FUZZY BASED SMART PV INVERTER PV-STATCOM TO ENHANCEMENT OF SOLAR FARM CONNECTIVITY

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Abstract—This paper describes an advanced smart PV inverter control as STATCOM (PV-STATCOM) that eliminates the need for a physically linked STATCOM in a distribution network for regulating steady state voltage and TOVs caused by unsymmetrical faults. In Ontario, Canada, two 10 MW PV solar systems are now linked to a utility's distribution feeder. A STATCOM is installed to avoid steady-state voltage and TOV problems from a third 10 MW PV solar farm being connected to the same bus. All of the above voltage problems are satisfactorily mitigated as expected by the utility Grid Code if the proposed PV-STATCOM regulation is applied on the incoming third 10 MW PV solar farm, as demonstrated by MATLAB. As a result, the proposed smart inverter PV-STATCOM regulation reduces the need for a physical STATCOM, saving utilities a significant amount of money while grappling with voltage rise and TOV problems of grid-connected PV systems utilizing fuzzy systems. Under equivalent network circumstances, such a control will efficiently increase the Distributed Generator hosting ability of distribution feeders at an expense that is more than an order of magnitude smaller. Furthermore, this novel grid support functionality can provide PV solar farms with new revenue opportunities.

Index Terms— Photovoltaic Solar system, Smart Inverter, PVSTATCOM, Voltage Control, Reactive Power Control, Temporary Over Voltage, FACTS

I.INTRODUCTION

Distributed Generators (DGs) bring several benefits to distribution networks. However, these benefits come along with new challenges [1]-[2]. Some of these challenges include steady state overvoltage, temporary overvoltage (TOV), unbalanced voltage, power quality issues such as harmonics, frequent operation of conventional voltage regulators such as load tap changers and capacitor banks, changes in feeder power factor, etc [1]-[5]. High penetration of solar farms is known to cause reverse power flows resulting in over voltages at PCC which potentially limit any future DG installations [6]-[7]. Traditionally, shunt capacitor banks (SCs), on-load tap changers (OLTC) and step type voltage regulators (SVRs) are utilized for voltage control in the distribution systems [8]. However, these devices are slow acting with a response time ranging from seconds to few minutes. Moreover, these devices such as OLTC and SVR operate based on unidirectional flow of power and cannot operate reliably during bidirectional power flows caused by Distributed Generators e.g.solar farms. Flexible AC Transmission Systems (FACTS) such as Static Var Compensator (SVC) and STATCOM are utilized in general for voltage regulation purposes in power systems [9]. These devices can provide voltage control with a response time of 1-3 cycles with STATCOM being much faster than SVC [9]. The Ontario Independent Electricity System Operator (IESO) proposed the installation of a -33/+48 Mvar Static Var Compensator (SVC) to provide the dynamic reactive power requirement of the 100 MW PV solar farm at the Grand Renewable Energy Park (GREP) in Haldimand County, Nanticoke, Ontario [10]. An SVC is proposed to prevent rise in customer voltage caused by interconnection of PV solar systems in a Japanese distribution feeder [11].

Small size STATCOMs are also proposed in Japan to mitigate voltage rise issues due to surplus power injected by PV solar farms in distribution feeders [8]. Studies for determining optimal size and location of SVC for improving voltage regulation at different operating conditions of residential PV solar systems connected in an Egyptian distribution feeder are described. A D-STATCOM is proposed to improve voltage regulation due to variability of power output from PV solar systems in an Australian distribution network. Four STATCOMs in the range 1-2 Mvar have been actually installed in Massachusetts, USA, at various locations to mitigate feeder voltage rise and voltage fluctuations in a distribution feeder caused by variability of power output from a cluster of 13 MW PV solar systems. A 6 Mvar STATCOM is installed at the substation of 52.5-megawatt (MW) Shams Ma'an PV solar project in Jordan to maintain a smooth voltage profile under different network conditions and variable PV output.

A case study of a 44 kV distribution feeder with two 10 MW PV solar farms is reported. Connection of a third 10 MW solar farm failed the power distance test of the utility indicating that voltage issues will be caused by its interconnection. Reconductoring the feeder to improve X/R ratio or relocation of the PCC of the solar farms to another feeder were considered to be economically unviable solutions. The utility decided to install a STATCOM for regulating the steady state voltage to within utility acceptable limits. It is noted that the conventional symmetrical voltage control provided by SVCs (and STATCOMs) worsen the problem of Temporary Overvoltages in an actual transmission system in California. Hence a new unsymmetrical control is needed, which is considered in this paper. Smart inverters have been proposed for PV solar systems to effectively counteract voltage issues. Smart inverter functions such volt/var, volt/watt, off-unity power factor, Low/High Voltage Ride Through, Low/High Frequency Ride

Through and Dynamic Reactive Current Injection, etc. have been demonstrated in field applications. Grid Codes such as IEEE 1547 have been revised in the interim. The newly proposed smart inverter functions as described in the revised IEEE 1547 (2018) although provide ride through capability but not Temporary Overvoltage mitigation explicitly. A unique control of PV solar farms as STATCOM during nighttime for providing various grid support functions with full inverter capacity and for delivering the same benefits during daytime with PV inverter capacity remaining after real power generation was introduced in 2009. The proposed control, termed PV-STATCOM, was utilized for increasing the connectivity of wind farms and for improving the power transmission capacity. The above control however has a limitation of available reactive power capacity especially during noontime when the inverter is completely utilized for real power generation. The control of PV solar farms as a smart inverter PVSTATCOM was proposed. The control presented in this paper provided only steady state voltage control in the grid by three-phase symmetrical real power generation by PV systems. However, the control strategy proposed and cannot provide mitigation of Temporary Overvoltage (TOV) during unsymmetrical faults which is a major issue in the integration of PV solar farms. For suppressing TOV, an entirely different control is required, which is the main contribution of this paper. This paper is based on a patent-pending technology for modulation of real and reactive power of PV solar farms. Implementation of this control on a PV solar farm allows the solar farm to provide a 24/7 functionality as a STATCOM with rated inverter capacity both during nighttime and any time during the day as needed by the grid, including full-noon. The novelty of this paper is that a new smart inverter PVSTATCOM solution is proposed for mitigating steady state voltage rise and more importantly Temporary Overvoltage caused by high penetration of PV solar systems. Traditionally, to address these issues, dynamic reactive power compensators such as Static Var Compensator (SVC) and STATCOM, have not only been proposed [8] but actually installed in several parts of the world including Canada and USA. In this paper, the effectiveness of the PV-STATCOM technology has been shown on a realistic distribution feeder in Ontario where an actual STATCOM has been installed for steady state voltage control . It is demonstrated that the proposed PV-STATCOM can provide the same functionality of steady state voltage control and moreover provide TOV mitigation, thus eliminating the need of the installed STATCOM. The PV-STATCOM solution is highly costeffective (about 50 times cheaper) compared to actual SVCs and STATCOMs as it utilizes the existing electrical substation infrastructure such as buswork, transformers, breakers, protection systems, of the PV solar system (which are quite similar to those in actual SVCs and STATCOM installations). The PV-STATCOM technology can therefore potentially bring significant cost-savings to utilities in that they may not need to install expensive SVCs or STATCOMs. Moreover, this novel grid support functionality can open new revenue making opportunities for PV solar farms.

II. LITERATURE SURVEY

This paper presents a literature review of the recent developments and trends pertaining to Grid-Connected Photovoltaic Systems (GCPVS). In countries with high penetration of Distributed Generation (DG) resources, GCPVS have been shown to cause inadvertent stress on the electrical grid. A review of the existing and future standards that addresses the technical challenges associated with the growing number of GCPVS is presented. Maximum Power Point Tracking (MPPT), Solar Tracking (ST) and the use of transformless inverters can all lead to high efficiency gains of Photovoltaic (PV) systems while ensuring minimal interference with the grid. Inverters that support ancillary services like reactive power control, frequency regulation and energy storage are critical for mitigating the challenges caused by the growing adoption of GCPVS.

This paper describes a granular approach for investigating the impacts of very high PV generation penetration. Studies on two real-world distribution feeders connected to PV plants are presented. The studies include both steady-state and time series power flow analyses, which include the effects of solar variability. The goal of the study is to predict the effects of increasing levels of PV generation as it reaches very high penetration levels. Impact results from the analyses are described along with potential mitigations.

III.PHOTOVOLTAIC CELL

A PV cell is a simple p-n junction diode that converts the irradiation into electricity. Fig.1 illustrates a simple equivalent circuit diagram of a PV cell. This model consists of a current source which represents the generated current from PV cell, a diode in parallel with the current source, a shunt resistance, and a series resistance.

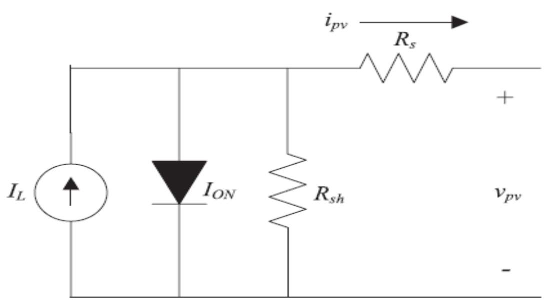

Fig.1 Equivalent circuit diagram of the PV cell

IV. STATCOM

The STATCOM is a solid-state-based power converter version of the SVC. Operating as a shunt-connected SVC, its capacitive or inductive output currents can be controlled independently from its terminal AC bus voltage. Because of the fast-switching characteristic of power converters, STATCOM provides much faster response as compared to the SVC. In addition, in the event of a rapid change in system voltage, the capacitor voltage does not change instantaneously; therefore, STATCOM effectively reacts for the desired responses. For example, if the system voltage drops for any reason, there is a tendency for STATCOM to inject capacitive power to support the dipped voltages.

STATCOM is capable of high dynamic performance and its compensation does not depend on the common coupling voltage. Therefore, STATCOM is very effective during the power system disturbances.

Moreover, much research confirms several advantages of STATCOM. *These advantages compared to other shunt compensators include:*

• Size, weight, and cost reduction

• Equality of lagging and leading output

• Precise and continuous reactive power control with fast response

• Possible active harmonic filter capability

V.PROJECT DESCRIPTION AND CONTROL DESIGN

5.1 CONCEPT OF SMART PV INVERTER CONTROL AS STATCOM

The real power generation from a solar farm on a sunny day and the remaining unutilized inverter capacity over a 24 hour period is depicted in Fig. 1. The operating modes of the proposed PV-STATCOM are described below: i) Full PV mode: The PV solar farm operates at unity power factor with no reactive power control. ii) Partial STATCOM Mode: The inverter capacity remaining after active power production is utilized for dynamic reactive power control as STATCOM. ii) Full STATCOM mode: During a power system disturbance or fault in the day, when the need for reactive power support is high, the solar farm temporarily (for typically less than a minute) reduces its real power output to zero by varying the voltage across the solar panels. It further makes its entire inverter capacity available for dynamic reactive power control as STATCOM. After the grid support need is fulfilled, the solar farm returns to its pre-disturbance power output. The Full STATCOM mode can be activated at any time during the day depending upon system need. As an example, this FullSTATCOM mode is depicted by the thin rectangle around 8 am in Fig. 2. The width of the rectangle is less than a minute but is shown over an exaggerated time period of an hour, just for ease of understanding. This mode is also fully available during night.

5.2 STUDY SYSTEM

Fig. 2 shows a 44 kV feeder in a utility distribution network in Ontario, Canada (name and location withheld for confidentiality reasons). The study feeder system includes three 10 MW PV systems with a total capacity of 30 MW connected about 35 km away from the utility transformer station (TS). The 30 MW PV plants are connected to the distribution system through a 30 MVA interface transformer, although each 10 MW PV system uses an intermediate transformer prior the interface transformer. Two solar systems with 10 MW generation are already connected to the PCC. Connection of the additional 10 MW PV system causes increased reverse power flow during light load conditions resulting in steady state over voltages. A 3.5 Mvar STATCOM is installed at PCC to mitigate steady state overvoltages. The TOV is also observed to exceed the permissible limits during single line to ground faults (SLGF) or line to line ground (L-L-G) fault scenarios. According to an Ontario utility requirement [29] the TOV caused by a DG facility should be less than 1.25 p.u. and in no circumstance exceed 1.30 p.u.

MODELING OF THE STUDY SYSTEM

This section presents the modeling of different components of the study system in EMTDC/PSCAD software. The model of the study system is depicted in Fig. 3. The substation system is represented as an equivalent voltage source with 1.05 p.u. voltage to supply the 44 kV feeder. The 35 km line from substation to PCC is represented by a π model in which the shunt admittance (e.g. line charging) is neglected. In Fig. 3, Rg and Lg represent the line resistance and inductance, respectively. The electrical load is considered to be a constantpower static RL load. At nominal voltage of 44 kVL-L, the total load is considered to be 30 MVA. The peak-time active and reactive loads are considered to be 27 MW and 6 Mvar, respectively, whereas during off-peak hours, these loads are 6 MW and 1.5 Mvar, respectively. All three PV systems are utilized with 10 MVA two-level six-pulse IGBT-based voltage source inverters (VSI). The switching frequency is chosen to be 4 kHz to minimize the switching losses. For each PV system, an LCL filter is utilized to mitigate the harmonics caused by the switching frequency. The LCL filter consists of a series inductor (Lf), shunt capacitor (Cf) with series damping resistor (Rd) and another series inductor (Lt) corresponding to the transformer inductance. The combination of shunt capacitor in series with damping resistor is connected in delta configuration. The filter inductor is selected between 0.1 to 0.25 pu. The amount of reactive power generated by the filter capacitor also influences the reactive power compensation by the VSI. Hence, the filter capacitor value is designed to limit the reactive power exchange below 0.05 pu of the inverter power rate. To avoid resonance between filter capacitor and inductor, a damping resistor is added to filter capacitor in series [31].

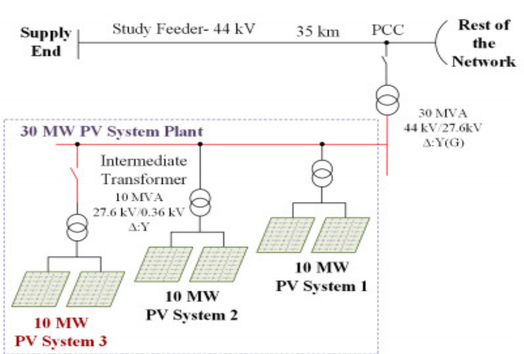

Fig. 2. Single line diagram of the study system

CONTROLLER DESIGN

This paper proposes that the additional (third) 10 MW PV system be equipped with the proposed patent-pending smart PV inverter PV-STATCOM control. The other two PV systems use only conventional controllers to generate real power at unity power factor. Fig. 3 illustrates the schematic of the smart PV inverter controller. The controller is designed in d-q frame and includes abc/dq transformation block, PLL, DC controller, current controllers, AC voltage controller, TOV detector unit and PWM unit. The PLL unit extracts the phase angle of PCC voltage for transforming currents and voltages from abc-frame to dq-frame or vice versa. The DC controller, in order to regulate DC link voltage at the reference value, generates the reference current for d-component of inverter current which represents the active current component. Consequently, the current controller in d-axis regulates the active current component to its reference value. During daytime, the smart PV control operates as a conventional PV system i.e., in Full PV mode. If steady state voltage control is required in all three phases, together with real power generation, Partial STATCOM mode is activated. The Full STATCOM mode is activated when a temporary overvoltage TOV occurs due to unsymmetrical faults. MPPT based on incremental conductance method is utilized during Full PV mode and Partial STATCOM mode. In FullSTATCOM mode, the MPPT mode is disabled and the real power generation is made zero by making the voltage across PV panel equal to its open circuit voltage. The entire inverter capacity is then utilized to absorb reactive power in order to reduce the phase voltage. After the TOV is mitigated, power production from the solar panels is enabled and control mode is switched to Partial STATCOM mode.

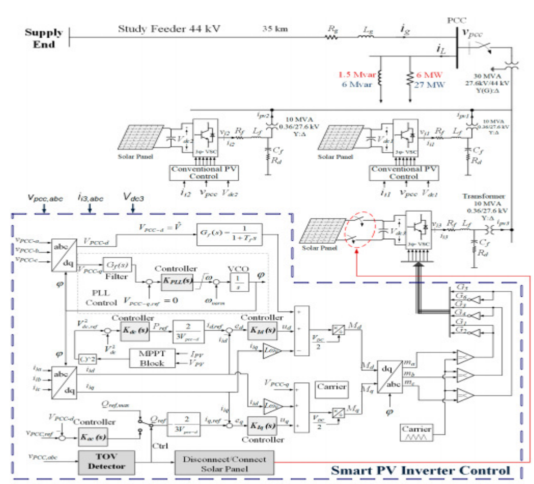

Fig. 3. Modeling of the study system and control components

The PCC voltage is controlled by the AC voltage controller. Therefore, either maximum reactive current or output of the AC voltage controller defines the reference value of reactive current control loop. The current controller in q-axis regulates the reactive current to its reference value. It is noted that the TOV Detector unit switches between voltage control mode and TOV mitigation mode. Also, this unit generates the command to enable or disable the power production from PV solar panels. The outputs of the controller are modulation indices in d-q frame, which are eventually converted to abc-frame using the phase angle of PCC voltage. The modulation indices in abcframe are compared with carrier signal to generate gate pulses for the VSC switches.

A. Operation Mode Selector

Fig. 4 shows the flowchart of the smart PV inverter control to select the operation mode. During daytime, the voltages in three phases are measured. If any phase voltage exceeds the TOV limit while the voltages in other phase/phases decrease substantially, the output of TOV Detector unit is trigged “ON”, and Full STATCOM mode is activated. The controller keeps the inverter current lagging the inverter voltage by 90 degrees (i.e. keeps absorbing reactive power) to reduce TOV until the phase voltages reach an acceptable value. After the fault is cleared all the phase voltages will rise to their normal values. The controller thus recognizes that TOV is mitigated. It therefore enables power generation from the solar panels and switches to Partial STATCOM mode for steadystate voltage control. In partial STATCOM mode, the controller regulates the PCC voltage with Qrem, which is the inverter capacity remaining after real power generation. During nighttime, the PV solar system operates in Full STATCOM mode to control either the steady-state voltage or TOV. The smart PV inverter control thus autonomously determines its operation mode 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.

VI.SIMULATION STUDIES

The performance of the smart PV inverter PV-STATCOM while fulfilling two control objectives, voltage control and TOV reduction, are presented in this section. In all these studies, light (small) load is defined as 6 MW and 2 Mvar, whereas a heavy (large) load is considered to be 27 MW and 9 Mvar. All the three solar farms are considered to be producing 7 MW each during light load conditions, i.e., a total of 21 MW power.

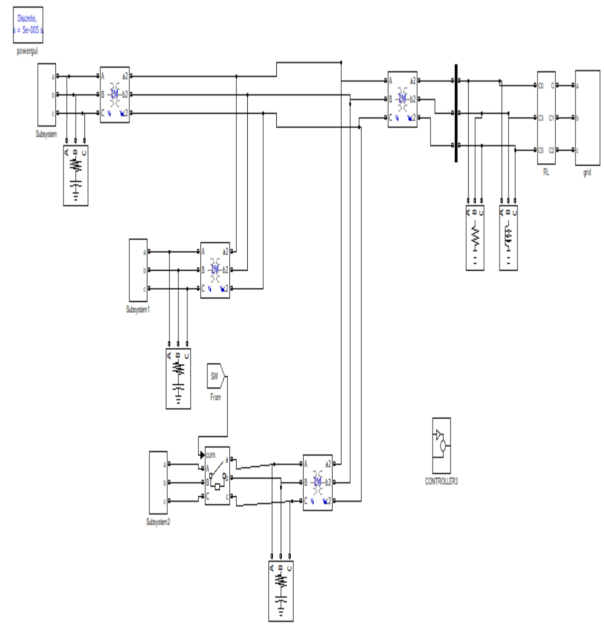

Fig4: Proposed Simulation diagram

A. Conventional PV System without Smart Inverter Control

In this study, the incoming third 10 MW PV solar system does not have a smart PV inverter control. It operates as a conventional PV solar system with real power generation at unity power. Fig. 7 illustrates the PCC voltages in the three phases and their per-unit rms values when PV systems generate their rated power during small load conditions. Before connection of PV systems, the PCC voltage is about 1.04 pu which is in the acceptable range per code. However, after the connection of the PV systems, the voltage rises to 1.10 pu which is unacceptable. At t= 0.54 sec a single line-to-ground (SLG) fault is initiated on phase “A”. This causes the voltage of phase “A” to fall to zero whereas the voltages in the other two phases reach 1.35 pu during the fault. This temporary overvoltage (TOV) during SLG fault is beyond the utility specified limit of 1.25 pu [29]. Therefore, there is a need to control both the steady-stateovervoltage and the TOV. Additional studies reveal that during large load condition the steady-state voltage is 1.01 pu whereas the TOV is 1.23 pu during SLG fault, both of which are within utility specified limits. These studies (although not included in the paper due to space limit) demonstrate that there is no need for either voltage regulation or TOV reduction during heavy loading condition.

B. Smart PV Inverter PV-STATCOM and Two Conventional PV systems

In this study, instead of using an external STATCOM, the incoming third PV system is equipped with the proposed smart PV inverter PV-

STATCOM controller, while the other two PV systems operate as conventional PV systems. The proposed smart inverter controller regulates the PCC voltage in steadystate with the remaining capacity of the inverter and also converts the PV system to Full STATCOM mode during a TOV event. Two different faults, single line-to-ground (SLG) fault and line-to-line-ground (LLG) fault, are considered to demonstrate the performance of the proposed controller.

1) Single Line to Ground (SLG) Fault

Fig. 8 demonstrate the per-unit value of the PCC voltage (Vpcc,pu), the three-phase instantaneous PCC voltage (vpcc), smart PV system current (is), output powers (PPV, QPV), reactive current (Iq) active current (Id), DC link voltage (Vdc), angular frequency, PLL angle output and TOV flag status, respectively. t< 0.5sec: The smart PV system is not connected, and hence the real and reactive power of PV system are respectively, zero. t=0.5 sec: Three conventional PV system connected: Due to 21 MW active power generation of PV systems, the PCC voltage increases from 1.04 pu to 1.10 pu which is unacceptable. The DC link voltage is controlled at reference value by controlling active current output. The reactive power is controlled at zero. t=0.54 sec: Partial STATCOM mode enabled: This operating mode for voltage control reduces the voltage to an acceptable range in less than one cycle utilizing the remaining capacity of the inverter. The reactive power output of the inverter reaches 7 Mvar capacitive from zero to maintain the voltage at acceptable range. However, the active power remains at same value since the reactive power control utilizes the remaining capacity of the inverter. The active and reactive

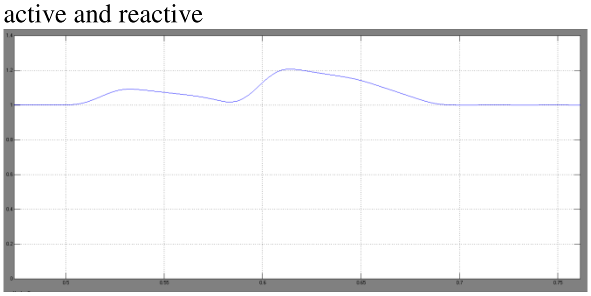

Fig5 :Pcc Voltage in PU

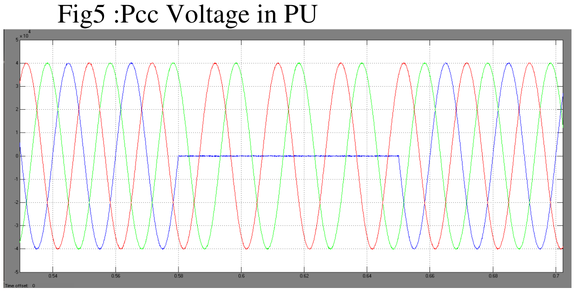

Fig6:Pcc Voltage

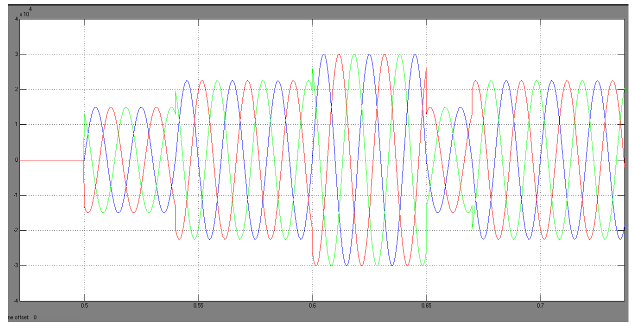

Fig7: Smart PV Current

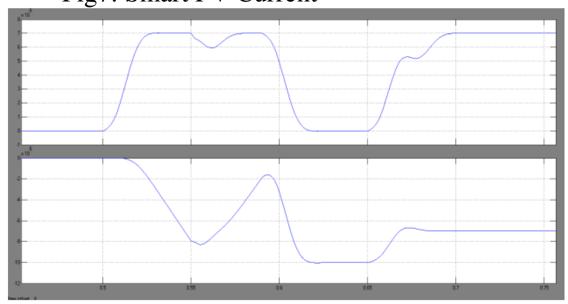

Fig8: Active and reactive powers of Smart PV

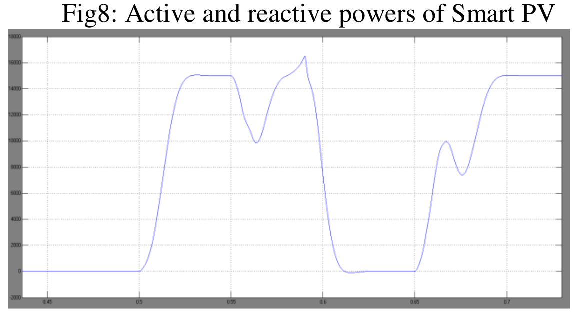

Fig9: Active current

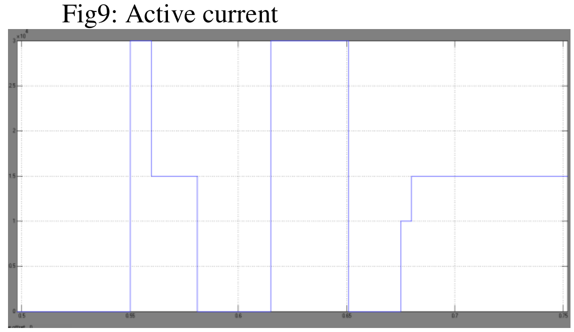

Fig10:Reactive Current

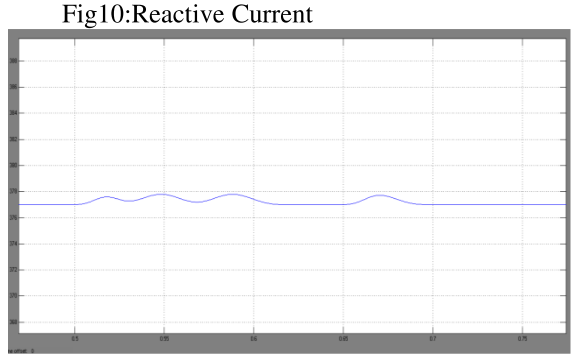

Fig11:Anugular Frequency

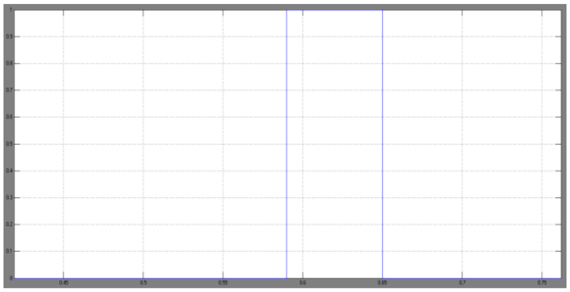

Fig12: TOV Flag

Fig. 8. Performance of the third 10 MW PV system as PV-STATCOM, together with two conventional PV systems, during small load and SLG fault a) PCC voltage (pu) b) PCC voltage c) Smart PV current d) Active and reactive powers e) Reactive current f) Active current g) DC link voltage h) Angular frequency of PCC voltage i) Angle output of PLL j) TOV flag status

2) Line to Line to Ground (LLG) Fault

The performance of the proposed smart inverter controller during an LLG fault is demonstrated in Fig. 9. As in the previous case of SLG fault, the smart PV inverter controls the PCC voltage to its reference value during steady-state. t=0.58 sec: LLG fault initiated: the voltages of two phases phase “A” and phase “B” fall to zero and a TOV is caused in phase “C” due to LLG fault. The TOV detection unit triggers the TOV flag and the controller changes its mode from Partial STATCOM mode for voltage control to Full STATCOM mode for TOV reduction. This smart inverter control effectively reduces the TOV in the healthy phase to an acceptable value of 1.22 pu in about a cycle. It is noted that the designed PLL performs in a stable manner both during steady state and during SLG and LLG faults.

currents follow their reference values to satisfy the voltage control objective. t=0.58 sec: SLG fault initiated: the SLG fault causes the voltage of phase “A” to fall to zero, whereas the other phase voltages experience TOV. The proposed TOV detection unit detects this TOV event and triggers the TOV flag. Hence, the smart inverter autonomously switches from Partial STATCOM

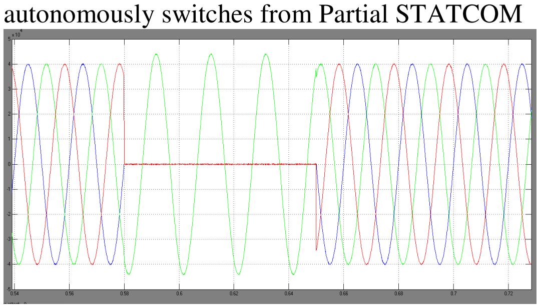

Fig13:PCC Voltage

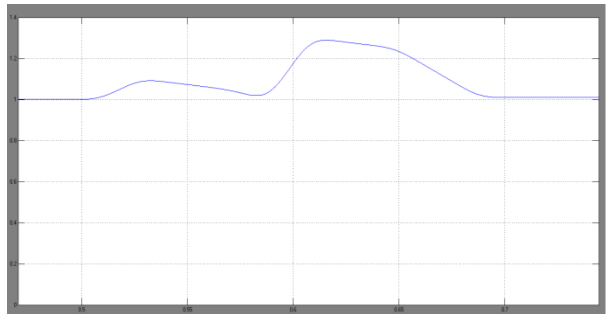

Fig14:PCC voltage in PU

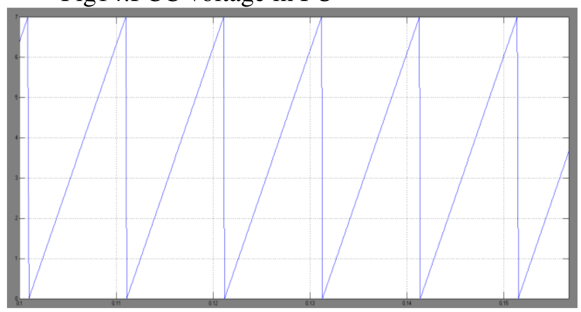

Fig15: PLL Angle

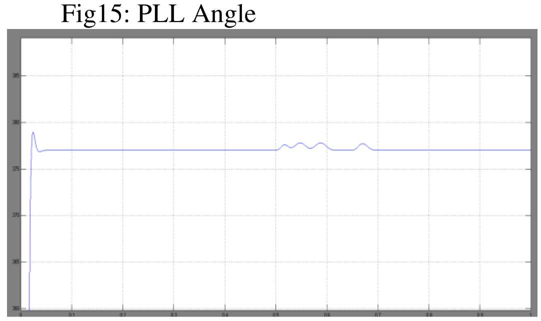

Fig16:Angular frequency

Fig. 13,14,15. Performance of one PV system with proposed smart inverter control, together with two conventional PV systems, during small load and LLG fault

VII.CONCLUSIONS

This Paper presents an innovative smart PV inverter control as STATCOM, named PV-STATCOM, for controlling the steady state overvoltage and more importantly, mitigation of Temporary Overvoltages (TOV) with fuzzy system. This novel control in Partial STATCOM mode regulates the steady state over voltage to the desired reference value within one and half cycle. Further, this smart inverter control in Full STATCOM mode successfully reduces the TOV caused during both single line to ground fault and line to line to ground fault to within utility acceptable values within one cycle using fuzzy. The PV-STATCOM thus provides the full function of a STATCOM for voltage control on a 24/7 basis. For the studied actual distribution system the proposed PVSTATCOM control can help integrate the third 10 MW PV solar farm thereby eliminating the need for the actually installed STATCOM for the same purpose. The proposed

PVSTATCOM control is expected to be at least 50 times cheaper than a conventional STATCOM. This control can therefore bring a significant saving for the concerned utility. Such a control can also help in increasing the hosting capacity of PV solar farms on distribution systems which may be restricted due to voltage issues. This control can potentially open a new revenue making opportunity for the solar farms for providing the STATCOM service.

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