Solar Inverter with A Battery For Microgrid Applications

R Supriya[1], S. Venkat Rao [2]
[2] Assoc Professor
[1, 2] Svpcet, Puttur

Abstract- *The aim of this work is the development of an 80kW solar photovoltaic generation system based on a standard power electronics cell for microgrid applications. The proposed system is capable to provide security of supply by delivering uninterrupted power to critical loads in standalone operation and transition seamlessly between stand alone and grid connected mode. To mitigate the effect of variability of the generation and load demand a state of the art 20kWh lithium- ion battery is used to balance the power flow in the system. This paper presents Description of the hardware, proposed controls strategies and simulation models of the system.*

I. INTRODUCTION

United States' dependence on fossil fuels has been identified as a major issue that is detrimentally affecting its economic growth and jeopardizing its national security. Also this dependence is putting US to compete for conventional fossil fuels with the emerging economies. The Department of Defense(DoD)consumesabout60percentof all energy used at federal government facilities. To address this problem the federal government through the Department of Energy (DoE) and Department of Defense (DoD) is strongly supporting the use of renewable energy sources by setting very challenging goals through the Energy Policy Act of 2005. This policy directs DOD to consume at least 3% of its total electricity needs from renewable sources through Fiscal Year (FY) 2009, 5% through FY 2012, and not less than 7.5 % beginning FY2013.

In addition to the energy savings that renewable energy may provide. There is a strong need to increase energy security and for DoD energy security means "having assured access to reliable supplies of energy and the ability to protect and deliver sufficient energy to meet operational needs". In this regard renewable energy and energy storage elements plays a fundamental role to diversify the portfolio of stand by energy sources to day dominated by diesel generators.

Main challenge for renewable to be able to fill the gap in terms of reliable supplies of energy is the un predictable nature of the energy source such as solar and wind and the stochastic nature of the load. However, with the introduction of new energy storage elements with higher energy storage capacity such as super-capacitors, lithium ion batteries and flow batteries clearly opens the possibility to develop a renewable energy source able to work in standalone mode and seamlessly transition from grid disconnected to grid connected mode of operation .

Solar PV and energy storage have been extensively used for standalone operation of pumps, telecommunications systems and houses in remote areas. Typically energy storage elements used in those applications are lead acid batteries. Grid-tie PV inverters and batteries haven used to smooth power injected to the grid . Recently grid-tie battery energy storage using Lithium-Ion batteries have been demonstrated for single phase systems.

The aim of this paper is the development of a 80k W solar photovoltaic micro-source with Lithium-Ion battery. The proposed system as oppose to the ones reported in the literature, is able to operate in standalone and grid connected mode and seamlessly transition from grid connected to grid disconnected mode of operation. The implementation is based on a standard power electronics cell concept for microgrid applications.Fig.1shows the connection diagram of the system.

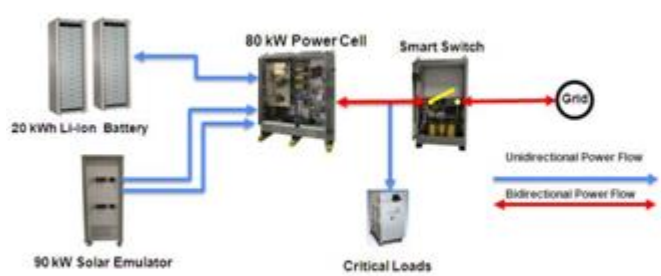

Fig. 1 Standalone and grid connected PV micro-source

Using these configuration critical loads will be powered either from the grid or the hybrid inverter. Also if the grid conditions are not up to the power quality standards required by the load it is possible to create an intentional islanding until the grid conditions return to normal. The worst case scenario is a sudden loss of the grid power; in this case the system should automatically transition to a standalone mode of operation and continue supplying energy to the critical loads. These and other possible operating conditions present a challenge to the local controller that needs to address all of them without human intervention or changing the control structure. The paper will present a description of the system and various components as well as simulation and experimental results. The outcome of this work will provide a solution that will help DoD to meet his ambitious clean energy programs.

II. STANDARD POWER ELECTRONIC CELL FOR DPS

The proposed standard power electronic cell is defined as a set of optimized modules such as power stage, power filters, EMI filters, signal conditioning board, control board, and a hierarchical control library. The modules can be configured perform a specific energy conversion function. For DPS the most common energy conversion functions are, ac-dc, dc-dc, and dc-ac unidirectional and bidirectional. Fig. 2 depicts a block diagram of the Standard Power electronics Cell partition.

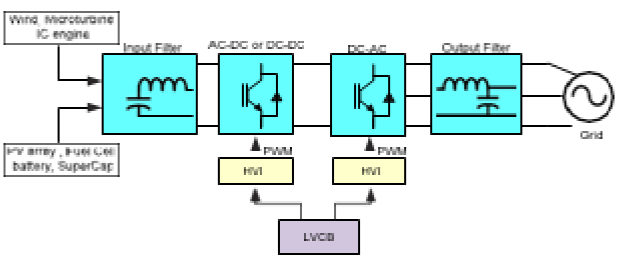

Fig. 2 Standard power electronics cell

A. Power structure

Power structure: many of the required energy conversion functions for DPS can be implemented using industry standard, high volume IPMs. This approach directly addresses two major industry concerns which are reliability and cost, mainly because it takes advantage of the large volume of IPMs already in the market for motor drive applications.

B. Control and interface board

High Voltage Interface (HVI) board: High voltage interface board provides interface between components of power structure and control circuitry implemented on a control board. Principal functions implemented on HVI board are: analog and digital signal conditioning, voltage and current sensing and gate drivers,

Low Voltage Control Board (LVCB): Low voltage control board is typically 4 to 8 layers board with components such as microprocessor, memory, digital logic, analog signal conditioning circuitry, digital Input and outputs

C. Modular control software architecture:

Software control functions can be grouped in different modules like PWM, transformation blocks, compensation,pllloops,filters,fluxobservers,deadbeatcurrentregulators, MPPT. These modules will allow the user to build or customize the control for the specific conversion function that the standard power electronic cell will be used for. The modules are called every switching cycle for real time control of the power structure current and voltages. The software modules are written in C therefore they can be also use in a simulation environment that runs C code such as Simulink or Psim. An integral part of this approach is that all the control software are developed and validated at the simulation level.

III. HYBRID SOLAR INVERTER SYSTEM LEVEL OVERVIEW

The system consist of an existing 72kWPVarray with 16 series and 26 paralleled Mitsubishi PV-UD175MF5. A lithium ion battery string is formed using VL41M Li-Ion cells from SAFT, The battery is formed by 15 battery modules connected in series for a total nominal battery voltage of 360V with a maximum voltage of 420V and a minimum voltage of 315V. This battery will be able to provide up to 40kW of power for half an hour.

Thepowerconditioningunitisan80kWstandardcell.At the dc side each leg is able to process 40kW at a minimum input voltage of 300V. Two legs are configured as unidirectional inter leaved boost converter to interface the PV array and one leg is configured as a bidirectional dc-to-dc converter to interface the battery. On the AC side the inverter unit is able to handle 80 kW plus twenty percent overload at 380 V RMS. Inverter output filter is a LCL filter designed to meet IEEE 1547 standard. A Delta - Y isolation transformer serve as the grid inductance for the filter as well as to boost the voltage to 480V to meet the nominal grid voltage.

The system connects to the grid using a smart switch. This device consists of three pairs of anti-parallel SCRs that allow a fast and smooth connection and disconnection to the grid. The most important functions of the static switch are synchronization with the grid and grid monitoring. By using the statics witch, power quality problems become transparent to the critical or sensitive loads because in the case of a large grid disturbance the smart switch will produce an intentional islanding until grid conditions return to normal.

Schematic of the implementation using the standard power electronic cell concept is depicted in Fig. 3. For the design of the system, very important system level objectives for the operation of the systems needs to be defined and listed in order of priority so that any situation where decisions needs to be made a set of rules will define the operating conditions of the system. More objectives can be added depending on the system requirements but for this

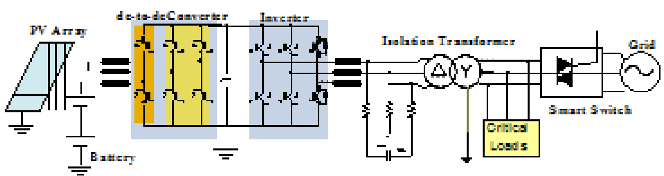

Fig. 3 System interconnecting diagram

project the following objectives where defined.

1. Provide power to critical load
2. Maintain an optimal battery state of charge(SOC)
3. Meet frequency and voltage THD standards
4. When grid connected power may be exported or imported depending if there is an excess or deficit of PV generation.

The first objective is based on the need to demonstrate security of supply, this objective dominate and override any other objective below in the order. The second objective support the first one, the requested state of charge is determined base on local measurement and weather forecast data processed by a supervisory control system, however if the only source of power is the battery, it will not follow the requested SOC but on the contrary the battery will be discharge in order to support the first objective. Third objective is related to the quality of supply critical loads while grid connected so that in the case large grid disturbances in terms of frequency or voltage the system may decided to create an intentional islanding. Finally the four objectives allow power export to the grid.

A. DC-DC Conveters' Control Strategy

In the proposed micro grid system, the DC-DC converters are used for interfacing the energy storage element and PV arrays. The DC-DC converters are controlled to achieve the following main objectives. To begin with, the dc-link voltage is maintained to a fixed reference value by the controlling the power flow from battery through a bi-directional converter. The interleaved unidirectional boost converter is used to control the bus voltage of the PV arrays and to extract the maximum power. The other main objective is to achieve dynamic control of the power flow between the battery and PV arrays in response to the fast changes of the load and the environmental conditions. Another key objective is to have the capability to follow the command of the supervisory controller for the charge and discharge of the battery. It is also important to maintain the SOC of the battery within its safe limits operation. Furthermore, it is essential to achieve the capability of independent operation under the loss of communication with supervisory controller; such that the system can maintain the power balance between the inverter demand, energy storage, and photo voltaic generation.

There are many challenges which need to be addressed to achieve the above objectives. Firstly, the combinations of PV generation conditions, battery operations, and grid connection status result in many operation modes. This makes it very challenging to obtain stable operation and fast transitions among the modes. The next challenge is to operate PV arrays under rapidly changing environmental conditions and to achieve MPPT which is fast yet very accurate. It also a major task to integrate the complex system, including the Battery Management System (BMS) and Energy Management System (EMS), smart switch, and the photovoltaic system. The realization of independent control of the converters while ensuring reliable power delivery the critical loads is also a significant challenge.

The schematics of the control block diagram for the bi- directional converter, interfacing the battery, is shown in Fig. 4. In the presented scheme, cascaded voltage regulator and current regulator are used to maintain the dc link voltage while controlling the charge and discharge currents from the battery.

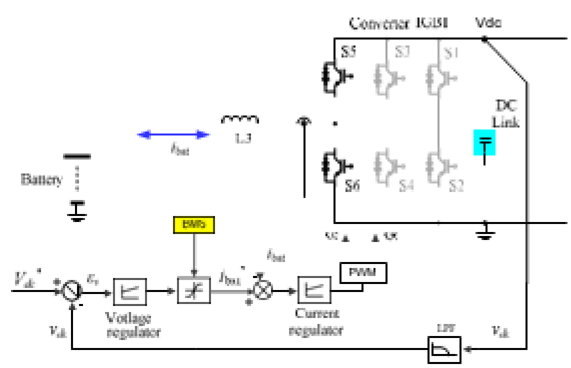

Fig.4 Control scheme block diagram of the bi-direction converter to inter face battery.

B. Inverter Control Strategy

A main requirement of the system is to support critical loads and provide seamless transition from grid connected to grid disconnected mode of operation. A grid-forming inverter would satisfy for standalone operation because they form a grid by controlling voltage and frequency at the inverter output terminals. However paralleling grid-forming inverters with the grid or other grid-forming inverter would not be possible if a paralleling control algorithm is not in place.

Fig. 5 shows the basic control scheme of a three-phase grid forming-inverter where currents and voltages are transformed to the d-q reference frame, a cascaded inner current-loop and outer voltage loop is used to control the inverter output voltage. In this work the q channel is the active channel.

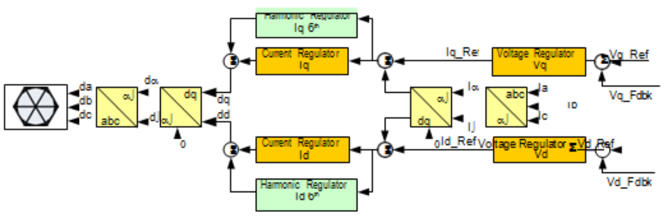

Fig. 5 Grid forming inverter control diagram

Harmonic regulato are added to the current loop control to make the control robust against 5th and 7th harmonics present in the grid. However, since the inverter is ultimately a voltage source a full compensation of this harmonics is not allowed because in standalone mode and grid connected mode priority is given to a good quality voltage waveform and current is whatever is demanded by the load.

The control algorithm for parallel operation with the grid is based on a P Q droop controller. The voltage source inverter controls both the magnitude and phase of its output voltage and uses the transformer leakage inductance as the impedance between the inverter and the grid as shown in Fig. 6 .

The vector relationship between the inverter voltage and the grid voltage along with the transformer reactance determines the flow of active and reactive power from the inverter to the grid.

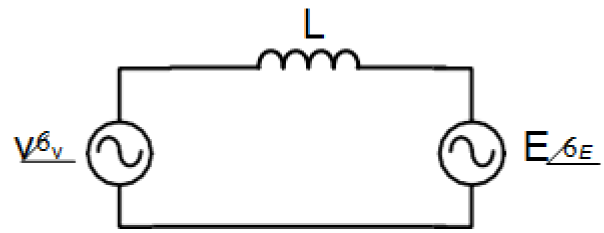

Fig. 6 Inverter P - Q control

Equations (1) and (2) shows the corresponding mathematical relations for P & Q.

$$P = \frac{VE}{\omega L}\sin\left(\delta_E - \delta_V\right)$$
$$Q = \frac{V^2}{\omega L} - \frac{VE}{\omega L}\cos\left(\delta_E - \delta_V\right)$$
(1) (2)

Where P is controlled by small changes on (*6* -*6*) andQ

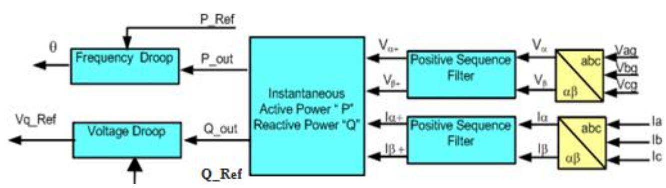

Fig. 7 P-Q droop control algorithm

The output of the frequency droop block is the angle for the park transformation and the voltage droop output is the reference for the inverter Vq channel voltage and Vd_ref is set to zero.

Output active power and reactive power are calculated by (3) and (4).

$$P_{out} = I_\alpha V_\alpha + I_\beta V_\beta \quad (3)$$

$$Q_{out} = I_\beta V_\alpha - I_\alpha V_\beta \quad (4)$$

To ensure that grid disturbances such as unbalance and or harmonics are not feed back in to the control through the instantaneous power calculation block only fundamental component for current and voltage should be used. This work uses a complex band-pass filter originally proposed for communication and signal processing and then tailored for microgrid application in. Experimental results demonstrate the advantage of this approach.

IV. SIMULATIONRESULTS

All systems control were first implemented in simulation by using the same control modules which are used in the low voltage control board. The Simpowersys Simulink tool box of MATLAB is used to model the power converters. All the control functions were embedded in a C-MEX S-Function, which are called at every switching instant. The values for various circuit parameters, used in the simulations, were obtained from measurements and specifications from manufactures.

The simulation results for various modes of operation of the DC-DC converters are shown in Fig. 8. In the scenarios presented in this figure, at first the interleaved DC-DC converter is controlled to obtained MPPT operation by changing the PV bus voltage (Fig 7b). The maximum power point of the PV is reached the time t_1 (Fig 8c); prior to this instant, the battery dynamically supplements the difference between the fixed load demand and the changing PV power (Fig 8b). At instant t_2, as shown in Fig 8(a) and Fig 8(c), the solar insolation is subjected to a step change. It can be seen that, although at this instant the PV power is substantially reduced, the DC-link voltage is maintained by the battery.
V E The DC-DC controller also successfully performs MPPT\depends on the inverter output voltage magnitude given that there is a minor coupling effect between P and Q. Fig. 7 depict the outer P-Q control loop of the inverter. under this fast changing condition. Afterwards, the load is stepped down at time t_3. Under this condition, the PV still produces the maximum power and the battery power is reduced to match the load demand.

Fig. 9 shows the simulation result of the inverter in different operating conditions where the inverter is initially working in standalone mode feeding critical loads. In area two the inverter transition seamlessly to grid connected operation and follows a power command of 0.9 pu, area three shows the robustness of the converter against grid voltage harmonic disturbances by injecting sinusoidal currents even though the grid voltage present a high harmonic distortion. And area four show the seamless transition to grid disconnected mode.

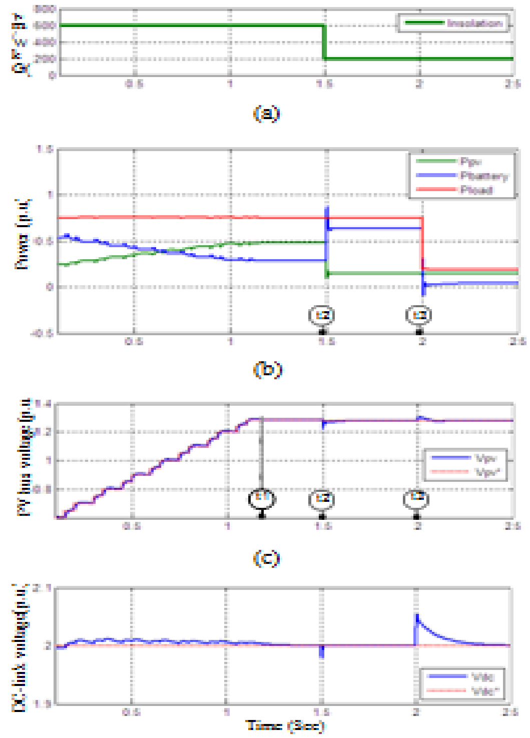

Fig. 8 Simulation results for the DC-DC converter control under various modes.

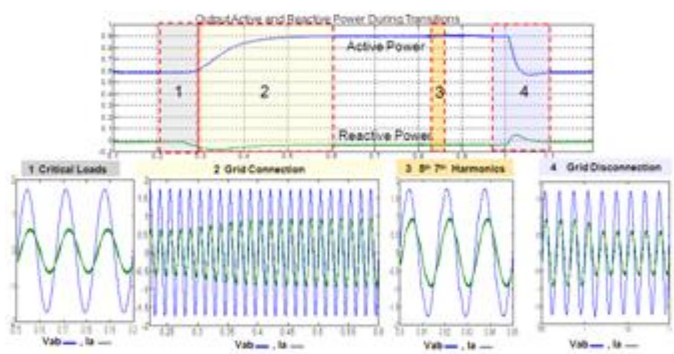

Fig. 9 Simulation results for inverter control

V. EXPERIMENTALSETUP

An experimental setup including all system components except for the PV Array was built to demonstrate the operation of the system in multiples operating conditions. In thelaboratorythePVarrayhasbeenreplacedbya90kWPV emulator capable to reproduce the static behavior of the PV array in the field. Full demonstrations including PV arrays will be carried out at a DoD site. Fig. 10 shows all the components under test at UTRC energy conversion lab.

Fig. 10 Experimental Setup

VI. EXPERIMENTALRESULTS

At first, the experimental result for MPPT operation by controlling the PV bus voltage is presented in Fig 11. It can be mentioned that in presented work, the MPPT is obtained by using Perturb and Observe method. Special control algorithm is used to obtain perturb free operation of the converter after reaching the maximum power point (t_1 in Fig 11). Different operation modes of the DC-DC converter are presented in Fig 12. In this case, the load is increased from 10 kW to 15 kW at instant t_1; and to cater the increased load demand, the battery starts to discharge more power. Further, at time t_2, the load is stepped down from 15 kW to 5 kW. Under this condition, the maximum power of PV is more than the 5 kW load. It can be noted as the load is reduced, the battery operation is changed from discharge mode to charge mode while still maintaining the MPPT operation. Finally, at instant t_3, the load is stepped up back to 15 kW from 5 kW. In can seen from Fig 12, that the under all these operation modes, the dc bus voltage was successfully regulated to a desired voltage level while achieving unperturbed MPPT operation.

Next, experimental results presented are in the standalone mode of operation of the inverter, considering a critical load of 15kW. Fig. 13 shows the inverter voltage soft-start implemented to avoid any transformer inrush current. This is also a critical operating mode because the only damping in the system is a 0.2 ohms damping resistor in series with the filter capacitor plus the transformer no load losses. Then a 5kW and 10 kW resistive load steps are applied.

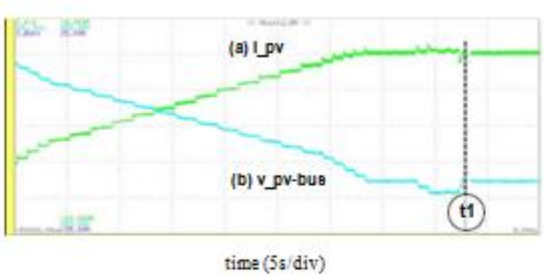

Fig. 11 Maximum Power Point Tracking (MPPT) operation

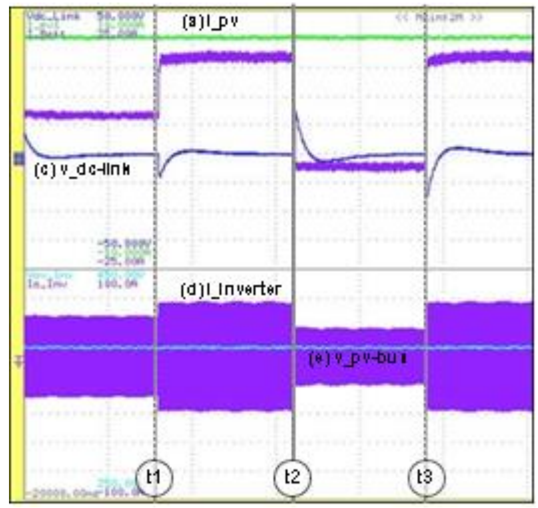

Fig.12OperationmodesoftheDC-DCconverters

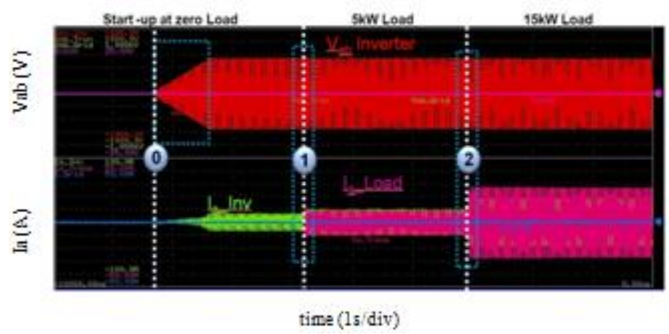

Fig. 13 Stand alone operation inverter side

A zoom view during the transition from 5kW to 15kW showninFig.14illustratethatatlightloadconditionthereis a high distortion on the current originated by non-linearities in the isolation transformer. In these conditions the inverter is still able to produce a voltage waveform within power quality standard requirements thanks to the action of the complex band-pass filters.

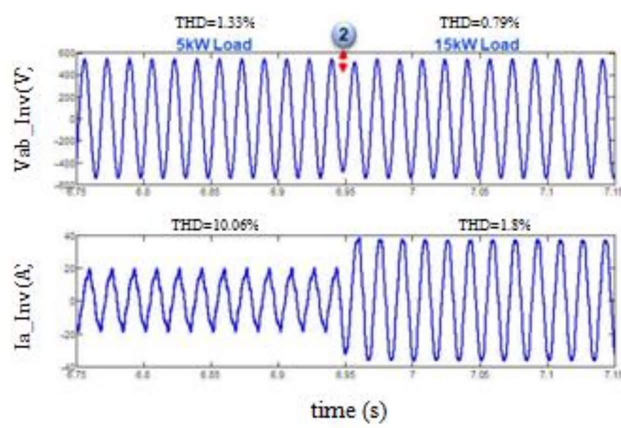

Fig. 4 Load step from 5kW to 15Kw

Experimental result shown in Fig.15, depict the seamless transition from standalone mode to grid connected mode. For a successful connection to the grid the smart switch waits until the two systems are within a synchronization window defined by:

- Vab_grid –Vab_inv voltage < 10% of the nominal voltage
- Vab_grid angle – Vab_inverter angle <20°
- The slip frequency between the voltages is less than the maximum slip frequency setting=0.3Hz

When the conditions above are met a synchronization signal (Synch_signal) goes to a low state giving the order to the thyristor bridge to connect with the grid. For the critical loads the transition is seamless because there are no transients in the voltage during the connection.

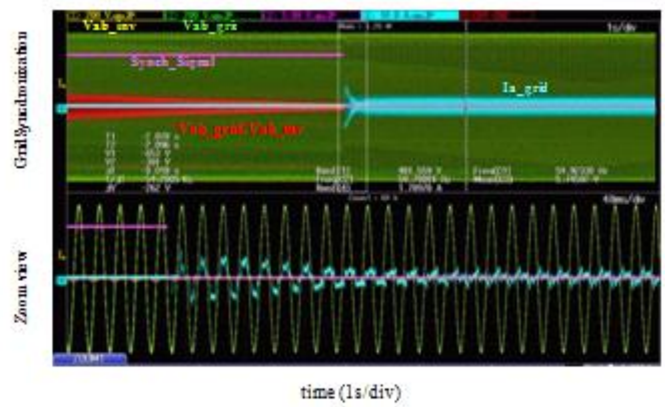

Fig. 5 Grid synchronization

Once the inverter is connected to the grid both P and Q droop controller will follow their respective reference values. Fig. 16 shows an example on how the critical loads are served either from the inverter, the grid or a combination of both. In this case a 5kW P_ref is given to the inverter so that 10kW needed to serve the critical loads comes from the grid (importing). Then P_ref is increased from 5 kW to 30kW.

In this case, the inverter is supplying 15 kW to the critical loads and 15kW goes to the grid (exporting). not be construed as an official department of defense position or decision unless so designated by other official documentation.

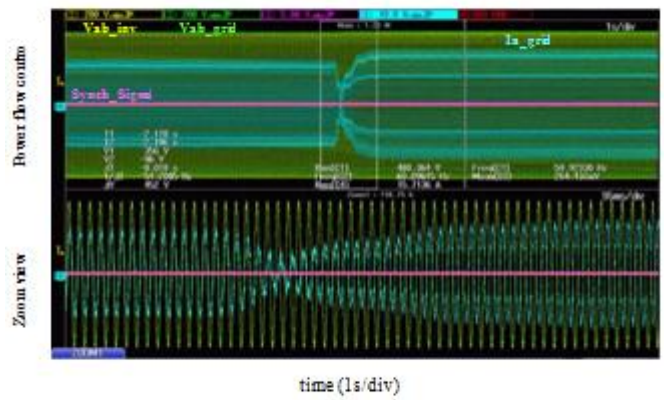

Fig. 6 Inverter active power control

VII. CONCLUSIONS

An 80kW solar photovoltaic generation system based on a standard power electronics cell for micro grid applications has been presented; simulation and experimental results demonstrated the feasibility of this approach. Subsystems and systems control developed for this application is able to successfully provide security of supply by providing uninterrupted power to critical loads in standalone operation and transition seamlessly between stand alone and grid connected mode. Furthermore, the proposed integration of the DC-DC converters and the control schemes demonstrate the capability of stable and fast dynamic operation under various modes operation of PV array and the battery.

Because of the multiples advantages that Lithium Ion battery offers compared to the other battery technologies, it is a very promising technology that can be successfully used to mitigate the effect of variability of the generation and load demand a state of the art 20kWh lithium-ion battery is used to the system to balance the power flow in the system.

VIII. ACKNOWLEDGMENT

The research work, presented in the paper, is partly supported by the US Army Corps of Engineers, Humphreys Engineer Center Support Activity under Contract No. W912HQ-09-C-0055. Views, opinions, and/or findings contained in this paper are those of the author(s) and should

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