\rm Cf\ peak}^*$, and the reference phase angle of $(\alpha + \theta)$. Thus the injection current can be regulated also sinusoidal and in phase to the main voltage.

When the main voltage is normal, the control system indirectly regulates the injection current sinusoidal and in phase to the main voltage by controlling the filter capacitor voltage as described above.

When the main voltage is in fault, the control angle α slowly reaches to its maximum limit value $\alpha_{\max}$ while the PLL generates constant speed phase angle $\theta = \omega_{\rm fix} t$. Here $\omega_{\rm fix}(= 2\pi f)$ is a fixed angular frequency by the PLL. Thus the resultant reference phase angle to the inner PI controller will be $(\alpha_{\max} + \theta)$. The reference magnitude to the inner PI controller $V_{\rm Cf\ peak}^*$ slowly decreases to $V_{\rm nominal} - 10\%$ that is assumed the critical low voltage allowed by the utility standard. Therefore the filter capacitor voltage is maintained stable with the decreased magnitude of $V_{\rm nominal} - 10\%$ during intentional islanding operation.

III. Feasibility Study

A. Simulation

To investigate the feasibility of the proposed topology and control algorithm for utility interactive inverters, simulation has been done. Simulation scenario is as follows.

1) Initially, main power system is in normal condition (utility protection switch S_u is ON state). Although the inverter interactive switch S_i is ON, the utility interactive inverter just supplies 25% of its rated power to emergency load without injecting current into the grid.
2) At 0.2 s, the utility interactive inverter starts to increase the grid injection current up to 75% of its rated power.

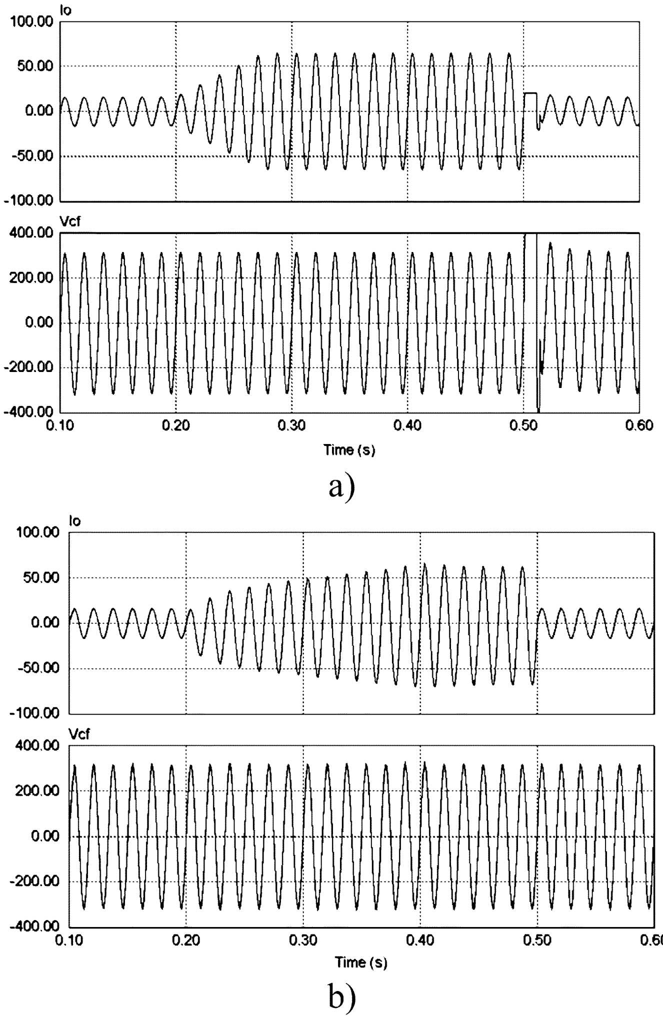


Fig. 4. Simulation for inverter output current and filter capacitor voltage according to each control algorithm: (a) conventional direct current control algorithm and (b) proposed indirect current control algorithm.

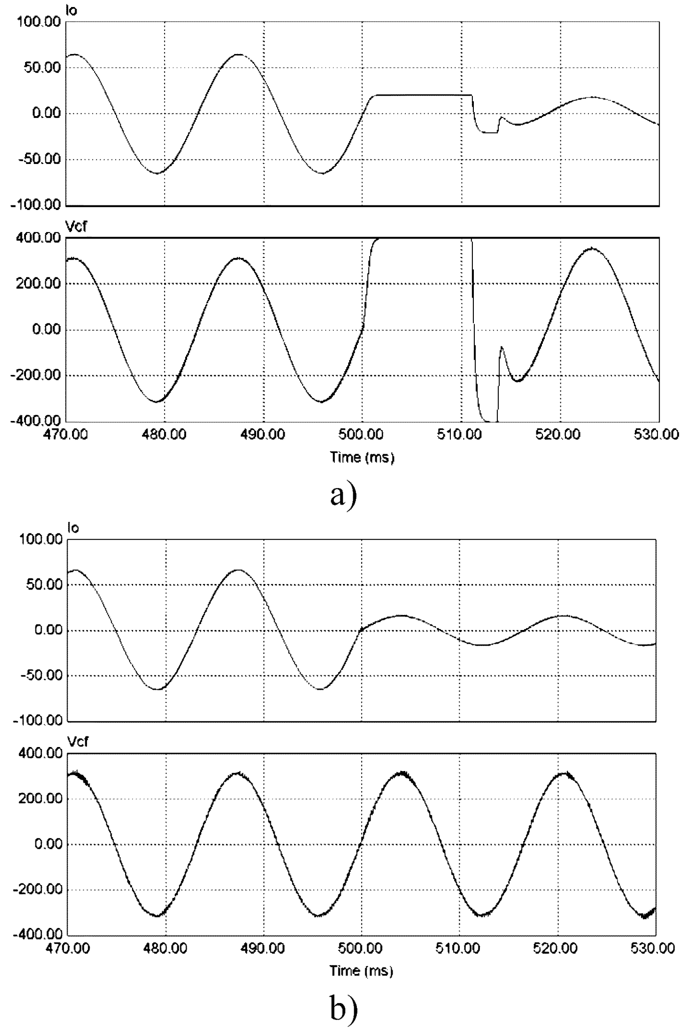


Fig. 5. Zoomed-in simulation waveforms when the fault occurred in the main: (a) conventional direct current control algorithm and (b) proposed indirect current control algorithm.

3) Interruption occurs in the grid at 0.5 s. It is assumed that the utility protection switch S_u is immediately tripped while the inverter interactive switch S_i acknowledges and trips after 3/4 cycle from the fault.
4) On acknowledging the main power fault at 0.515 s, the utility interactive inverter enters into intentional islanding operation by tripping the inverter interactive switch S_i while continuously supplying power to the emergency load.

Fig. 4 shows waveforms of the inverter output current and the filter capacitor voltage according to each control algorithm in the simulation scenario. As can be seen in the simulation results, both of conventional direct current control method and proposed indirect current control method nicely regulate the injection current in normal utility interactive operation mode. However, when the main power fails at 0.50 s, the performance between the two control algorithms becomes very much different during transferring from utility interactive operation mode to intentional islanding operation mode.

Fig. 5 shows zoomed in waveforms of the inverter output current and inverter ac terminal voltage according to each control algorithm when the power interruption occurs at 0.50 s. In case of conventional direct current control method shown in Fig. 5(a), the voltage applied on the emergency load is floated and distorted by circuit conditions during the time delay in sensing the grid fault, since the inverter is still in current control mode and lost controllability on the filter capacitor voltage. However, in case of proposed indirect current control method shown in Fig. 5(b), the voltage applied on the emergency load is very much stable during the same sensing delay.

B. Experiment

To verify proposed theory, an experimental utility interactive inverter system has been established as specified in Table III. The exact calculation of the filter inductance L_f is 1.284 mH and that of the filter capacitance C_f is 8.77 μF. However, since the available capacitor in the market is 10 μF, the filter parameters in the experimental system were adjusted as $L_f = 1.2$ mH and $C_f = 10$ μF. Although the line inductor L_g was calculated to 3.21 mH, 7.8 mH of it was used in the experiment for convenience. If high performance voltage controller is used instead of the simple PI controller, the size of the line inductor is expected to be decreased. As shown in Fig. 6, the control system

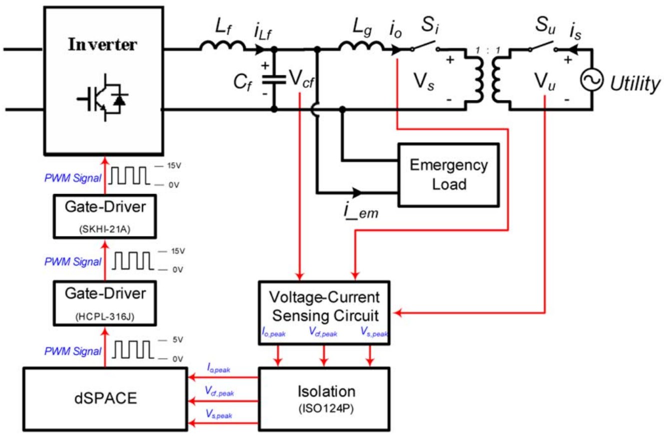


Fig. 6. Block diagram of experimental system.

TABLE III
EXPERIMENTAL SPECIFICATION AND LCL FILTER

Rated power		1kW
Nominal voltage		110V
Nominal frequency		60Hz
Switching frequency		15kHz
LCL filter	L_f	1.2mH
	C_f	10μF
	L_g	7.8mH

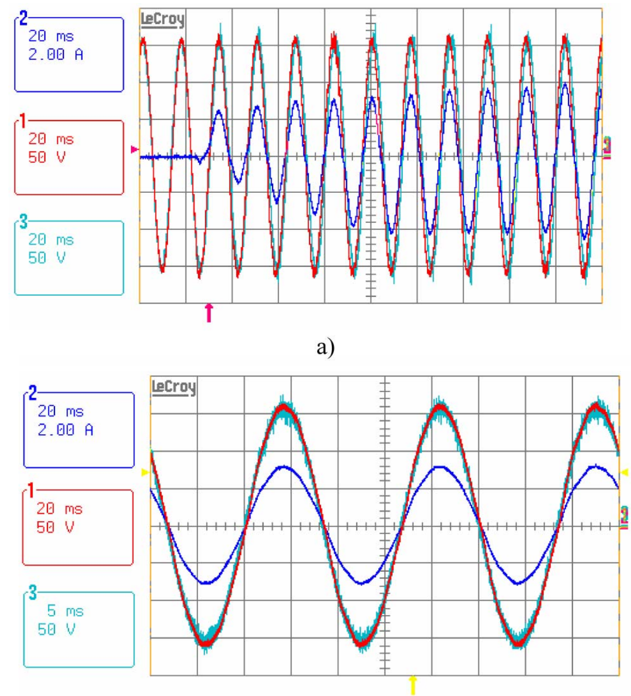
for the experimental system was implemented fully digitally by a dSPACE 1104 control board.

Fig. 7 shows the experimental waveforms by the proposed indirect current control algorithm during utility interactive operation. Fig. 7(a) explains for the build-up characteristic of the injection current related with the main voltage and the filter capacitor voltage. The injection current is always in phase with the main voltage, and the magnitude of it is slowly built up to the reference value since the control angle difference α between the filter capacitor voltage and the main voltage is increased slowly by the outer PI controller. Fig. 7(b) describes the zoomed in waveforms during utility interactive operation in the steady state. Since the injection current is relatively small (around 25% from the rated current), control angle difference α between the filter capacitor voltage and the main voltage is very small (around 1.5°).

The experimental waveforms in Fig. 8 demonstrate the stability of the filter capacitor voltage when the main voltage is abruptly decreased around to 30% from the nominal value. Although the fault sensing delay is set to infinite here, there is almost no transient in the filter capacitor voltage that supplies the emergency load during the main power fault.

Fig. 9 illustrates synchronization performance of the filter capacitor voltage into main voltage when the main power is restored. After the synchronization is completed, the utility interactive inverter can be returned to utility interactive operation.

Through the simulations and experiments, it was verified that proposed indirect current control algorithm can supply stable power to emergency load seamlessly during transition from utility interactive operation mode to intentional islanding operation mode and vice versa.



b)

Fig. 7. Experimental waveforms for filter capacitor voltage (ch. 1), grid injection current (ch. 2), and main voltage (ch. 3) by proposed indirect current control algorithm during utility interactive operation: (a) transient operation and (b) steady state operation.

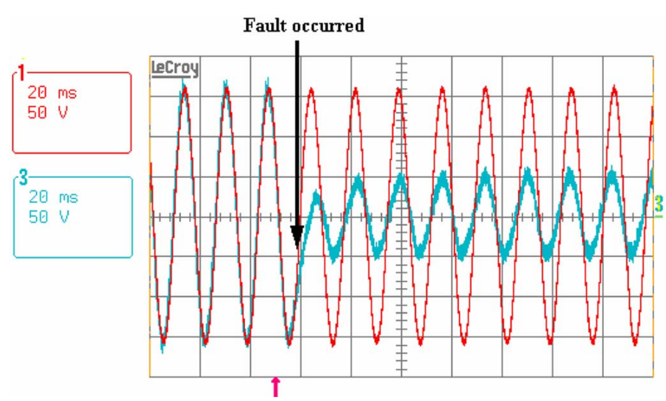


Fig. 8. Experimental waveforms for filter capacitor voltage (ch. 1), and main voltage (ch. 3) by proposed indirect current control algorithm when fault was occurred in main voltage.

In the proposed control algorithm, one voltage sensor on the filter capacitor terminal supplies feedback information to the inner control loop to regulate the voltage, while it also supplies high frequency resonance information to the parallel inner compensation loop to dampen the voltage resonance instantaneously. Thus the outer current control loop can concentrate on regulating the injection current in relatively slow frequency domain [9]–[13].

IV. CONCLUSION

This paper has proposed an inverter topology and control algorithm for utility interactive inverter systems that has emergency load. Since the utility interactive inverter controlled by

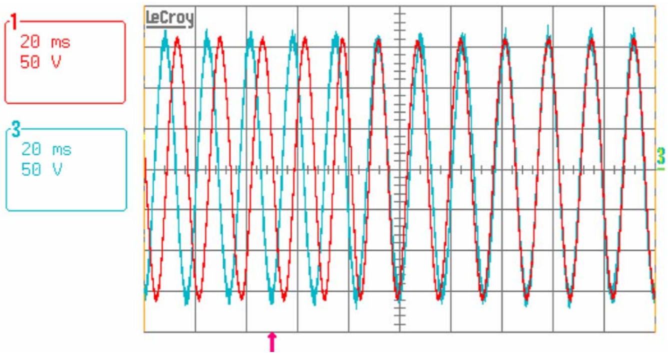


Fig. 9. Experimental waveforms for filter capacitor voltage (ch. 1), and main voltage (ch. 3) by proposed indirect current control algorithm during synchronization when main voltage is restored.

the proposed indirect current control method always operates in voltage control mode, the supplying voltage to the emergency load could be maintained stable without any transient problem that would occur in conventional direct current control method when the grid fails. This paper also has presented filter design guideline and data for a LCL filter for the proposed inverter topology and control algorithm. Through simulations by PSIM and experiments using a dSPACE 1104 control board, the feasibility of the proposed topology and control algorithm were verified. Proposed inverter topology and control algorithm are expected to be useful in DG systems.

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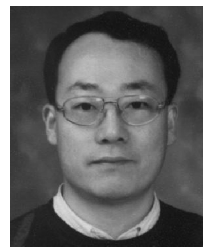

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