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Seamless Transitions between Grid-Connected and Stand-Alone Operations of Distributed Generation in Microgrids

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Abstract:- Control of the Distributed Generation (DG) system is important in both grid-connected and stand-alone modes and the system stability becomes very crucial during the transfer between these two modes. If the system does not have a proper transfer procedure, severe transient voltages or currents will occur, which may damage the entire system. A seamless transfer can ensure smooth operation and quick attainment of steady state. In order to solve these transition problems, this paper presents the development and test of a control strategy for DG capable of working in grid-connected and intentional islanding connection modes with seamless transitions from both operational modes.

Keywords:- Distributed generation, grid-connected operation, stand-alone operation, islanding detection, seamless transitions

I. INTRODUCTION

The current model for electricity generation and distribution in the United States is dominated by centralized power plants. The power at these plants is typically combustion (coal, oil, and natural) or nuclear generated. Centralized power models like this require distribution from the center to outlying consumers. This system of centralized power plants has many disadvantages. Electric utilities are becoming more and more stressed since existing transmission and distribution systems are facing their operating constraints with growing load. Greenhouse gas emissions have resulted in a call for cleaner renewable power sources. Under such circumstances, distributed generation (DG) with alternative sources such as fuel-cell, wind-turbine, bio-mass, micro-turbine and solar-cell systems, has been considered as a promising solution to the above problems [1-3].

DG is defined as small, modular electricity generators located close to the end customer's load connection point. DGs can enable utilities to decrease investment costs in transmission and distribution system upgrades while still meeting increasing power demands. Also, DGs provide customers with improved quality and reliability of energy supplies without imposing undesirable effects on environment [4-5]. In general, DG can be intended as small sized power plants that are designed to be installed and operated within a local load center.

Control of the DG system is important in both grid-connected and stand-alone modes and the system stability becomes very crucial during the transfer between these two modes. If the system does not have a proper transfer procedure, severe transient voltages or currents will occur, which may damage the entire system [6]. A seamless transfer can ensure smooth operation and quick attainment of steady state.

This paper presents the development and test of a control strategy for DG capable of working in both intentional islanding (stand-alone) and grid-connected modes. The stand-alone control features an output voltage controller capable of loss of main detection and seamless transition from grid-connected to stand-alone operation modes with minimum interruption to the load. The grid-connected mode with current control is also enabled for the case of power grid connection. This grid-connected control features an output current controller capable of synchronization with the grid and re-synchronization for grid reconnection with minimum interruption to the load.

The operational principle and control methods of the proposed system are explained in detail. A DG inverter system has been designed, built and set up for testing. Simulation and experimental results are provided in order to verify the validity of the developed DG system.

II. SYSTEM DESCRIPTION

Fig. 1 shows the proposed main circuit topology for a grid-connected and stand-alone operation voltage source inverter. The system consists of a DG unit that is modelled by a DC source, a sinusoidal pulse-width-modulated (SPWM) voltage source inverter, an LCL filter to achieve attenuation of the switching frequency ripple that causes harmonics in the output voltage [1, 7-10], a parallel load, and the controller needed to implement grid connected and stand-alone operations with seamless transition between both modes of operation.

The controller includes control for grid-connected and stand-alone operations, PLL, coordinate transforms, parallel interconnection to the grid (represented by ideal, sinusoidal voltage sources behind line impedances) through the Point of Common Coupling (PCC) breakers. The loss of main detection, seamless transition from grid-connected to stand alone, and re-connection to the grid for seamless transition from stand alone to grid-connected are also included.

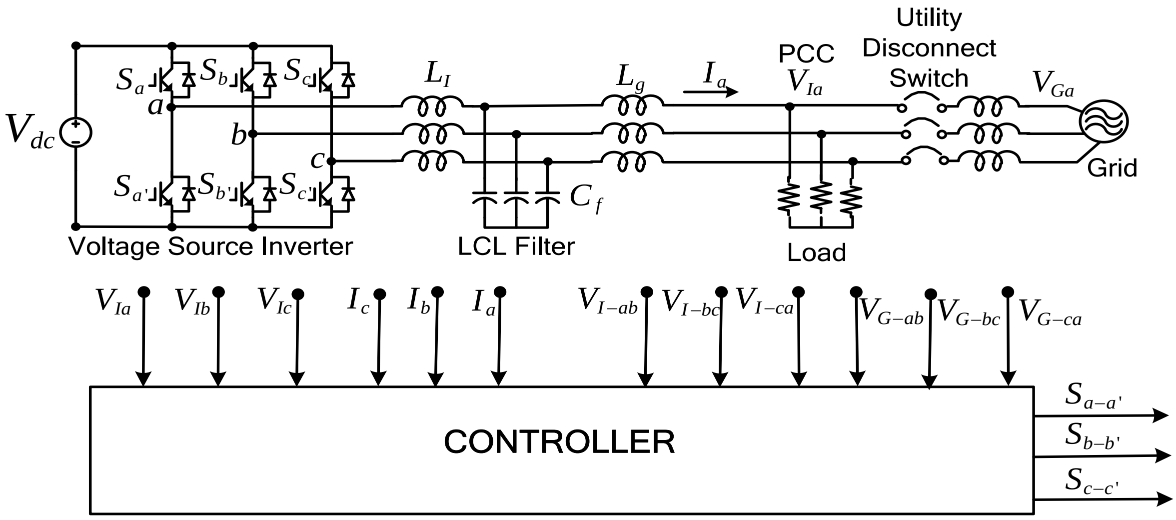

Fig. 1: Schematic diagram of the grid-connected inverter system.

III. PROPOSED CONTROL FOR INTENTIONAL ISLANDING OPERATION WITH SEAMLESS TRANSITION FROM GRID-CONNECTED OPERATION

Control of the DG system is important in both grid-connected and stand-alone modes, moreover the system stability becomes very crucial during the transfer between these two modes. If the system does not have a proper transfer procedure, severe transient voltages or currents will occur, which may damage the entire system [6]. A seamless transfer can ensure smooth operation and quick attainment of steady state.

In order to solve this transition problem, this section presents the development and test of a control strategy for DG capable of working in intentional islanding connection mode with a seamless transition from grid-connected to stand-alone operation modes. The control scheme proposed is based on a voltage-controlled method for the stand-alone DG inverter [11-12]. The stand-alone mode with voltage control features a grid condition detection algorithm to detect the instant at which the DG is cut from the main grid and a controller with seamless transition from grid-connected to stand-alone operation modes.

A. Transitions from Grid-connected to Stand-alone

The proposed voltage closed loop control for stand-alone operation with seamless transition is shown in Fig. 2. The control works as voltage regulation through current compensation. The controller uses voltage compensators to generate current references for the current regulation.

As shown, the load voltage, V_D and V_Q, are forced to track their references (V_{Dref} and V_{Qref}) by using a voltage regulator (PI compensator). The outputs of this compensator, I_{Dref} and I_{Qref}, are compared with the load current (I_D and I_Q), and the error is fed to a current regulator (PI compensator). The output of the current regulator acts as the voltage reference signal that is fed to the sinusoidal pulse-width modulator (SPWM) to generate the high frequency gating signals for driving the three-phase voltage source inverter. The current loop is included to stabilize the system and to improve the system dynamic response by rapidly compensating for near-future variations in the load voltages [13]. In order to get a good dynamic response V_{DQ} is fed forward. This is done because the terminal voltage of the inverter is treated as a disturbance and the feed-forward is used to compensate for it [14].

A compensation coefficient, K, is added to the current control loop as a control unit. This control achieves accurate tracking of the sinusoidal reference. The compensation coefficient processes the magnitude of the input voltage of the PWM modulator and counterattacks the severe transitions influenced by the grid disconnection. Then, this input voltage is fed to the PWM modulator to produce the drive signals for the inverter switches. Therefore, the modulated wave does not include the transient components that resulted from the grid disconnection.

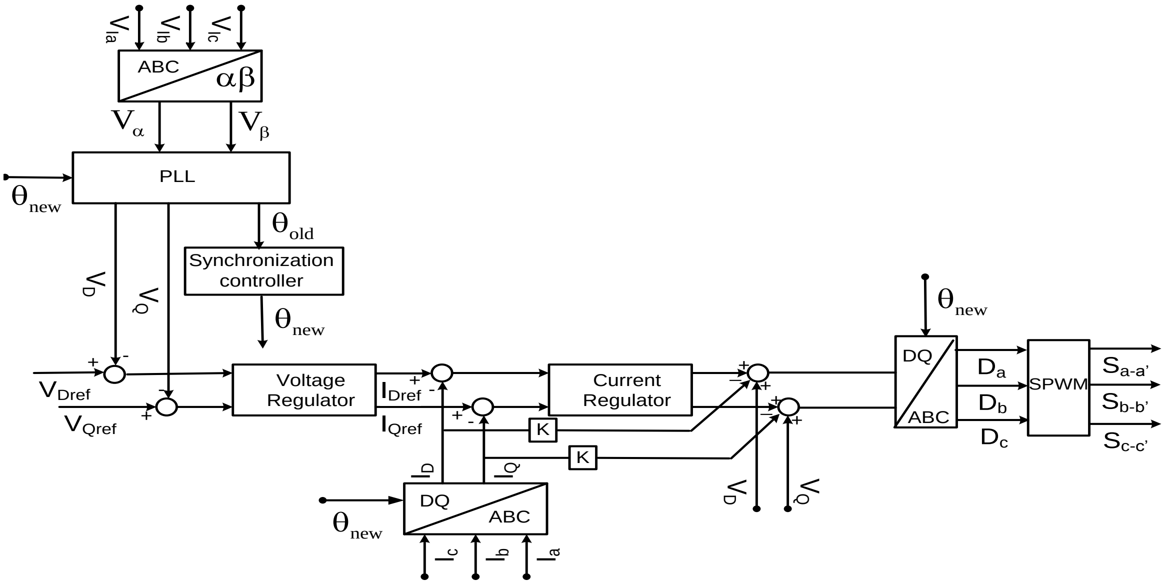

Fig. 2: Voltage controlled inverter.

IV. PROPOSED CONTROL FOR GRID-CONNECTED OPERATION WITH SEAMLESS TRANSITION FROM INTENTIONAL ISLANDING OPERATION

For grid-connected operation, the controller shown in Fig. 1 is designed to supply constant current output in order to provide a pre-set power to the main grid [11]. An important aspect to consider in grid-connected operation is the synchronization with the grid voltage [15-16]. For unity power factor operation, it is essential that the grid current reference signal be in phase with the grid voltage. This grid synchronization can be carried out by using a PLL [17]. Also, the PLL is used to determine the frequency and angle reference of the PCC. Fig. 3 shows the control topology used. When using the current control, the output current from the filter, which has been transformed into a synchronous frame by Park's transformation (Eq. 1) and regulated in DC-quantity [18-19], is fed back and compared with reference currents I_{DQref}.

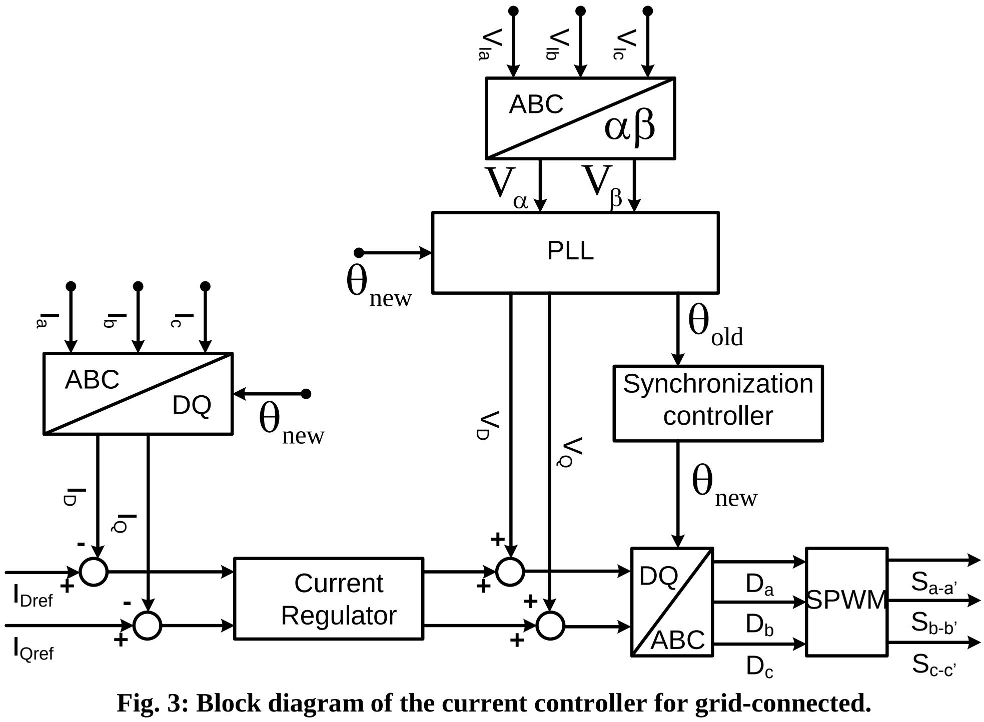

Fig. 3: Block diagram of the current controller for grid-connected.

This generates a current error that is passed to the current regulator (PI controller) to generate voltage references for the inverter. In order to get a good dynamic response V_{DQ} is fed forward. This is done because the terminal voltage of the inverter is treated as a disturbance and the feed-forward is used to compensate for it [14, 18-19]. The voltage references in DC-quantities, V_{DQref}, are transformed into a stationary frame by the inverse of Park's transformation (Eq. 2) and utilized as command voltages for generating high frequency pulse width modulated (PWM) voltages.

$$\begin{bmatrix} X_D \\ X_Q \\ X_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} -\cos\theta & -\cos(\theta+2\pi/3) & -\cos(\theta-2\pi/3) \\ \sin\theta & \sin(\theta+2\pi/3) & \sin(\theta-2\pi/3) \\ 1/2 & 1/2 & 1/2 \end{bmatrix}\begin{bmatrix} X_a \\ X_b \\ X_c \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} X_a \\ X_b \\ X_b \end{bmatrix} = \begin{bmatrix} -\cos\theta & \sin\theta & 1/2 \\ -\cos(\theta-2\pi/3) & \sin(\theta-2\pi/3) & 1/2 \\ -\cos(\theta+2\pi/3) & \sin(\theta+2\pi/3) & 1/2 \end{bmatrix}\begin{bmatrix} X_D \\ X_Q \\ X_0 \end{bmatrix} \tag{2}$$

A. Synchronization Controller for Grid Reconnection: Proposed Algorithm

When the DG is in islanded mode operation and the grid-disconnection cause disappears, the transition from stand-alone to grid-connected mode can be started [20]. To avoid hard transients in the reconnection, the DG has to be synchronized with the grid voltage [11, 15-16]. The DG is operated in synchronous island mode until both systems are synchronized.

Once the voltage in the DG is synchronized with the utility voltage, the DG is reconnected to the grid and the controller will pass from voltage control mode to current control mode.
This synchronization is achieved by implementing the following algorithm:

- Assume that the phase difference between grid voltage and inverter voltage is given by:

$$\phi = \angle V_G - \angle V_I \tag{3}$$

- In order to obtain information of ϕ, two sets of voltage values are used:

$$k = V_{Ia}V_{Ga} + V_{Ib}V_{Gb} + V_{Ic}V_{Gc} = \frac{3}{2}[\cos(\phi)] \tag{4}$$

$$g = V_{Ia}V_{Gb} + V_{Ib}V_{Gc} + V_{Ic}V_{Ga} = \frac{3}{4}\left[-\cos(\theta) + \sqrt{3}\sin(\phi)\right] \tag{5}$$

where,

$$V_{Ga} = V_{Gm}\sin(\omega t)$$
$$V_{Gb} = V_{Gm}\sin(\omega t + 120^O)$$
$$V_{Gc} = V_{Gm}\sin(\omega t - 120^O)$$
$$V_{Ia} = V_{Im}\sin(\omega t + \theta)$$
$$V_{Ib} = V_{Im}\sin(\omega t + 120^O + \theta)$$
$$V_{Ic} = V_{Im}\sin(\omega t - 120^O + \theta)$$

Using the variables k and g, $\sin(\phi)$ can be found as:

$$\sin(\phi) = \frac{\frac{4}{3}g + \frac{2}{3}k}{\sqrt{3}} \tag{6}$$

Fig. 4 shows how $\sin(\phi)$ is used to obtain the compensated phase angle for which the grid voltage and the DG voltage are synchronized. When the grid is recovered, a PLL observer, whose output will generate the grid frequency and phase, processes the grid phase voltages. If the amplitude and frequency of the voltages are within the limits defined by standards, a synchronizing signal will be generated. When the sine of the phase error is between -0.04 and 0.04 radians, the voltages are considered to be synchronized and the control of the supply-side inverter will be switched from stand-alone to grid-connected control mode.

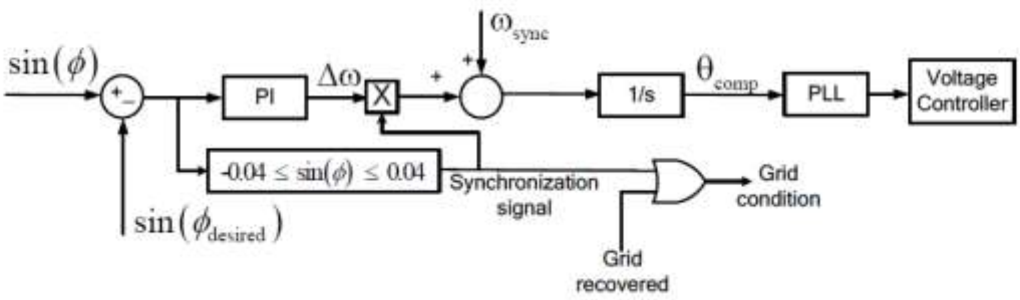

Fig. 4: Synchronization controller

V. SIMULATION RESULTS

The performance of the proposed control strategies was evaluated by computer simulation using SABER. Fig. 5 shows the simulated system. This system was tested under the following conditions:

- Switching frequency, f_s, 10 *kHz*
- Filter inductor, L_I, 1 *mH*
- Filter inductor, L_g, 0.5 *mH*
- Filter capacitor, C_f, 31 μF
- Output capacity 10 kW from DG
- Total load 10 kW

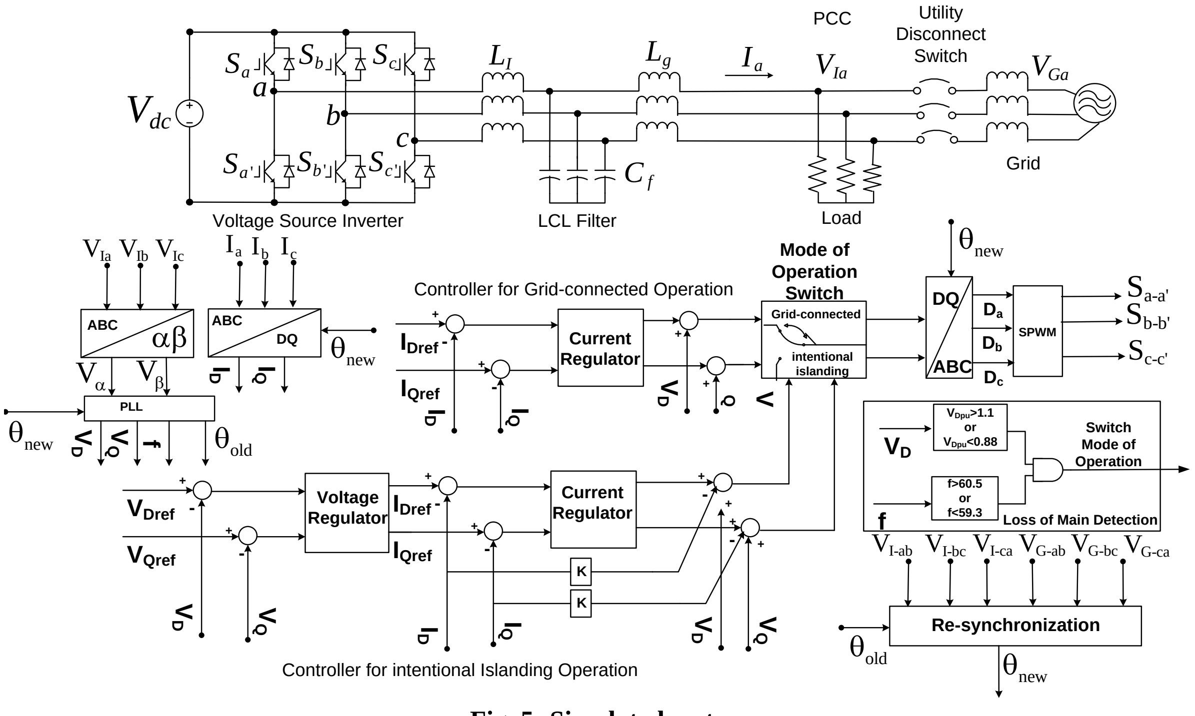

Fig. 5: Simulated system.

The load was adjusted to consume 10 kW. The DG system was simulated to supply 10 kW and zero reactive power. The system was operated initially in grid-connected operation. After the island was detected the control mode was changed from current controlled to voltage controlled operation.

Fig. 6 shows the voltages and currents at the PCC before and after grid disconnection without the seamless transition controller implemented, while Fig. 7 shows the voltages and currents at the PCC before and after grid disconnection with the seamless transition controller implemented.

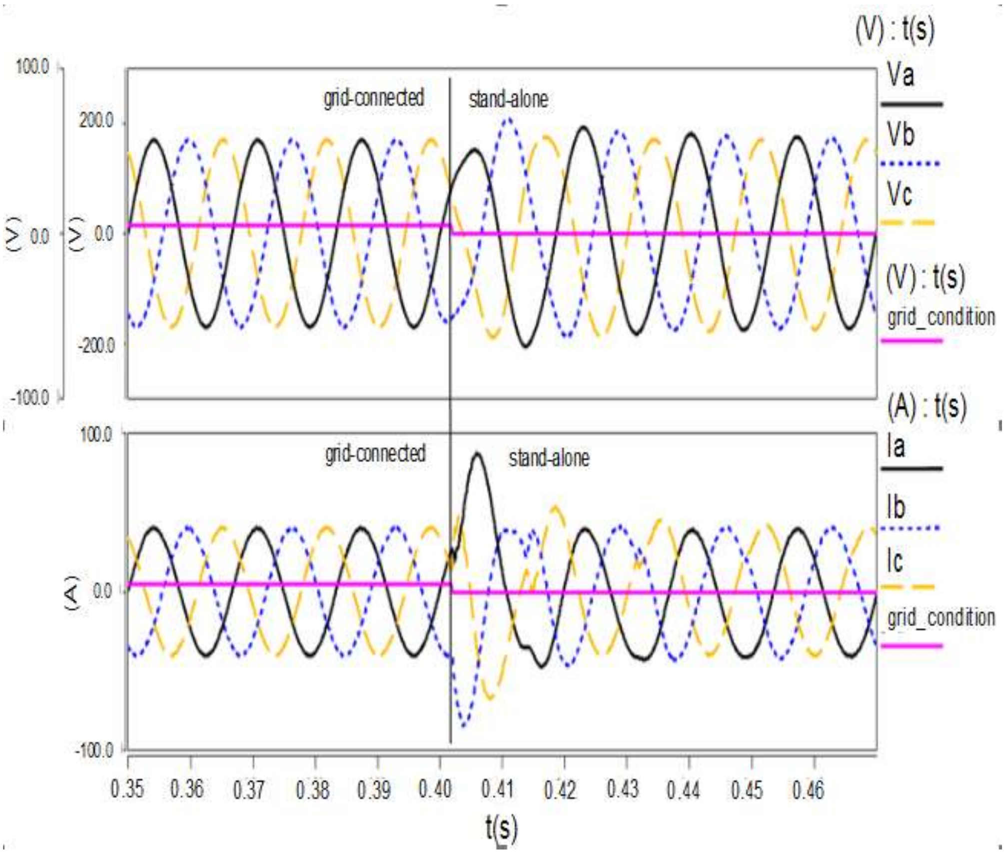

Fig. 6: From grid-connected to stand-alone operation with severe transients

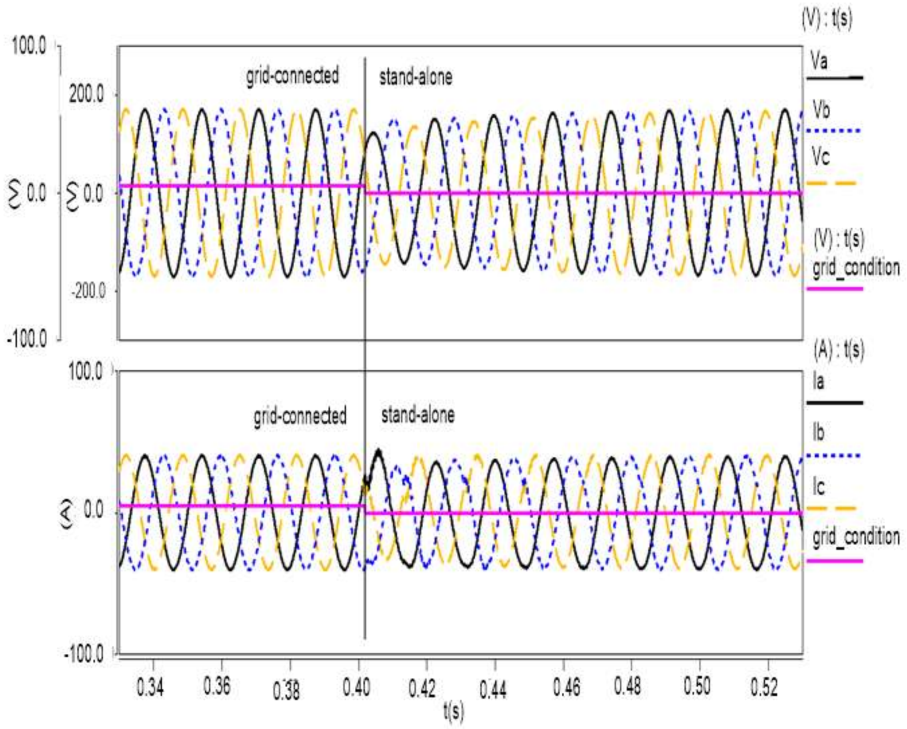

Fig. 7: From grid-connected to stand-alone operation without severe transients.

Fig. 8 shows a line-to-line voltage and a phase current at the PCC before and after grid disconnection with the seamless transition controller implemented. As can be noticed from Figs. 7 and 8, the proposed controller successfully suppresses the severe transients caused by the disconnection of the grid.

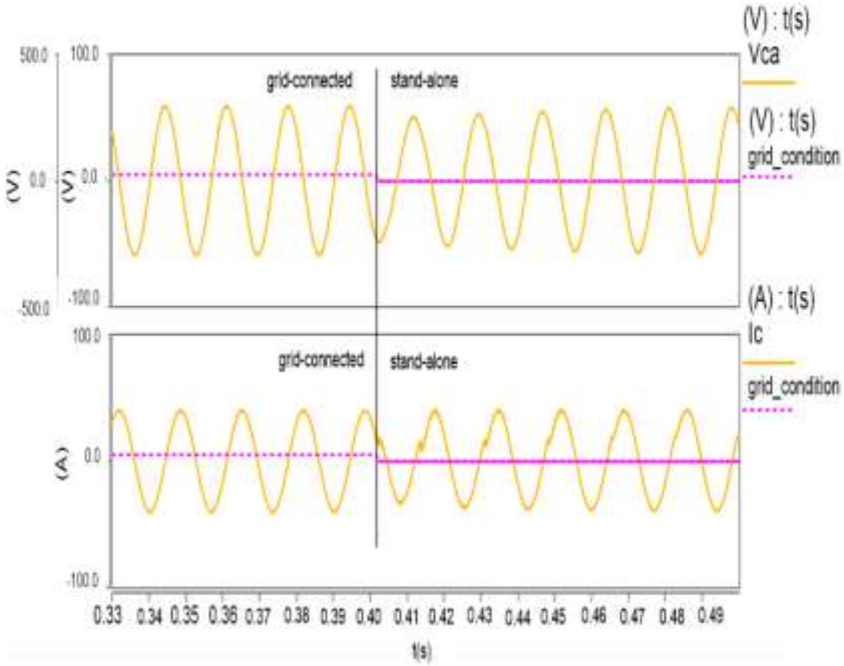

Fig. 8: From grid-connected to stand-alone operation without severe transients.

When the grid-disconnection cause disappears, the transition from stand-alone mode to grid-connected mode can be started. The DG was operated in synchronous island mode until both systems were re-synchronized. While in synchronous island mode, the synchronization controller decreases the frequency to a limited value, as seen in Fig. 9.

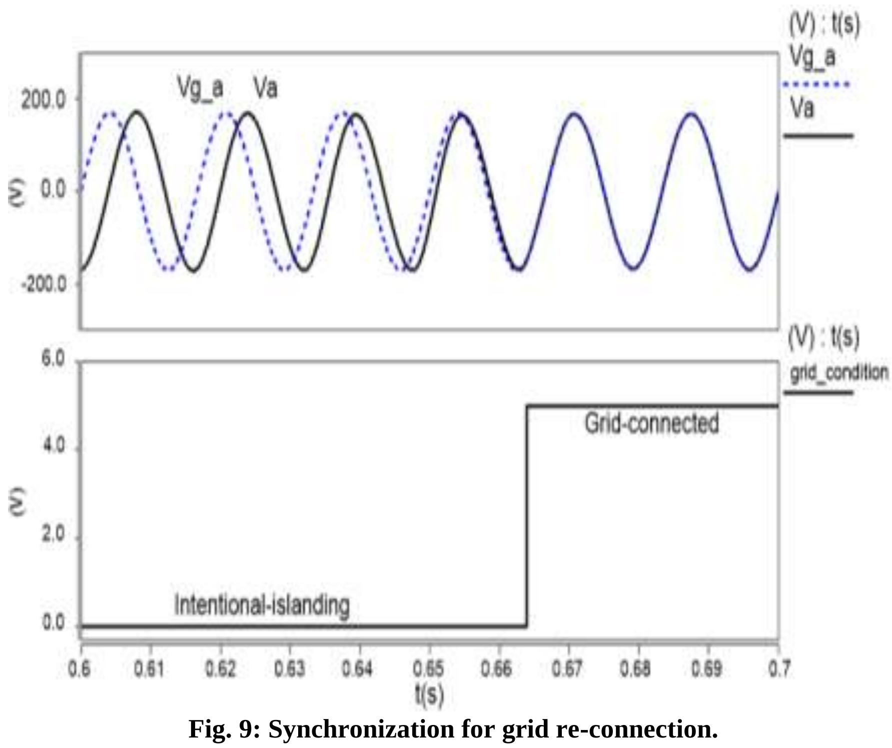

Fig. 9: Synchronization for grid re-connection.

Also seen in that figure are the voltages of the DG and grid; here the DG voltage can be seen to synchronize with the grid and when the phase angle between the two voltages are approximately equal, the algorithm reconnects the system to the utility and switches the mode of control from voltage control to current control. As can be seen, the proposed algorithm successfully forces the voltage at the DG to track the voltage at the grid.

Once the synchronization was completed, the DG was reconnected to the grid and the controller was switched from voltage control mode to current control mode. Fig. 10 shows the phase voltage V_a without and with the synchronization algorithm implemented. As can be noticed, the transients are minimal and virtually negligible indicating that the algorithm avoids a hard transient in the reconnection from stand-alone operation to grid-connected operation.

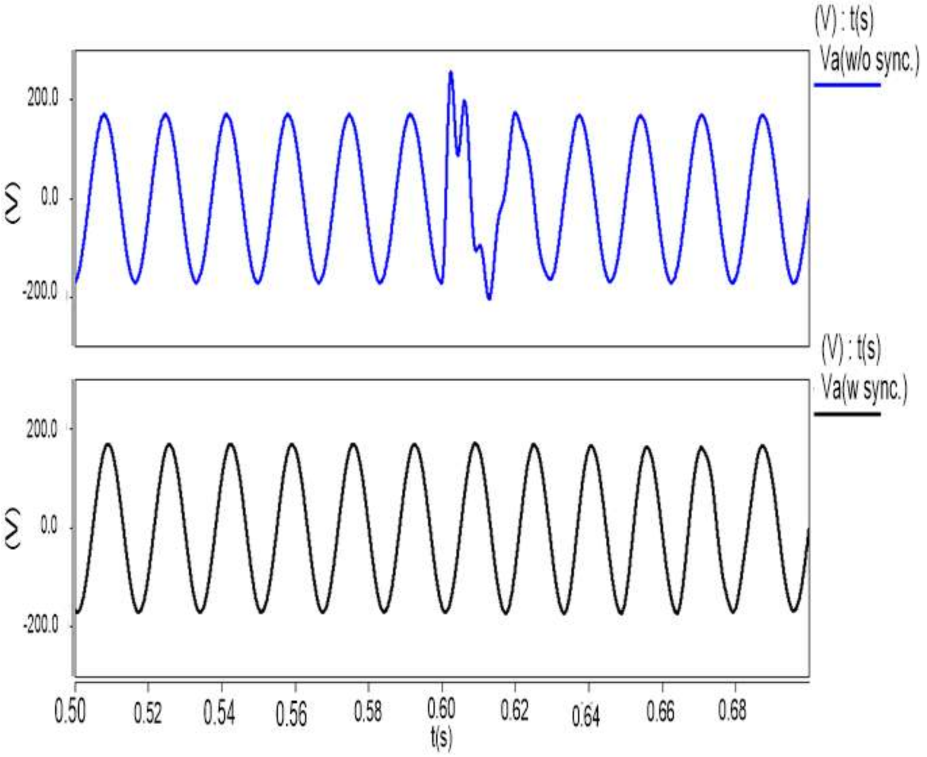

Fig. 10: Phase voltage without (top) and with (bottom) synchronization

VI. EXPERIMENTAL RESULTS

The hardware prototype of Fig. 5 was implemented for experimental verification. The control, PLL, grid condition detection, and re-closure algorithms were programmed using a universal DSP control board developed at the Power Electronics and Motor Drives Laboratory at the University. The system was tested under the following conditions to experimentally verify the simulation results:

- Switching frequency, f_s, 10 kHz
- Dead time 3μs
- Filter inductor, L_I, 1 mH
- Filter inductor, L_g, 0.5 mH
- Filter capacitor, C_f, 50 μF
- Simulated Output voltage 104 V_{RMS-LL}, 3Φ @ 60 Hz grid connection, with V_{dc} = 200 V
- Output capacity 2.5 kW from DG
- Total load 2.5 kW
-

The reason for simulating the output voltage is to ensure the algorithms and controllers are functioning properly under low-power tests; such that there is a reduced risk of operator and equipment damage if the system fails.

Shown in Fig. 11 are the inverter, the DSP board, the filter, and the rectifier. The DG is started up in grid-connected operation mode, and then the separation device is opened. When the DG is disconnected from the grid it operates in stand-alone mode. Fig. 12 shows a voltage and phase currents when the disconnection device is opened and the seamless controller from grid-connected to stand alone is not implemented.

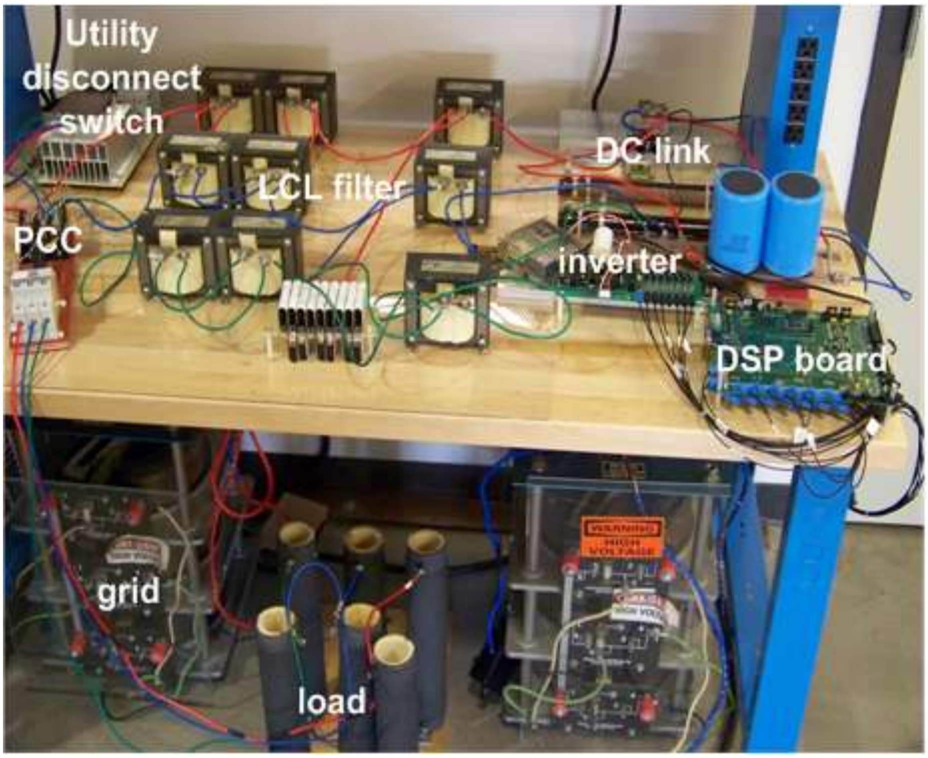

Fig. 11: Experimental set-up

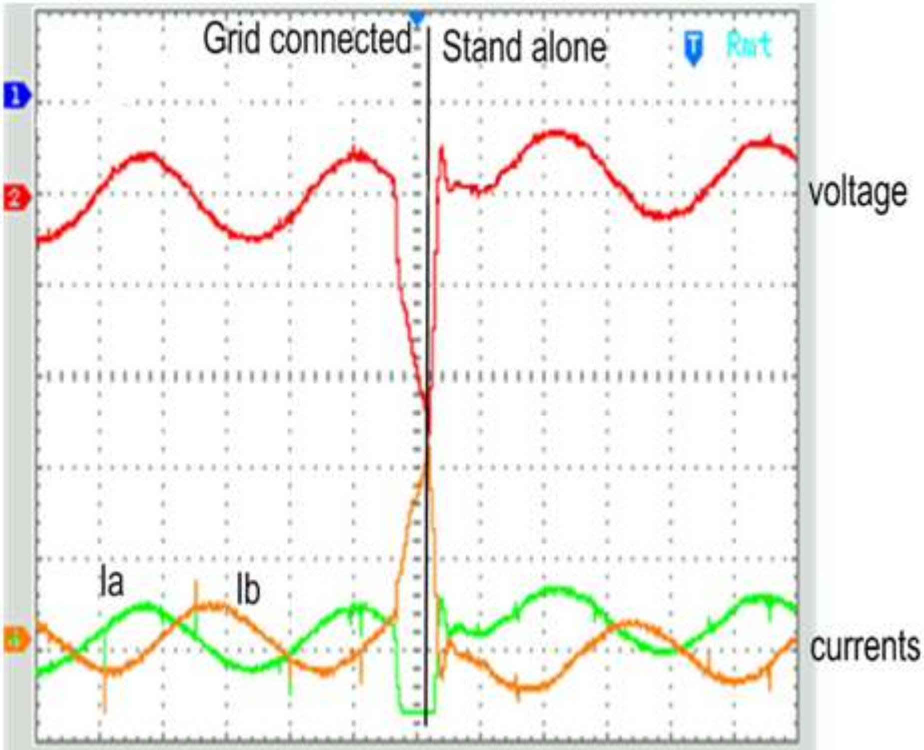

Fig. 12: Transition from grid-connected to stand-alone operation with severe transients.

Fig. 13 shows the grid voltage, the DG line to line voltage, and the phase current before and after grid disconnection with the seamless transition controller implemented. As can be noticed, the proposed controller successfully suppresses the severe transients caused by the disconnection of the grid.

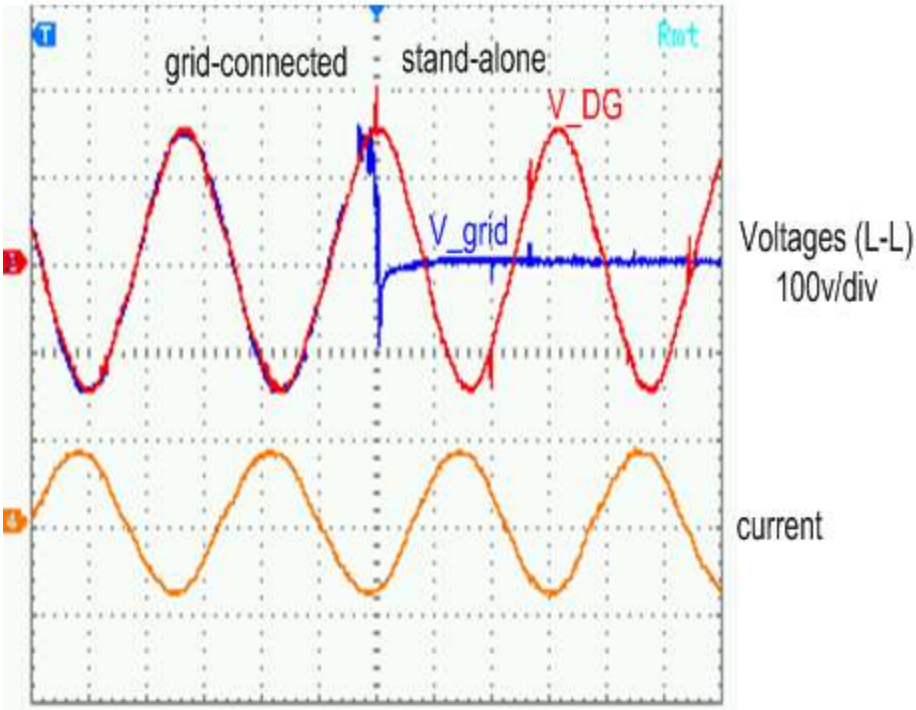

Fig. 13: Transition from grid-connected to intentional islanding operation without severe transients.

Fig. 14 shows the process of synchronization where the line to line voltage at both ends of the separation device is illustrated. At the beginning of the synchronization, both voltages are out of phase. As can be seen, the proposed algorithm successfully forces the voltage at the DG to track the voltage at the grid until the synchronization process is completed. Also shown is the smooth transition of the currents.

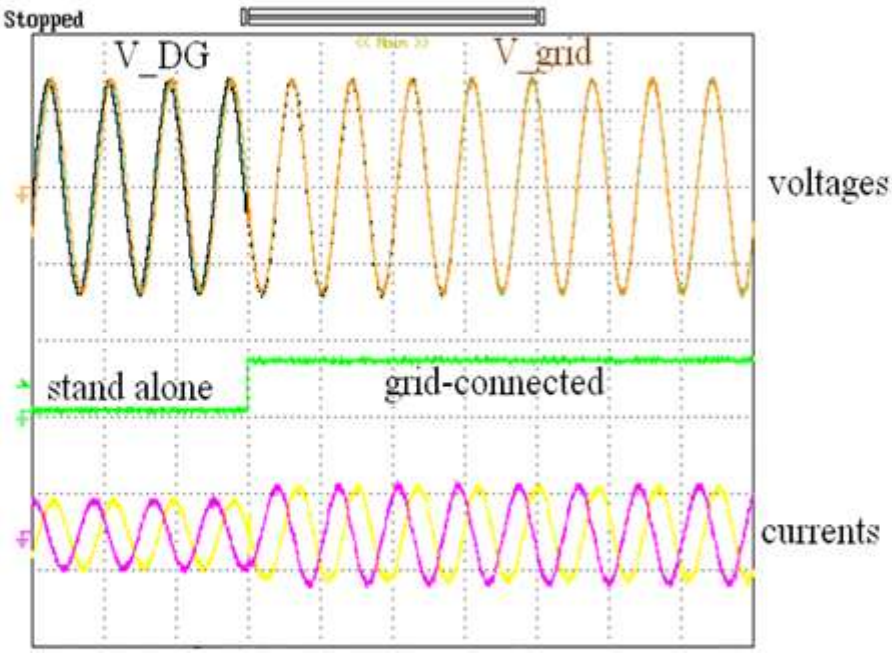

Fig. 14: Transition from stand-alone to grid connected operation

VII. CONCLUSIONS

Through this paper, a novel seamless transfer of grid-interactive inverters between grid-connected mode and stand-alone mode has been proposed. A controller was designed with two interface controls: one for grid-connected operation and the other for stand-alone operation. The principle and realization conditions of both control methods have been analysed. An islanding detection algorithm, which was responsible for the switch between the two controllers, was presented. The detailed process of a seamless transition between grid-connected and stand-alone modes has been illustrated. The proposed algorithm is able to switch the inverter operation from voltage-controlled mode to current-controlled mode and vice versa with no interruption to the load. The simulation and experimental results show that the seamless transfers have been achieved.

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