This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TSTE.2018.2808601, IEEE Transactions on Sustainable Energy

PV-STATCOM: A New Smart Inverter for Voltage Control in Distribution Systems

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***Abstract*—This paper presents a novel smart inverter PV-STATCOM in which a PV inverter can be controlled as a dynamic reactive power compensator - STATCOM. The proposed PV-STATCOM can be utilized to provide voltage control during critical system needs on a 24/7 basis. In the nighttime, the entire inverter capacity is utilized for STATCOM operation. During a critical system disturbance in the daytime, the smart inverter discontinues its real power generation function temporarily (for about a few seconds), and releases its entire inverter capacity for STATCOM operation. Once the disturbance is cleared and the need for grid voltage control is fulfilled, the solar farm returns to its pre-disturbance real power production. The Low Voltage Ride Through (LVRT) performance of the PV-STATCOM is demonstrated through both EMTDC/PSCAD simulations and laboratory implementation using dSPACE control. This proposed PV-STATCOM with a response time of 1-2 cycles, can provide an equivalent service as an actual STATCOM in a given application and possibly seek revenues for providing this service.**

***Index Terms*—Photovoltaic (PV) Solar system, Smart Inverter, STATCOM, Voltage Control, Power Factor Correction, Flexible AC Transmission System (FACTS), Distributed Generators**

I. Introduction

SMART Inverters (also previously known as Advanced Inverters) represent a paradigm shift in the integration of Distributed Energy Resources (DER) [1]–[5]. These inverters can perform multiple functions involving both reactive and real power control in addition to their main task of converting DC power to AC power. These functions include voltage regulation, power factor control, active power controls, ramp-rate controls, fault ride through, and frequency control, etc. Various grid support functions offered by smart inverters are presently being demonstrated on real distribution and transmission systems in different counties, to motivate their rapid deployment [6]–[8]. The benefits of reactive power control strategies with PV inverters are described in [9]–[11]. Grid interconnection standards are currently being revised to facilitate the adoption of smart inverter functions [12]–[14]. The voltage control related smart inverter functions e.g., volt/var are mainly a set of operating points [4] which are implemented in open-loop with time constants of a few seconds. The ongoing IEEE P1547 Standard Full Revision is contemplating that DERs shall be capable of injecting a finite amount of reactive power (typically 44%) even at 100% of nameplate active power rating (kW). This implies that DER inverters will have to be oversized. The LVRT function requires that the DER shall stay connected even if the voltage goes below a specified limit [4], [12]. However, if the voltage continues to be at a low level for more than a prespecified period of time, the DER must disconnect.

A unique concept of utilizing PV solar farms as STATCOM during nighttime for providing different grid support functions as well as for providing the same benefits during daytime with inverter capacity remaining after real power generation was proposed in 2009 [15], [16]. STATCOM is a Voltage Source Converter (VSC) based Flexible AC Transmission System (FACTS) device [17]. It can provide dynamic reactive power compensation with a response time of 1-2 cycles, and can provide rated reactive current for voltages as low as 0.2 pu. The utilization of PV solar farm as STATCOM, termed PV-STATCOM, was demonstrated for increasing the connectivity of neighbouring wind farms [18], [19] and enhancing the power transmission capacity during night and day [18]–[20]. The controller design of a Voltage Source Converter based Distribution STATCOM (D-STATCOM) on an RTDS and its subsequent laboratory implementation with DSP/FPGA platform is presented in [18], [21].

A patent-pending technology for modulating real and reactive power of PV inverters was proposed in [22]. According to this concept, during a critical system disturbance the real power generation function of PV solar farm is autonomously discontinued for a brief period, and the entire inverter capacity is released to provide dynamically modulated reactive power for grid support. The exchange of modulated reactive power can continue for as long as needed by the grid. The PV solar farm returns to its normal operation after the grid support need is fulfilled. The novel features of this smart inverter technology, which distinguish it from the currently available smart inverter functions described above, are: i) PV inverter need not be oversized, ii) rated reactive current is provided even at a highly reduced voltage for as long a period as required by the grid, and iii) the exchange of dynamic reactive power exchange is very rapid (1-2 cycles).

This paper presents: a) the proposed PV-STATCOM control concepts, b) EMTDC/PSCAD simulation studies and c) Laboratory implementation of this technology on a 10 kW PV solar inverter, for voltage control with full inverter capacity during night and day.

The remainder of this paper is organized as follows. Section II illustrates the concept of proposed smart PV inverter control as STATCOM (PV-STATCOM). The study system is described in Section III. Section IV explains the controller design

The financial support from Ontario Centres of Excellence (OCE), Bluewater Power, Sarnia, and Hydro One under the grants WE-SP109-E50712-08 and CR-SG30-11182-11; NSERC; and Western University WSS-NSERC Accelerator program are gratefully acknowledged. Rajiv K. Varma and Ehsan. M. Siavashi are with the ECE Department, The University of Western Ontario, London, Ontario, N6A 5B9, Canada (e-mail: rkvarma@uwo.ca; emohamm4@uwo.ca).

process for the study system. The proposed control is validated through PSCAD/EMTDC software simulations in Section V. The laboratory implementation results are presented in Section VI. Section VII concludes the paper.

II. Concept of Smart PV Inverter Control As STATCOM

Fig. 1 depicts the active power generation and reactive power exchange capability of the proposed smart inverter operation as PV-STATCOM. The different operating modes for the PV-STATCOM (shown in Fig. 1) are defined as below:

(i) *Partial STATCOM mode:* This mode is applicable during day when the smart inverter exchanges reactive power with the grid using the inverter capacity remaining after real power injection. Real power generation is given priority in this mode.

(ii) *Full STATCOM mode:* The Full STATCOM mode is utilized during disturbances, such as faults, when there is a critical need for reactive power support. In this mode, the smart PV solar system autonomously discontinues the real power generation function and releases the entire inverter capacity for STATCOM operation for as long a duration as needed by the grid. The real power generation is discontinued by either disconnecting the solar panels or increasing the voltage across solar panels beyond their open circuit voltage. Reactive power exchange is given priority in this mode. Once the need for grid support is fulfilled, the PV solar system returns to normal real power generation mode. This mode is utilized during daytime on need basis, while it is fully available during night as there is no sun. The smart PV inverter autonomously determines its mode of operation and prioritizes between active power generation and reactive power exchange based on the system requirements, nature of transient/disturbance, time of the day and remaining inverter capacity.

(iii) *Full PV Mode:* In this daytime mode, the solar system generates only real power without any reactive power support.

III. Study System

The single line diagram of the study system is depicted in Fig. 2. The study system comprises a 10 kW PV solar system operating as PV-STATCOM connected through a -Y isolation transformer to a 208 V_{L-L} distribution system equivalent model having impedance parameters (R_g, L_g). The total 10 kVA constant-impedance RLC load for a nominal voltage of 208 V is connected at the PCC. The PV system utilizes a 10 kVA two-level six-pule IGBT-based VSC operating with a switching frequency of 10 kHz. An LCL filter is used to mitigate the harmonics generated by the inverter. In Fig. 2, R_f represents the sum of IGBT ON-state resistance and internal resistance of filter inductor, while L_f models the filter inductance. Generally, to limit the VSC current ripple, the reactance of the filter inductor is selected between 0.1 to 0.25 pu [23]–[25]. C_f represents the filter capacitor in Delta configuration with a damping resistor R_d. C_f is chosen to limit the reactive power exchange below 0.05 pu of the inverter rating [25].

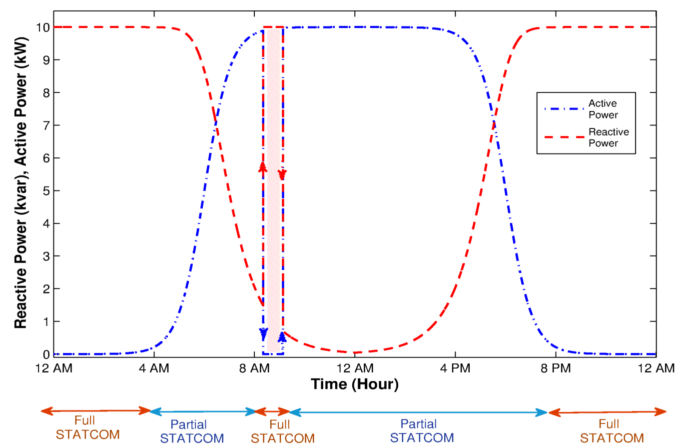

Fig. 1. Concept of smart PV inverter control as STATCOM

IV. Controller Design

Fig. 2 illustrates the control system of the proposed smart PV inverter control.

A. Phase Lock Loop

The q-component of PCC voltage in dq-frame is given as:

$$V_{pcc-q} = \hat{V}\,\sin\left(\omega_0 t + \theta_0 - \varphi\right) \tag{1}$$

where $\hat{V}$ is the amplitude of PCC phase voltage, ω_0 is the system frequency and θ_0 is initial phase angle of the AC system. For decoupling active and reactive power controls, V_{pcc-q} is regulated to zero. The open loop transfer function of PLL with PI controller is:

$$H_{PLL}(s) = \frac{\hat{V} \times k_{PLL,gain}}{T_f}\left(\frac{s + z_{PLL}}{s + T_f^{-1}}\right)\frac{1}{s^2} \tag{2}$$

Where $k_{PLL,gain}$ and z_{PLL} are PLL controller parameters. The Symmetrical Optimum technique [26] is used to design the PI controller with phase margin $\delta_m = 60°$ at cross over frequency $\omega_c = 268\ rad/s$.

B. Currents Control

The inverter currents in dq-frame are [18], [23]:

$$L_f\frac{di_{id}}{dt} = L_f\omega(t)\,i_{iq} - R_f i_{id} + V_{id} - V_{pcc-d} \tag{3}$$

$$L_f\frac{di_{iq}}{dt} = -L_f\omega(t)\,i_{id} - R_f i_{iq} + V_{iq} - V_{pcc-q} \tag{4}$$

where $V_{pcc,dq}$ is PCC voltages, $i_{i,dq}$ is inverter current, $V_{i,dq}$ is the voltage at AC side of the inverter in dq-frame, respectively. A PI controller is used for each current component [23]. The active and reactive power outputs of the inverter in dq-frame are:

$$P_i(t) = \frac{3}{2}\left(v_i\,(t)\,i_{id}(t) + v_i\,(t)i_{iq}(t)\right) \tag{5}$$

$$Q_i(t) = \frac{3}{2}\left(-v_{id}\,(t)\,i_{iq}(t) + v_{iq}\,(t)\,i_{id}(t)\right) \tag{6}$$

Due to PLL operation $v_{id} = \hat{V}$ and $v_{iq} = 0$. Consequently, the active power output of the inverter can be controlled by

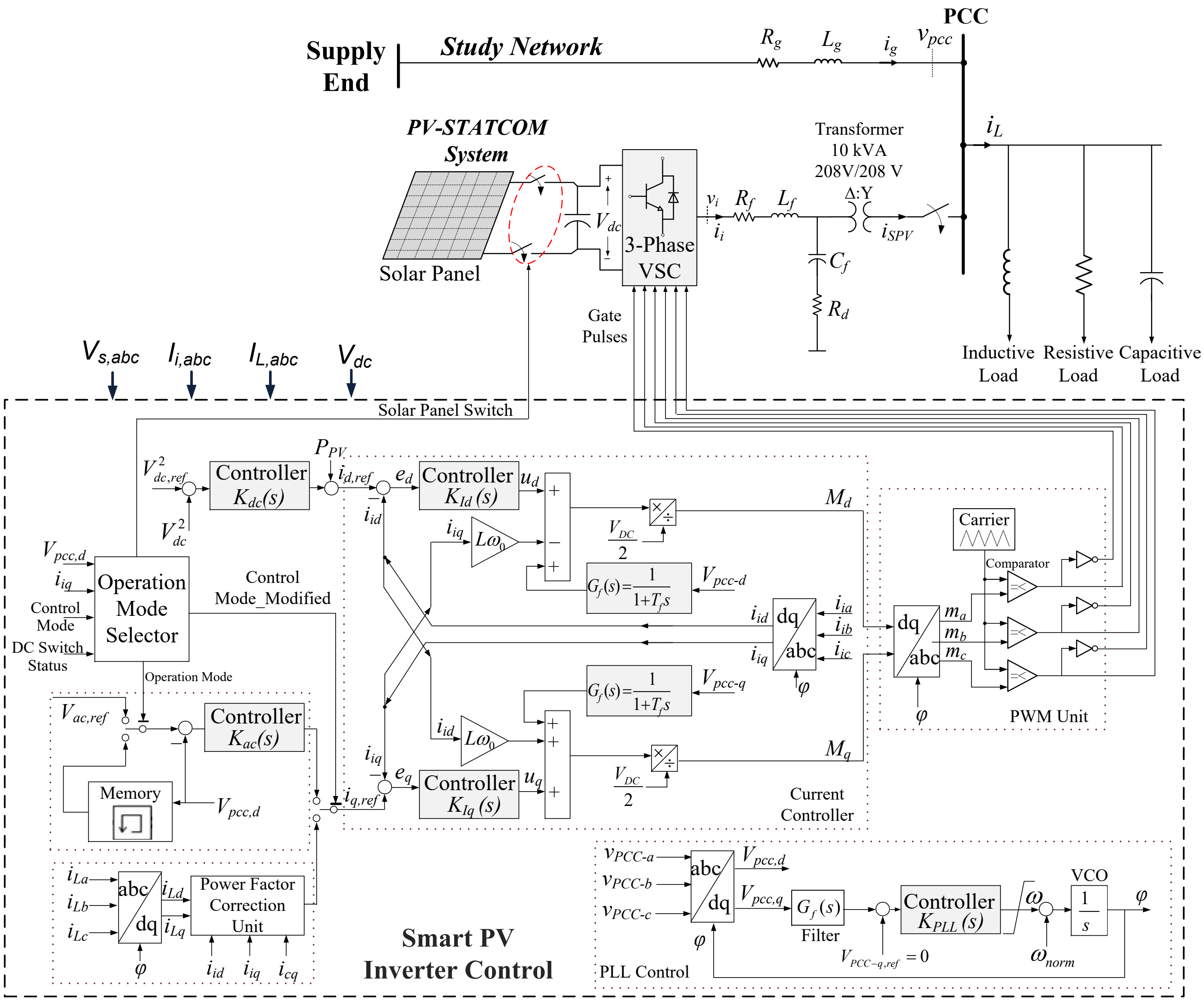

Fig. 2. Modeling of the study system and control components

i_{id} whereas reactive power output is controlled by i_{iq}. The reference values of the current controllers are received from outer loops based on the control objectives and operation mode.

C. DC Link Voltage Control

The DC link capacitor provides real power to compensate the power loss of the inverter IGBT switches. Consequently, the DC link capacitor voltage gets reduced gradually. The inverter needs to absorb small amount of active power to keep the DC link capacitor charged. When sun is available, the smart inverter control utilizes a small amount of dc power from the solar panels to keep the capacitor charged, while the rest of the solar power is injected into the grid. During night the inverter control absorbs a small amount of real power from the grid and charges the capacitor through inverter diodes. The open loop transfer function of DC link voltage control with PI controller is [23], [24]:

$$H_{dc}(s) = -\frac{3 \times V_{pcc-d} \times k_{dc,gain}}{2 \times \sigma_{i,d}} \left(\frac{s + z_{dc}}{s + \sigma_{i,d}^{-1}} \right) \frac{1}{s^2} \tag{7}$$

Where $k_{dc,gain}$ and z_{dc} are the parameters of DC link voltage controller. Symmetrical Optimum technique [26] is used to design this controller with phase margin 50° at frequency $\omega_c = 364\ rad/s$.

D. AC Voltage Control

Considering steady state behavior of PLL and assuming ($\varphi = \omega_0 t + \theta_0$) and $\omega = \omega_0$ and neglecting the small current of the shunt filter capacitor, the PCC voltage is expressed as:

$$V_{pcc-d} = -L_g \omega_0 \, i_{iq} + L_g \omega_0 i_{Lq} - L_g \frac{di_{id}}{dt} + L_g \frac{di_{Ld}}{dt} + \hat{V} \tag{8}$$

where,$i_{L,dq}$ are load current components in *d-q* frame. The voltage control loop generates the reference for the reactive component of the inverter current control. The open loop transfer function of the AC voltage control is:

$$H_{ac}(s) = \frac{k_{gain,ac}}{s} \times G_{iq}(s) \times (-L_g\omega_0) = \frac{-L_g\omega_0 k_{gain,ac}}{s(1+\sigma_{i,q}s)} \quad (9)$$

It is noted that the AC voltage control loop includes the inner loop which is the current control loop. Therefore, the outer control loop needs to be slower than inner loop. Also, the dynamics of *d*-axis as feed-forward term can be neglected when the current control loop is faster than AC voltage control loop.

E. Operation Mode Selector

Fig. 3 depicts the flowchart of the smart PV inverter control during nighttime and daytime, which is explained below. Index M denotes the specific operating mode.

(i) Full PV Mode: $M = 0$
(ii) Partial STATCOM Mode: $M = 1$
(iii) Full STATCOM mode: $M = 2$

Both during night and day, the PCC voltage control (VC) smart inverter function has the higher priority. Power Factor Correction (PFC) function is performed only if the PCC voltage is within the utility acceptable range.

Daytime Operation: During daytime, Q_{rem} - the inverter capacity remaining after real power generation based on available solar insolation is computed at every time step. If at any time due to any system disturbance (e.g. fault), the bus voltage violates the utility specified limit, the operating mode is switched to Full STATCOM mode ($M = 2$). Voltage control is then performed utilizing reactive power exchange up to the full inverter capacity S_{inv} ($Q_{lim} = Q_{rem}$). If during such voltage control, the amount of needed reactive power becomes less than Q_{rem}, the operating mode is switched to Partial STATCOM mode ($M = 1$) with ($Q_{lim} = Q_{rem}$). This implies that the available real power from solar insolation can still be made available to the grid while voltage regulation is being performed. If the voltage is successfully regulated to within the utility specified range, and if PFC is needed, it is performed in Partial STATCOM mode ($M = 1$) with reactive power up to the remaining inverter capacity ($Q_{lim} = Q_{rem}$). If PFC is not needed, the solar system reverts to Full PV mode of operation ($M = 0$).

Nighttime Operation: If any system disturbance causes the PCC voltage to violate the utility specified range, the operating mode is switched to Full-STATCOM mode ($M = 2$). Voltage control is then performed with reactive power exchange up to the entire inverter capacity ($Q_{lim} = S_{inv}$). If the voltage is successfully controlled to within the utility specified range, power factor control if needed, may be performed utilizing the entire inverter capacity for reactive power exchange ($Q_{lim} = S_{inv}$).

V. PSCAD/EMTDC Simulation Studies

This section presents the EMTDC/PSCAD software based simulation studies of the PV system with the proposed smart inverter controls in a distribution system as depicted in Fig. 2.

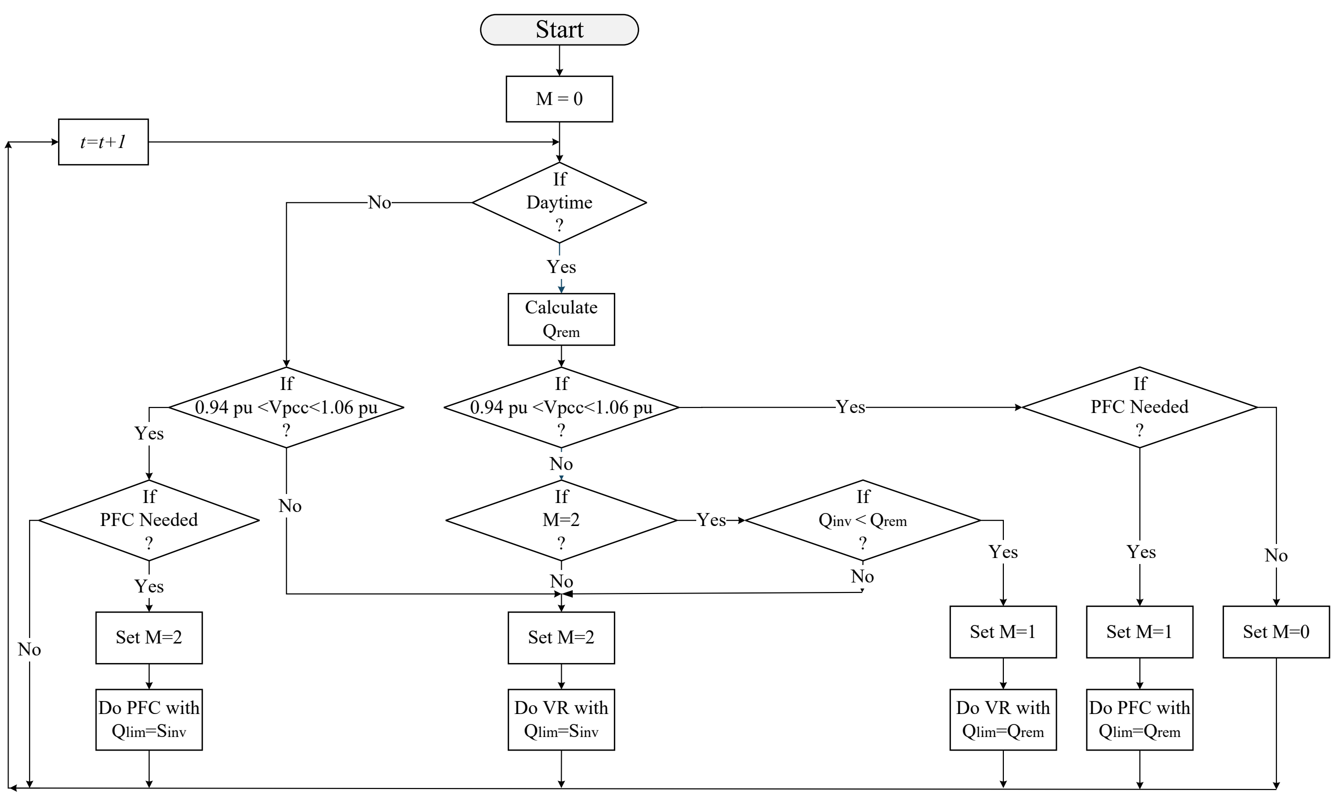

Fig. 3. Flowchart of the smart PV inverter operating modes

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System studies for the following smart PV inverter operation modes are described for different system operating conditions:

(i) Full STATCOM mode for voltage control during both forward and reverse power flow conditions during day
(ii) Full STATCOM mode for voltage control during night

In all the simulation results, the PCC voltage is denoted by v_{pcc}. Grid current and load current are represented by i_{grid} and i_{load}, respectively. The PV system currents before and after harmonics filter are represented by $i_{inverter}$ and i_{spv}, respectively.

It is noted that a small amount of reactive power is exchanged with the grid by the harmonics filter and partly by the interface transformer of the PV system. The harmonics filter generates reactive power while the interface transformer absorbs reactive power. These reactive power components are included with the smart inverter reactive power in the variable Q_{spv}. Hence, the reactive power of the grid Q_{grid} together with the reactive power of the smart PV system Q_{spv} balance the reactive power of the load Q_{load} at all times.

A. Full STATCOM Mode - Daytime

Fig. 4 (a)-(h) demonstrate the per-unit value of the PCC voltage ($v_{pcc,pu}$), the PCC voltage (v_{pcc}), grid current (i_{grid}), smart PV system current (i_{spv}), inverter current ($i_{inverter}$), load current (i_{load}), active power and reactive power, respectively.

t < 1 sec: The smart PV system is not connected, and hence the real and reactive power of load and grid are respectively, equal.

t=1 sec: Full PV Mode enabled: The PV system is connected to the grid when it generates 6 kW active power. Initially, 2 kW active and 2 kvar reactive loads are connected to the grid. Active power injection (P_{spv}) by the PV system increases the PCC voltage ($v_{pcc,pu}$) to 0.97 pu. The PV system supplies active power of the load (P_{load}) and the surplus power flows into the grid in reverse direction. Therefore, the active power of the grid (P_{grid}) becomes negative. The reactive power output of the inverter is kept zero by the controller in this Full PV mode. However, some reactive power is generated by the filter capacitor. In this mode, the 2 kvar reactive load (Q_{load}) is supplied by the grid (Q_{grid}) and the small amount of reactive power generated by the harmonics filter of the PV-STATCOM (Q_{spv}). *t=1.04 sec: Full STATCOM Mode enabled:* A large reactive load of 2 kW and 6 kvar is connected to the grid. This large load reduces the voltage to 0.91 pu, which is below the acceptable voltage range of the utility. The total load becomes 4 kW active and 8 kvar reactive. The proposed smart inverter controller virtually disconnects the solar panel in this situation and controls the PCC voltage to its pre-fault value with reactive power generation in Full STATCOM mode. The PCC voltage is successfully regulated to its pre-fault value of 0.97 pu within one cycle. Since solar panels are disconnected by the controller, the active power of PV-STATCOM becomes zero, and the entire active load is supplied by the grid. A large part of load reactive power is supplied by PV-STATCOM when it operates in Full STATCOM operation mode. The reactive power of the smart PV system (Q_{spv}) together with the reactive power of the grid (Q_{grid}) equal the reactive power of the load (Q_{load}).

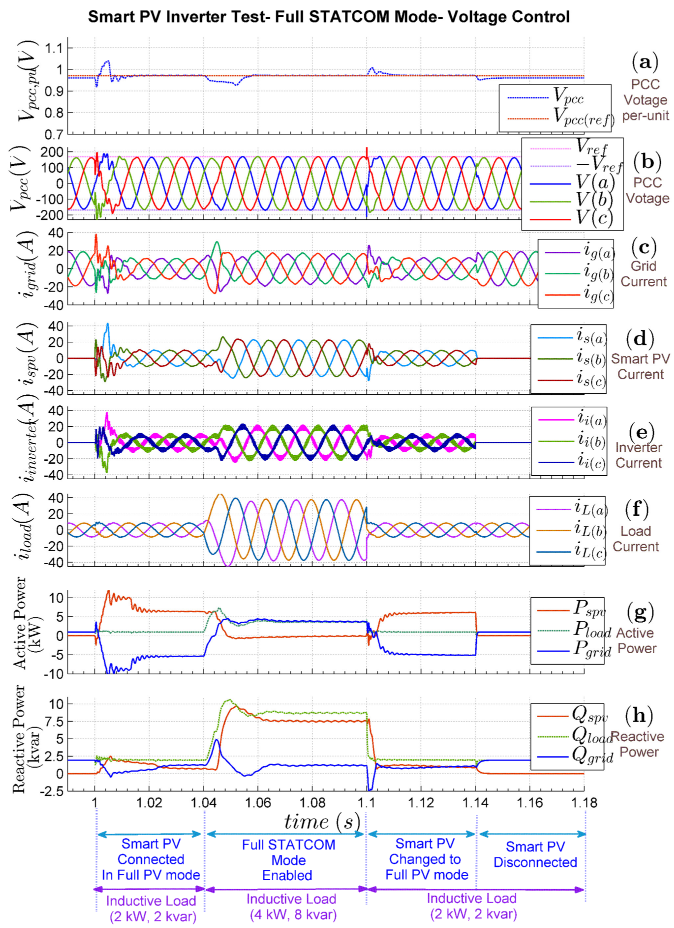


Fig. 4. Simulation results for full STATCOM mode with voltage control during daytime a) PCC voltage in per-unit b) PCC voltage c) Grid current d) Smart PV current e) Inverter current f) Load current g) Active power h) Reactive power

t=1.10 sec: Full PV Mode enabled: The large load is removed and the controller returns to Full PV operation mode. In other words, the controller connects the solar panel to the inverter and generates only active power. The voltage control mode is deactivated as the PCC voltage is within acceptable range. Since the active power generation of the PV-STATCOM system is more than the active power consumption of the load, the surplus power flows in the reverse direction in the grid. The reactive power of the inverter is zero during Full PV mode of operation, although some reactive power is generated by the filter capacitor. The reactive power of the grid (Q_{grid}) together with the reactive power of the smart PV system (primarily by the filter capacitor) Q_{spv} balance the reactive power of the load (Q_{load}).

t=1.14 sec: PV system disconnected: The disconnection of PV-STATCOM causes the PCC voltage to drop slightly. The PV-STATCOM current and inverter current fall to zero. The grid current increases to supply active and reactive loads. Hence, the real power and reactive power of the load become equal to the real power and reactive power supplied by the grid, respectively.

B. Full STATCOM Mode-Nighttime

During the nighttime, the inverter is used fully as STATCOM. The control objective is selected as PCC voltage control. The load power is kept 3 kW for this test. Fig. 5 (a)-(f) demonstrate the per-unit value of the PCC voltage (Vpcc,pu), the PCC voltage ($v_{pcc,pu}$), the PCC voltage (v_{pcc}), grid current (i_{grid}), smart PV system current (i_s), active power of load (P_{load}), grid (P_{grid}), PV system real power output ($P_{statcom}$) and reactive power of load (Q_{load}), grid (Q_{grid}), PV system reactive power output ($Q_{statcom}$), respectively.

t=1 sec: Full STATCOM Mode enabled: The PV system is connected to the PCC in Full STATCOM. The initial reference voltage is kept at 1.06 pu. The smart inverter control follows the reference value and increases the PCC voltage from 1 pu to 1.06 pu within less than a cycle. Due to additional STATCOM current, the grid current is increased. The STATCOM absorbs some active power to keep the DC link capacitor charged. At the instant of connection of the PV-STATCOM system to the grid, the inrush current for charging capacitor creates a transient in inverter active power.

t=1.04 sec: Operation mode changed from capacitive to inductive: The reference value of the voltage controller is changed from 1.06 pu to 0.94 pu. The proposed smart inverter control reduces the bus voltage and regulates it to 0.94 pu in less than one cycle. The STATCOM changes its operation mode from capacitive to inductive, with the phase of STATCOM current changing from 90° leading to 90° lag to reduce PCC voltage.

t=1.08 sec: Operation mode changed from inductive to capacitive: The voltage reference is changed in reverse from 0.94 pu to 1.06 pu. The STATCOM control changes the PCC voltage (v_{pcc}) to 1.06 pu within one cycle. This test verifies the rapid performance of the control system.

t=1.12 sec: STATCOM system disconnected: The STATCOM current (i_s) goes to zero instantaneously. Since the previous operation mode of the STATCOM was capacitive, the disconnection of the STATCOM reduces the PCC voltage (v_{pcc}) correspondingly.

C. Low Voltage Ride Through (LVRT) Test - Daytime

The Low Voltage Ride Through performance of the proposed smart inverter PV-STATCOM is now investigated. At first, the performance of proposed smart inverter in conventional Full PV operation mode is demonstrated. This test is performed when the solar system is generating about 8 kW real power. A large disturbance is created by switching on a large load at the PCC for 1.5 second duration causing the PCC voltage to drop to 0.85 pu.

Fig. 6 illustrates the performance of the smart PV inverter in Full PV operation mode during LVRT period. Fig. 6 (a)-(d) portray the per-unit value of the PCC voltage ($v_{pcc,pu}$), the instantaneous PCC voltage (v_{pcc}), PV system real power output (P_{pvs}), PV system reactive power output (Q_{pvs}) and the status of the large load connection, respectively.

As per the presently being revised Draft IEEE P1547 Standard (under the process of balloting, hence unpublished), for such a voltage dip to 0.85 pu, the PV system should provide

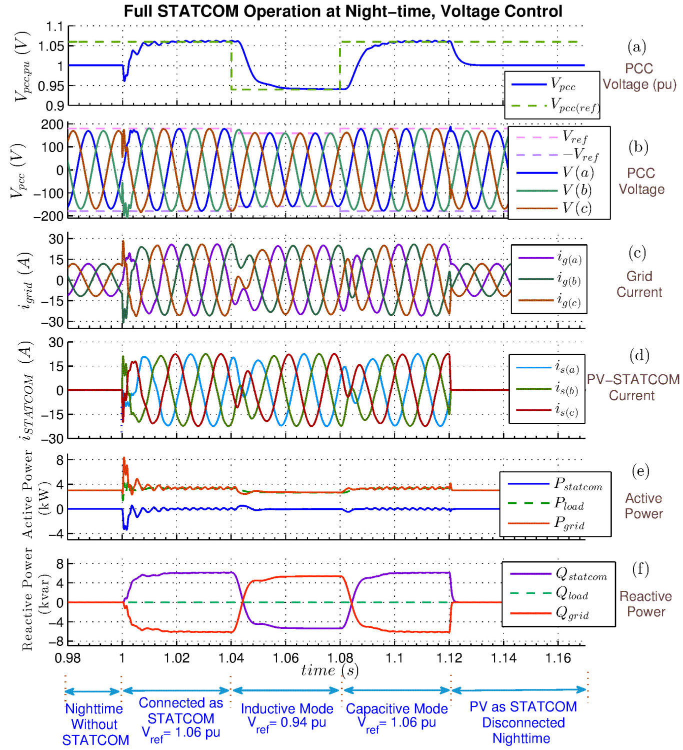


Fig. 5. Simulation results for full STATCOM operation with voltage control during nighttime a) PCC voltage in per-unit b) PCC voltage c) Grid current d) PV current e) Active power f) Reactive power

mandatory operation capability for 1.2 sec. Beyond this time duration, the PV system may ride through or may trip. It is evident from Fig. 6 that the proposed smart PV inverter under Full PV mode, stays connected and continues to generate real power of almost 8 kW for 1.5 sec. The proposed smart inverter therefore successfully meets the expected LVRT criterion.

It is noted that the Draft IEEE P1547 Standard makes reactive power compensation optional during the LVRT period.

The LVRT performance of the proposed smart inverter PV-STATCOM in providing dynamic reactive power compensation as STATCOM is now demonstrated. Fig. 7 displays the LVRT performance of the PV-STATCOM controller during daytime as simulated using EMTDC/PSCAD software.

The conditions for this LVRT test are the same as in the previous test, i.e. the real power output of PV system is about 8 kW and duration of large load connection is 1.5 seconds.

Fig. 7 (a)-(e) demonstrate the per-unit value of the PCC voltage ($v_{ac,pu}$), the instantaneous PCC voltage (v_{pvs}), smart PV system current (i_{pvs}), PV system real power (P_{pvs}), PV system reactive power (Q_{pvs}), and the status of the large load switch, respectively. The overall performance is described below:

t=1 sec: Full PV Mode enabled: The PV system is connected to the PCC in Full PV mode. The smart PV system generates 8 kW and a small amount of reactive output (0.5 kvar) due to the filter capacitor. The initial PCC voltage increases from 0.97 pu to 0.99 pu because of real power generation by the PV system.

t=1.10 sec: Partial STATCOM Mode enabled: The control

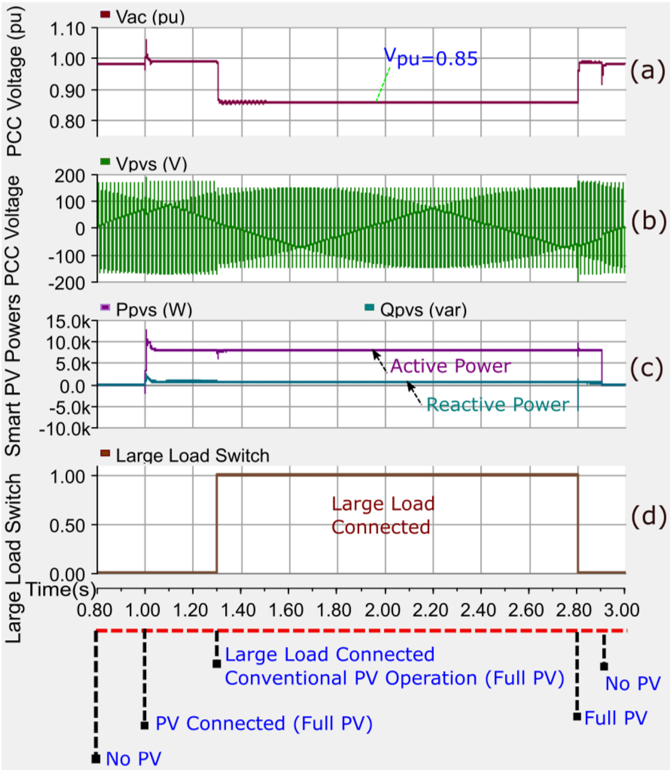


Fig. 6. Simulation results for LVRT test with conventional PV system during daytime a) PCC voltage in per-unit b) PCC voltage c) PV Active and reactive powers d) Large load switch status

objective is set to voltage control with a reference voltage of 1 pu. The controller uses the remaining capacity of the inverter to regulate the PCC voltage ($v_{ac,pu}$) to the reference value 1 pu in about one cycle. While the active power output (P_{pvs}) continues to be 8 kW the reactive power (Q_{pvs}) changes to 2 kvar.

t=1.30 sec: Full STATCOM Mode enabled: The large load is suddenly connected at the PCC voltage for 1.5 seconds. Since this causes the PCC voltage to dip to 0.85 pu, per the flow chart of Fig. 3, the Full STATCOM mode is enabled. The controller changes the reference value of DC link voltage to open circuit voltage of solar panel. This causes the controller to virtually disconnect the solar panel from the inverter and ideally reduce the active power output to zero.

In this test, however, the DC link reference voltage is chosen to be slightly lower (430 V) than the open circuit voltage (440 V) to ensure controller stability. Consequently, the active power reduces from 8 kW to 0.8 kW.

The available capacity of the inverter (which is almost equal to the full inverter capacity) is then used for reactive power generation to control the PCC voltage. The PCC voltage ($v_{ac,pu}$) is successfully regulated to 0.98 pu with the smart PV system generating about 10 kvar reactive power.

t=2.80 sec: Full PV Mode enabled: The large load is disconnected and the system returns to healthy state. The controller virtually reconnects the solar panel to the inverter (by changing the DC link reference voltage to the MPP voltage) and the smart PV inverter starts generating 8 kW active power. Although, the inverter reactive power is zero the

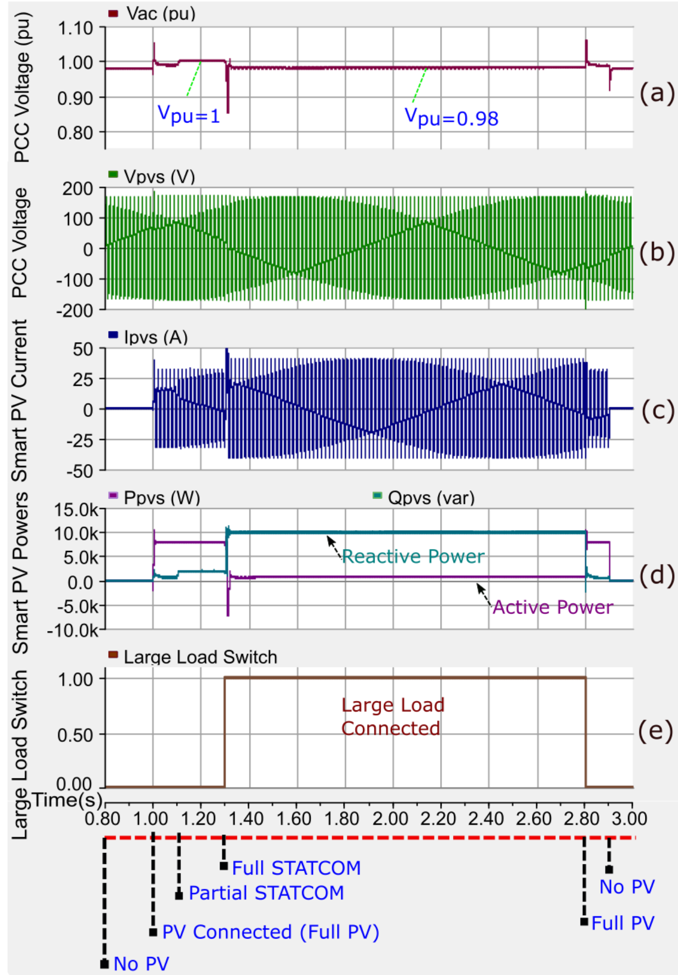


Fig. 7. Simulation results for LVRT test with conventional PV system during daytime a) PCC voltage in per-unit b) PCC voltage c) PV Active and reactive powers d) Large load switch status

PV system reactive power has a very small value due to the reactive power generated by the filter capacitor.

t=2.90 sec: PV System Disconnected: The smart PV current (i_{pvs}) goes to zero instantaneously. The disconnection of the PV system reduces the PCC voltage ($v_{ac,pu}$) correspondingly. This test clearly demonstrates that the proposed smart inverter PV-STATCOM not only meets the LVRT requirement of the Draft IEEE P1547 Standard, but surpasses it by providing dynamic reactive power compensation as STATCOM and successfully regulating the PCC voltage to within the utility acceptable range.

VI. Laboratory Study

This section presents the laboratory implementation and validation of the smart PV inverter performance for Full STATCOM operation mode of smart PV inverter.

A. Laboratory Setup

Fig. 8 depicts the single-line diagram of the lab setup for the study system. The study system is chosen to be the equivalent model of the utility network of Bluewater Power

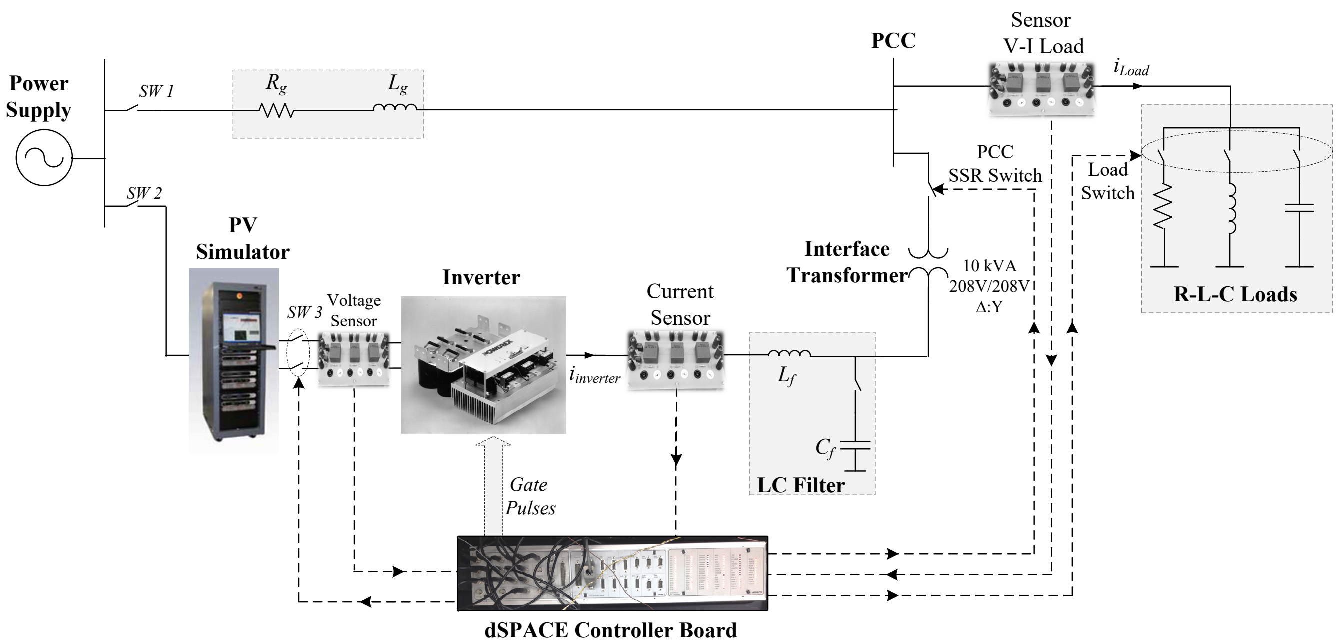


Fig. 8. Lab setup of the study system with the smart inverter PV-STATCOM

Distribution Corporation, Sarnia, Ontario, Canada, where a pilot demonstration of the proposed PV-STATCOM has been actually performed in December 2016.

The combined short circuit impedance of the network and line impedance is represented by (R_g) and (L_g). A 10 kVA interface transformer is used for interconnecting the PV system to PCC. The transformer configuration is Delta/Wye whereas the Delta winding connection is located on the inverter side. A two-level three phase IGBT power module supplied by Powerex with 10 kHz switching frequency is chosen as the PV system inverter. An LCL filter is installed after the inverter to remove the switching frequency ripples. The filter inductor is in series with the inverter and the filter capacitor is in shunt with Delta connected transformer winding. A 10 kVA Ametek PV Simulator (TerraSAS) is employed to simulate the behavior of the PV solar panels. The PV Simulator can generate variable real power based on the pre-settable temperature and irradiance profiles. The maximum irradiance is chosen to be 1000 W/m^2. The open-source voltage and short circuit current of the solar panels are selected as 440 V and 17 A, respectively. Three types of loads - resistive, inductive and capacitive, having a total 10 kVA rating (in any combination of R, R-L, C, R-C, etc.) are used. The dead-band time is chosen 400 ns for the PWM signals to avoid inverter bridge shoot through. The voltage and current sensors are designed to measure PCC voltage, inverter current, load current and DC link voltage. The sensor signals are delivered to dSPACE controller board through ADC channels. The smart PV inverter controller is implemented on dSPACE controller board (DS1103), which generates appropriate firing pulses for the IGBT gates of the inverter based on the selected control objectives and operation modes.

Fig. 9 shows the actual lab setup of the study system with the proposed PV-STATCOM control. The controller is

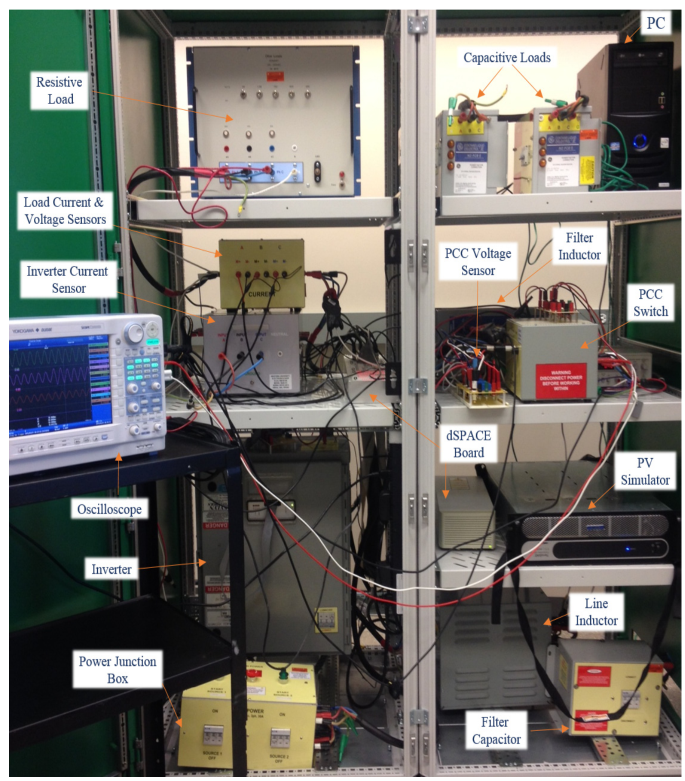


Fig. 9. Actual Lab setup of the study system with PV-STATCOM

designed in MATLAB/Simulink software and implemented on dSPACE controller board. The outputs of current and voltage sensors are assigned to specific ADC. Also, the PWM pulses out of the dSPACE board are applied to the inverter interface panel through the level shifter circuit. A graphics user interface (GUI) is designed in ControlDesk software to provide an environment to supervise the PV system operation.

B. Lab Implementation: Full STATCOM Mode of Operation

First, the impact of the large load switching during the conventional Full PV mode is demonstrated. A 1.5 kW resistive load is already connected to the PCC while the PV system generates 6 kW active power.

The Yokogawa oscilloscope (DL850E) with time scale 20 ms/div is used to capture the waveforms. Fig. 10(a) depicts the PCC voltage (Phase A), PV system current (Phase A), load current (Phase A) and the status of the large load switch, when a large load of 6.5 kW, 3 kvar is connected to the PCC. The PCC voltage drops from 1.02 pu to 0.96 pu (122 V_{rms} to 115 V_{rms}) as soon as the large load is connected. After about six cycles, the loading is returned to initial value by disconnecting the load switch. The voltage returns to its initial value of 1.02 pu (122 V_{rms}). The performance of the smart inverter in Full STATCOM mode is then investigated.

In this mode, as soon as it is sensed that the PCC voltage has dropped to an unacceptable limit, the controller shuts down the real power production temporarily and transforms to a Full STATCOM. In this mode, the entire capacity of the inverter is utilized to regulate the voltage to an acceptable value. Fig. 10(b) illustrates the PCC (Phase A), PV reactive power, Load Current (Phase A), and large load switch status for voltage control during the large load connection in the Full STATCOM mode. The large load with total 6.5 kW and 3 kvar power is now connected to the PCC. The PV-STATCOM controller injects a substantial amount of reactive power and successfully regulates the PCC voltage to its prefault level of about 1.02 pu (122V_{rms}) within almost one cycle. This rapid response matches that of an actual STATCOM [17]. This test validates the controller performance in Full STATCOM mode for voltage control.

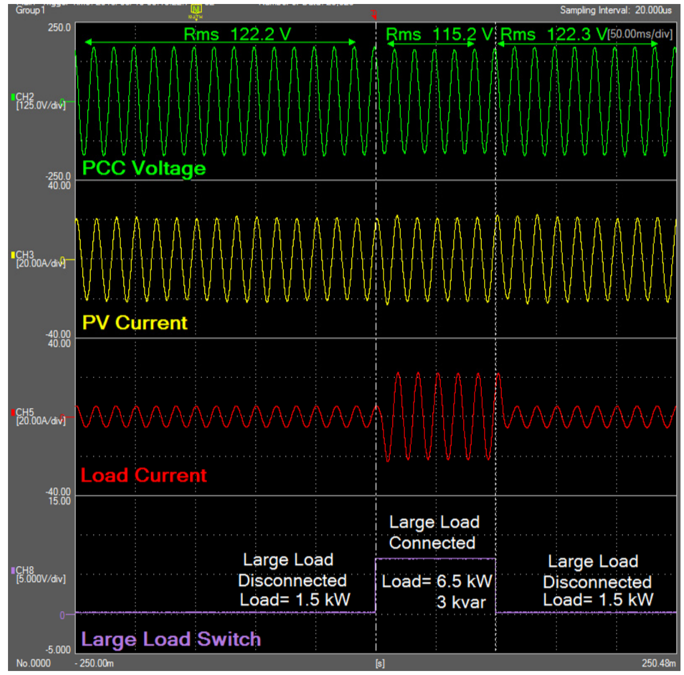
The PSCAD simulation results and Lab validation for daytime voltage control in Partial PV-STATCOM mode are not shown due to lack of space.

C. Lab Implementation - Low Voltage Ride Through (LVRT)

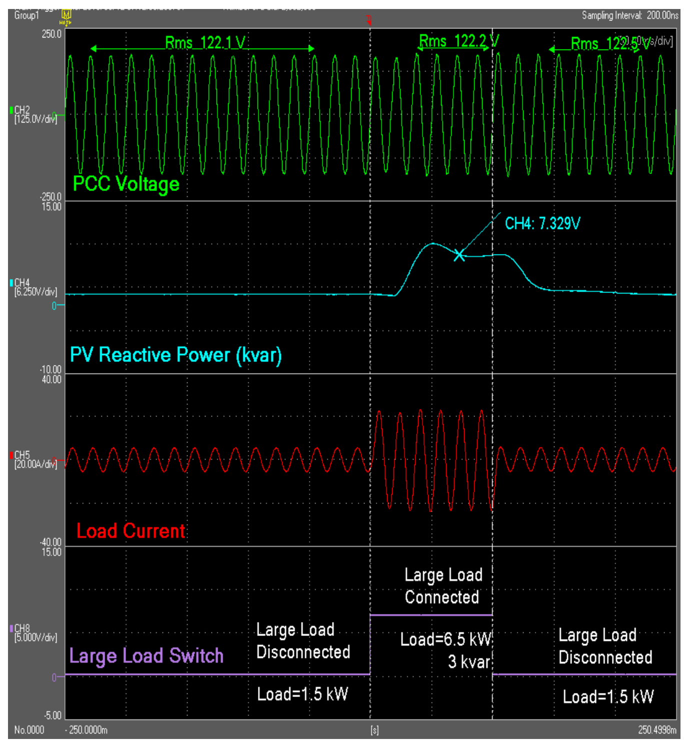
In this test, the Low Voltage Ride Through capability of the proposed smart inverter PV-STATCOM is demonstrated under a severe voltage dip condition.

Fig. 11(a) depicts the Phase A PCC voltage in pu, instantaneous PCC voltage, Phase A load current and the status of the large load switch during LVRT test. The term *RMath* indicates the number of the Yokogawa oscilloscope Channel for that variable. In the pre-disturbance period, the PV system is generating 4 kW real power while a 1.5 kW resistive load is connected to the PCC. Since the load is smaller than the real power output of the PV system, reverse power flow results causing the steady state PCC voltage to rise to 1.07 pu. A severe disturbance is then created by suddenly connecting a large load (3 kW, 9 kvar) to the grid for 1.2 seconds. This causes the load current to increase and the PCC voltage to drop to 0.62 pu. According to the Draft IEEE P1547 Standard, this period is more than the Permissive Operation Capability of the inverter and therefore the inverter may ride through or may trip. The proposed smart inverter successfully rides through and stays connected for this entire period in the conventional Full PV Mode. As mentioned earlier, according to the Draft IEEE P1547 Standard, reactive power compensation in this period is optional.

The performance of the proposed smart inverter PV-

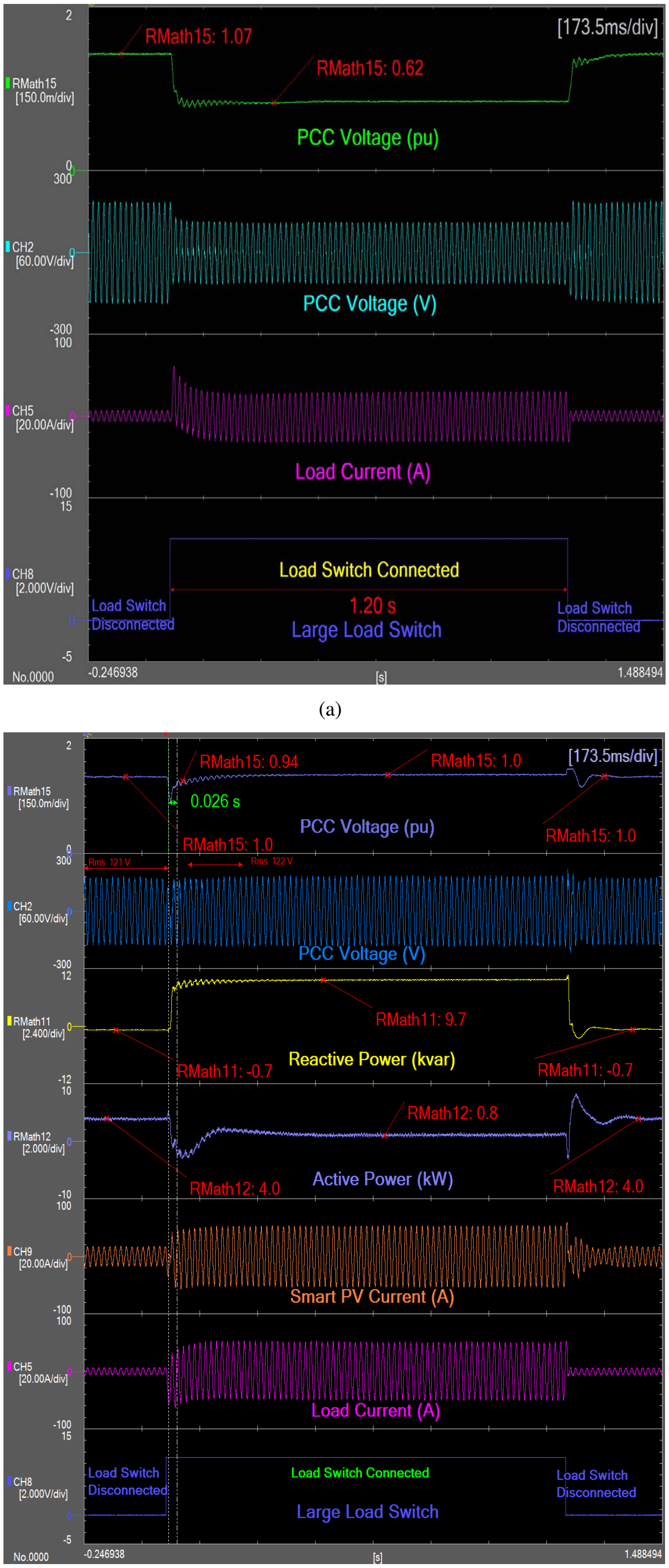


(a)



(b)

Fig. 10. Lab results of a) conventional Full PV mode of operation during sudden connection of a large load b) smart PV inverter operation in Full STATCOM mode for voltage control during sudden large load connection



(a)

(b)

Fig. 11. Lab results of a) conventional Full PV mode of operation during LVRT test b) smart PV inverter operation in Full STATCOM mode for voltage control during LVRT test

STATCOM under this stringent LVRT test is now demonstrated. Fig. 11 (b) illustrates the Phase A PCC voltage (per-unit), instantaneous PCC voltage, reactive power and active power outputs of the smart PV system, current of smart PV system, Phase A load current, and the status of the large load switch during LVRT test. As described in the previous test, the initial power generation of 4 kW by the smart PV system causes the voltage to rise to 1.07 pu. The PV-STATCOM regulates this initial voltage from 1.07 pu to 1 pu in Partial STATCOM mode. A severe disturbance condition is simulated by connecting the same large load to the grid for 1.2 seconds.

The smart PV system controls the DC link voltage to slightly less than the open circuit voltage value (for ensuring controller stability) and uses almost the entire inverter capacity of the inverter for dynamic reactive power support in Full STATCOM mode. The PV-STATCOM regulates the voltage from 0.62 pu to 0.94 pu in less than two cycles (as expected of a STATCOM [17]). The reactive power and active power during LVRT period are 9.7 kvar and 0.8 kW, respectively. After 1.2 seconds, the large load is disconnected and the system become healthy. The control system changes the operation mode from Full STATCOM to Partial STATCOM for subsequent voltage control if needed.

This test clearly demonstrates the successful LVRT operation of the proposed smart inverter PV-STATCOM. The PV-STATCOM not only meets the LVRT criterion of the Draft IEEE P1547 Standard but also exceeds it. It provides rapid voltage regulation during the LVRT period as well.

The Anti-islanding performance of the proposed PV-STATCOM is outside the scope of this paper. However, it is worth mentioning that the PV-STATCOM is provided with a unique control [27], however not shown in this paper. If there is a grid fault which may possibly cause the PV solar system to inject a short circuit current into the grid in excess of the rated inverter current, the fast predictive control detects this condition in almost 1 millisecond. In addition, before the inverter current exceeds the rated value, the controller either:

(i) disconnects the solar farm from the grid, or
(ii) transforms the PV solar system into a STATCOM (PV-STATCOM) to support the grid voltage.

The first feature is helpful in anti-islanding process, while the second feature provides improved LVRT performance.

VII. Conclusion

This paper presents a novel autonomous smart PV inverter control as STATCOM, termed PV-STATCOM, for voltage control. The smart inverters being presently proposed in literature have the limitation of available reactive power for voltage control during high solar power output. They are unable to provide voltage control during large dips in grid voltage due to large disturbances occurring around noon hours. Moreover, their response time under volt/var control [4] is in the range of 1-2 sec. The proposed smart inverter PV-STATCOM overcomes both these limitations. It operates as a STATCOM with full inverter capacity in nighttime as well as during any time of the day to provide critical grid support. During a large system disturbance during daytime, it discontinues its real power generation function for a short period, typically a few seconds, and releases its entire inverter capacity for

STATCOM operation. It returns to normal pre-disturbance power production as soon as the need for grid support is fulfilled. The response of the proposed smart inverter (1-2 cycles) matches that of an actual STATCOM.

The performance of different modes of operation of a 10 kVA PV-STATCOM, during night and day, through both EMTDC/PSCAD software based simulation studies and Laboratory implementation are demonstrated.

The Low Voltage Ride Through (LVRT) performance of the proposed smart inverter PV-STATCOM is investigated through both EMTDC/PSCAD simulation and laboratory implementation studies using dSPACE control. The LVRT tests clearly demonstrate that the proposed smart inverter PV-STATCOM not only meets the LVRT requirement of the Draft IEEE P1547 Standard, but surpasses it by providing dynamic reactive power compensation as STATCOM and successfully regulating the PCC voltage to within the utility acceptable range during the LVRT period.

The LVRT tests further demonstrate that the PV-STATCOM control system continues to remain stable despite transitioning between widely different operating modes. The stability of the PV-STATCOM is ensured by appropriate design of the various PI controllers within the control system to have sufficient gain and phase margins. In addition, during the Full PV-STATCOM mode, the voltage across the solar panels is made slightly less than the open circuit voltage of the solar panels instead of exceeding it.

This paper thus presents a novel concept of utilizing a PV solar farm as a STATCOM on a 24/7 basis, for supporting the grid as needed. Such applications will of course require grid code approvals and appropriate agreements amongst the different stakeholders, i.e., the solar farm owner, inverter manufacturer, the interconnecting utility and system operator.

This PV-STATCOM function also opens up a potential revenue making opportunity for the PV solar farm by providing similar grid support functions at critical times as an actual STATCOM in a given application.

This lab validated PV-STATCOM has been successfully installed and demonstrated in the utility network of Bluewater Power Distribution Corporation, Sarnia, Ontario, Canada, in December 2016. This demonstration was performed for the first time in North America, the results of which will be described in a subsequent paper.

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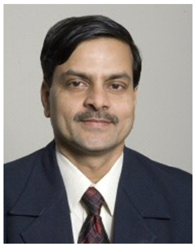

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