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

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Abstract— This paper presents a novel smart inverter PVSTATCOM in which a PV inverter can be controlled as a dynamic reactive power compensator - STATCOM. The proposed PVSTATCOM 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.

Keywords**—**Photovoltaic (PV) Solar system, Smart Inverter, STATCOM,Voltage control,Power factor Correction,Flexible AC transmission system,(FACTS).

1. INTRODUCTION:

The integration of Distributed Energy Resources (DER) has undergone a paradigm shift with the introduction of SMART Inverters, formerly known as Advanced Inverters [1]–[5]. In addition to its primary job of converting DC power to AC power, these inverters can carry out a variety of other tasks requiring reactive and actual power control. Voltage regulation, power factor management, active power controls, ramp-rate controls, fault ride through, frequency control, and other features are some of these functions.

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

2. PHOTOVOLTAICARRANGEMENTS

Photovoltaic cell

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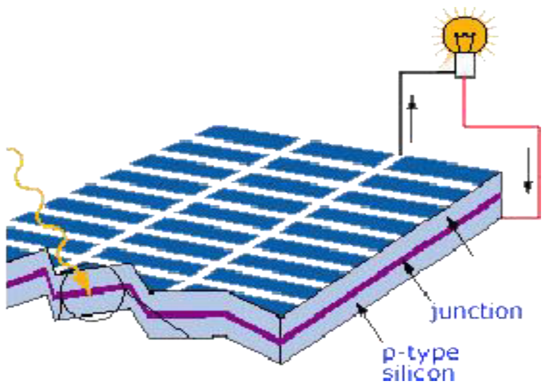


The basic ingredients of PV cells are semiconductor materials, such as silicon. For solar cells, a thin semiconductor wafer creates an electric field, on one side positive and negative on the other. When light energy hits the solar cell, electrons are knocked loose from the atoms in the semiconductor material.

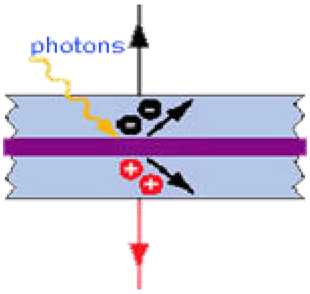


Fig: Basic structure ofPV ce

2.1 Photovoltaic Module

The Multiple PV cells are connected in series for high voltage and parallel for high current to build a PV module for the desired output because a single PV cell only generates about 0.5V of voltage. Separate diodes could be needed at night and in situations where there is partial or complete shade in order to prevent reverse currents.

3.1 Working of PV cell

The basic principle behind the operation of a PV cell is photoelectric effect. In this effect electron gets ejected from the conduction band as a result of the absorption of sunlight of a certain wavelength by the matter (metallic or non-metallic solids, liquids or gases) **.** So, in a photovoltaic cell, when sunlight hits its surface, some portion of the solar energy is absorbed in the semiconductor material.

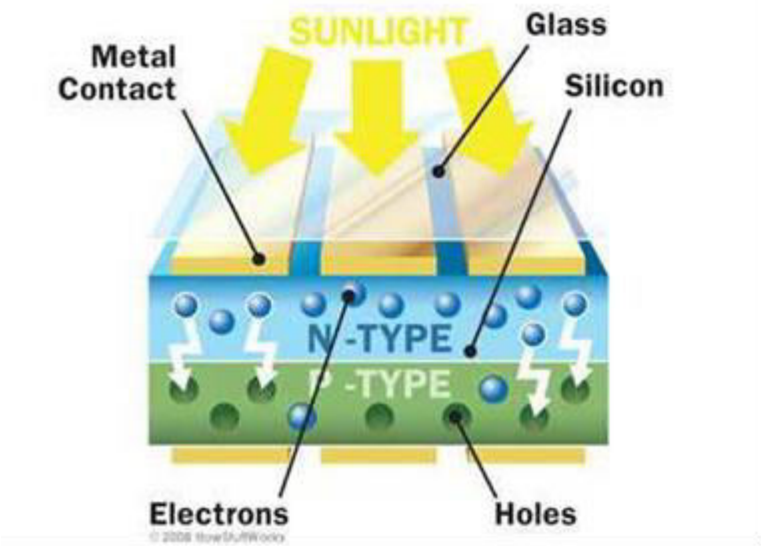


Fig working of PV cell

The electron from valence band jumps to the conduction band when absorbed energy is greater than the band gap energy of the semiconductor. By these hole-electrons pairs are created in the illuminated region of the semiconductor. The electrons created in the conduction band are now free to move.

3.2 Modeling of PV Panel

The photovoltaic system can generate direct current electricity without environmental impact when is exposed to sunlight. The basic building block of PV arrays is the solar cell, which is basically a p-n junction that directly converts light energy into electricity. The output characteristic of PV module depends on the cell temperature, solar irradiation, and output voltage of the module. The figure shows the equivalent circuit of a PV array with a load.

4.Necessity of power point tracking:

In the power versus voltage curve of a PV module there exists a single maxima of power, i.e. there exists a peak power corresponding to a particular voltage and current. The efficiency of the solar PV module is low about 13%. Since the module efficiency is low it is desirable to operate the module at the peak power point so that the maximum power can be delivered to the load under varying temperature and irradiation conditions.

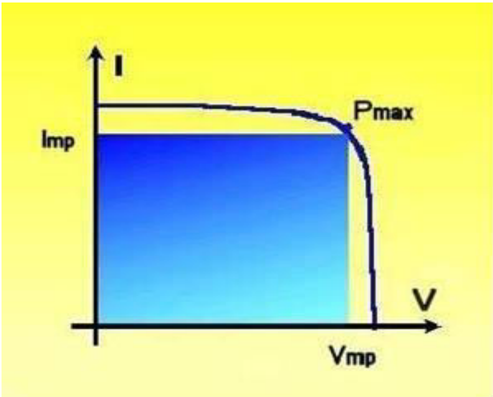


Fig MPP characteristic

5. Structure of statcom

As can be seen in the figure below, STATCOM is primarily made up of three components: a controller, a step-up coupling transformer, and a The step-up power transformers' voltage source converter leakage inductances can serve as coupling reactors in a very high voltage system. The coupling inductors' primary function is to filter out the current harmonic components, which are mostly produced by the power converters' oscillating output voltage In order for the STATCOM to generate or absorb the desired VAR at the point of coupling connection, the controller of a STATCOM runs the converter in a certain way that allows the phase angle between the converter voltage and the transmission line voltage to be dynamically adjusted and synced.

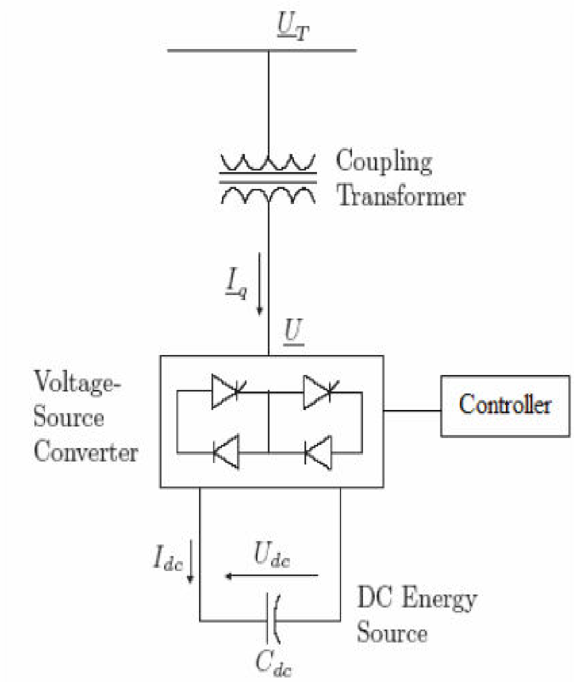


Fig Reactive power generation by a Statcom

5.1 Controlling of statcom

The controlling of statcom is of two types

1.Currently controlled statcom

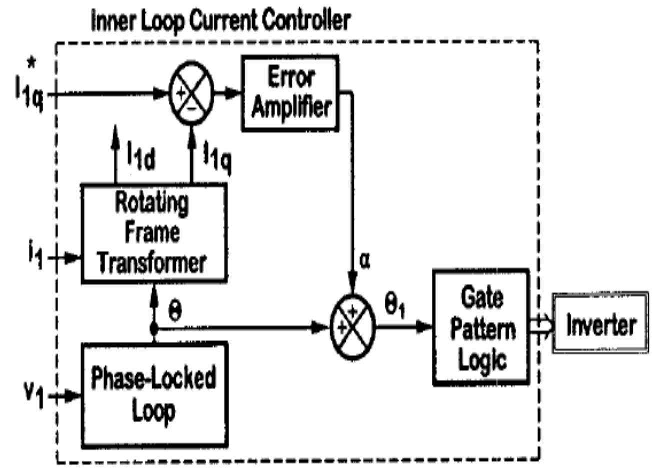


Figure above shows the reactive current control block diagram of the STATCOM. The reference angle, θ, is phase-locked to the phase an of the line voltage, vla, and is computed using an instantaneous three-phase set of line voltages, vl, at BUS 1. Real or direct component I1d and reactive or quadrature component I1q are the two components of an instantaneous three-phase set of measured converter currents,

2.Volatge controlled statcom

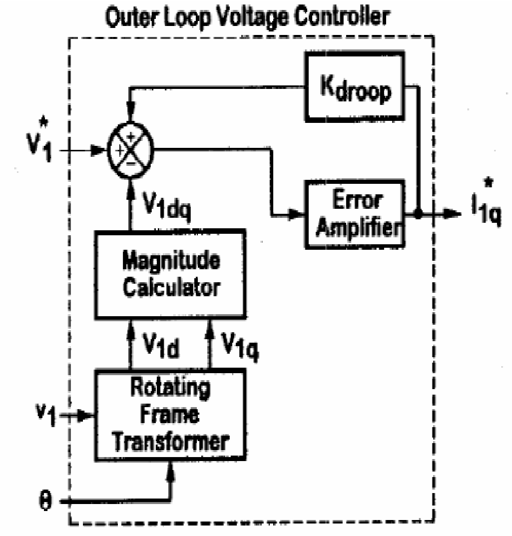
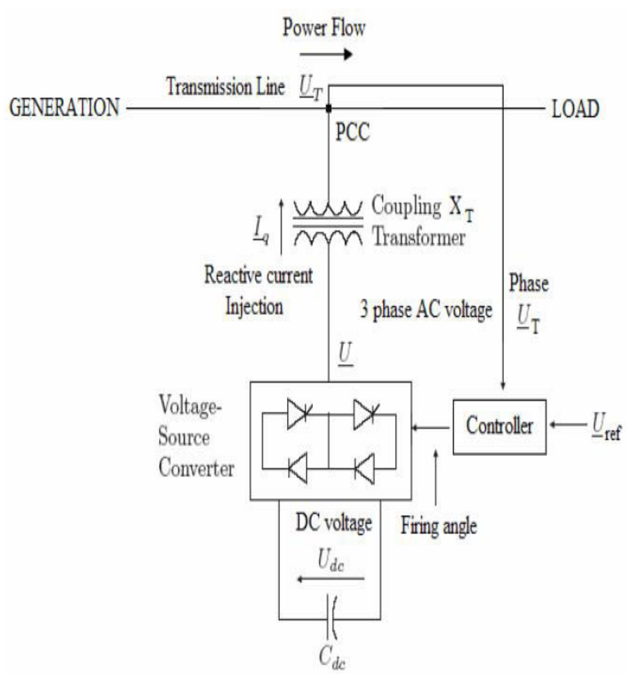


Figure shows The STATCOM's voltage control block schematic. When compared to the desired reference value, V1* (adjusted by the droop factor, Kdroop), an instantaneous three-phase set of measured line voltages, v1, at BUS 1 is broken down into its real or direct component, V1d, and reactive or quadrature component, V1q. The error is then passed through an error amplifier, which generates the reference current, I1q*, for the inner current control loop. The permitted voltage error at the rated reactive current flow through the STATCOM is known as the droop factor, or Kdroop.

5.2 Statcom operation in a power system

A set of adjustable three-phase output voltages, U, in synchronism with the AC system are produced by the converter using a DC voltage, Udc, supplied by the charged capacitor Cdc. An extra controller is required to synchronize the three-phase output voltage with the transmission line voltage. The voltage reference, Uref, representing the required voltage across STATCOM, is manually set on the controller. Thus, the voltage control is to match the elaborated Uref with UT. The firing angle that the controller sets allows the output voltage U to change, which is how the voltages are matched. In this way, the controller sets UT identical to Uref. It is also possible to regulate the reactive power exchange that occurs between the converter and the AC system.



6.Aerodynamic Power control

To avoid component overload, the shaft power should be lower than the wind energy available. Limiting the aerodynamic efficiency at high wind speeds can be accomplished in two ways. Using the first approach, the aerodynamic stall effect is exploited. The airflow will eventually stop flowing down the blade and separate from it at the back when the angle at which the wind strikes the blade (also known as the "angle of attack") is steadily increased. There will be large eddy formations that cause the Cp to drop sharply.

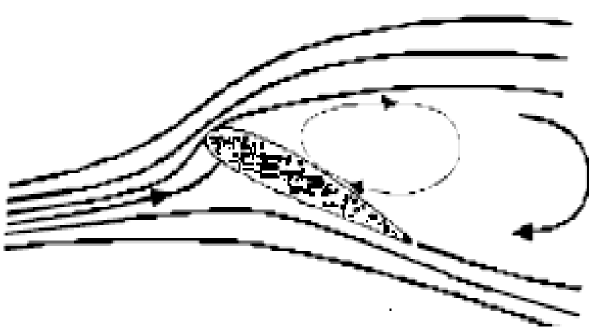


Fig Stalled flow around an aerofoil.

6.1 Energy Yield

The annual energy yield *E* of a wind turbine depends on its power curve *P(vw)* and the probability density distribution function *u(vw)* of the wind speed at the turbine site:

$$E = \int_0^\infty P(v_w) \cdot u(v_w) dv_w$$

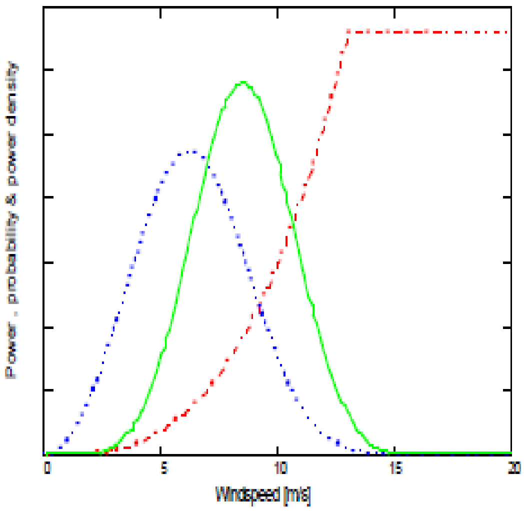


Fig: Power P (red, dashed), probability density U (blue, dotted) and power density (green, solid) as a function of wind speed (arbitrary units).

6. Modeling of the system

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.

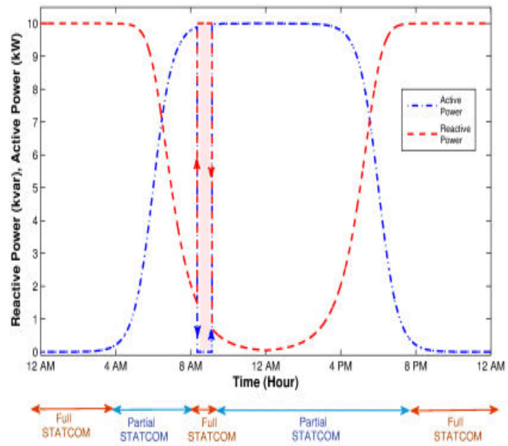


Fig Concept of smart PV inverter control as STATCOM

6.1 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 VL−L distribution system equivalent model having impedance parameters (Rg, Lg). 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, Rf represents the sum of IGBT ON-state resistance and internal resistance of filter inductor, while Lf 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]. Cf represents the filter capacitor in Delta configuration with a damping resistor Rd. Cf is chosen to limit the reactive power exchange below 0.05 pu of the inverter.

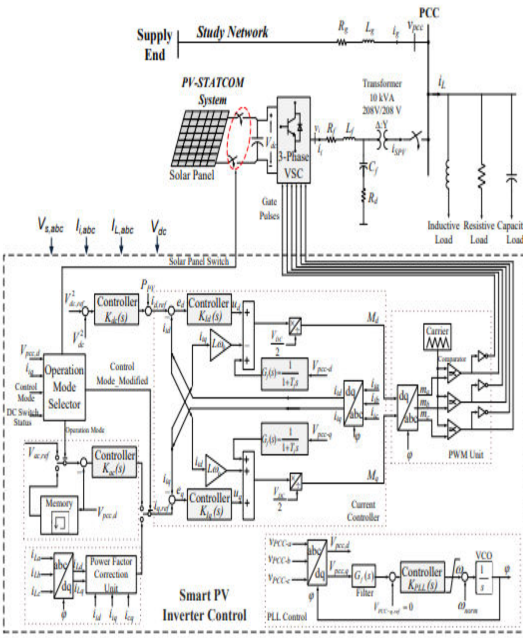


Fig Modeling of the study system and control components

6.2 DC 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

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

is

Where kdc,gain and zdc are the parameters of DC link voltage controller. Symmetrical Optimum technique [26] is used to design this controller with phase margin 50◦ at frequency ωc = 364 rad/s.

6.3 Operational Mode Selector

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

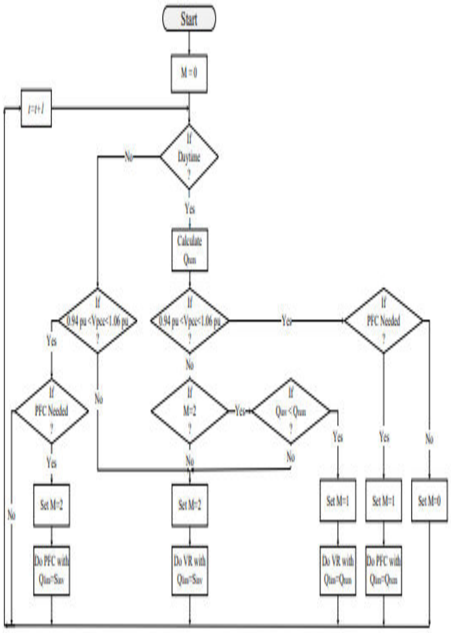
(i) Full PV Mode: M = 0

(ii) (ii) Partial STATCOM Mode: M = 1

(iii) (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, Qrem - 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), thebus 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 Sinv (Qlim = Qrem). If during such voltage control, the amount of needed reactive power becomes less than Qrem, the operating mode is switched to Partial STATCOM mode (M = 1) with (Qlim = Qrem). 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 (Qlim = Qrem). 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 (Qlim = Sinv). 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 (Qlim = Sinv).



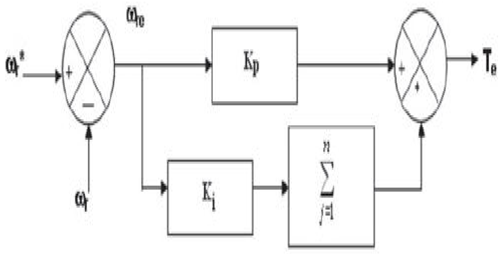
7. Discrete PI Controller

Digital controllers are implemented with discrete sampling periods and a discrete form of the PI equation is needed to approximate the integral of the error. This modification replaces the continuous form of the integral with a summation of the error and uses Δt as the time between sampling instances and nt as the number of sampling instances.

u(t)=ubias+Kce(t)+KcτInt∑i=1ei(t)Δt

7.1 Overview of PI Control

PI control is needed for non-integrating processes, meaning any process that eventually returns to the same output given the same set of inputs and disturbances



Fig

Block diagram of PI speed controller

A P-only controller is best suited to integrating processes. Integral action is used to remove offset and can be thought of as an adjustable ubias. Common tuning correlations for PI control are the ITAE (Integral of Time-weighted Absolute Error) method and IMC (Internal Model Control). IMC is an extension of lambda tuning by accounting for time delay. The parameters Kc, τp, and θp are obtained by fitting dynamic input and output data to a first-order plus dead-time (FOPDT) model.

The output Of the speed controller (torque command) at *n*-thinstant is expressed as follows

$Te(n)=Te(n-1)+Kp\_\omega re(n)+Ki\omega re(n)$ (10)

Where $Te(n)$ is the torque output of the controller at the *n*-th instant, and *Kp*and K*i* the
proportional and integral gain constants, respectively.

A limit of the torque command is imposed as

$$T_{e(n+1)} = \begin{cases} T_{emax} & \text{for } T_{e(n+1)} \geq T_{emax} \\ -T_{emax} & \text{for } T_{e(n+1)} \leq -T_{emax} \end{cases}$$

8. MATLAB DESIGN CIRCUIT

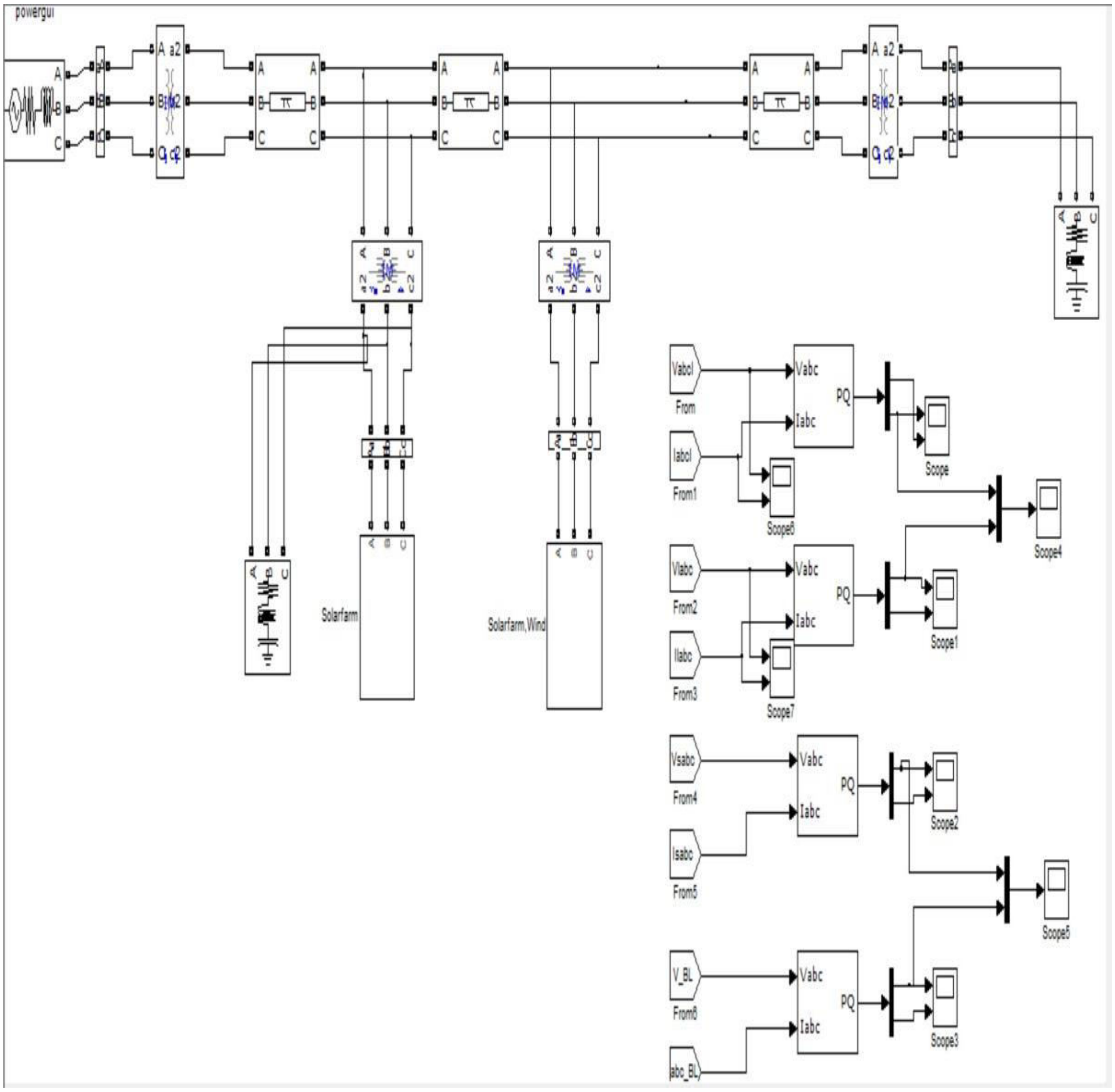
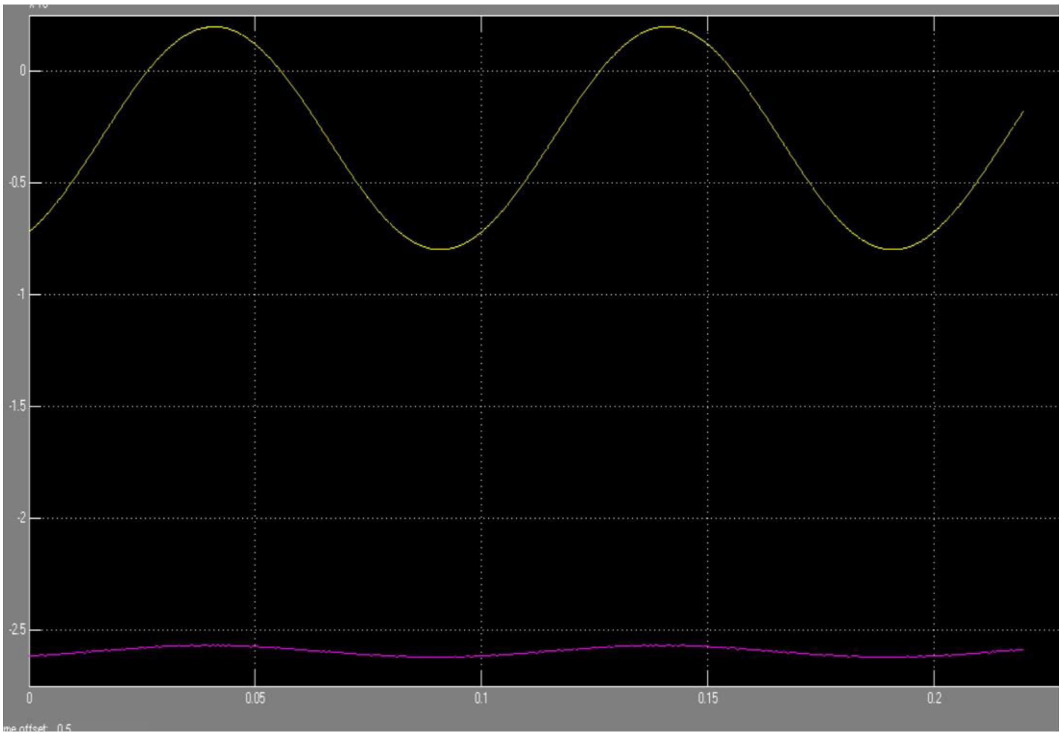


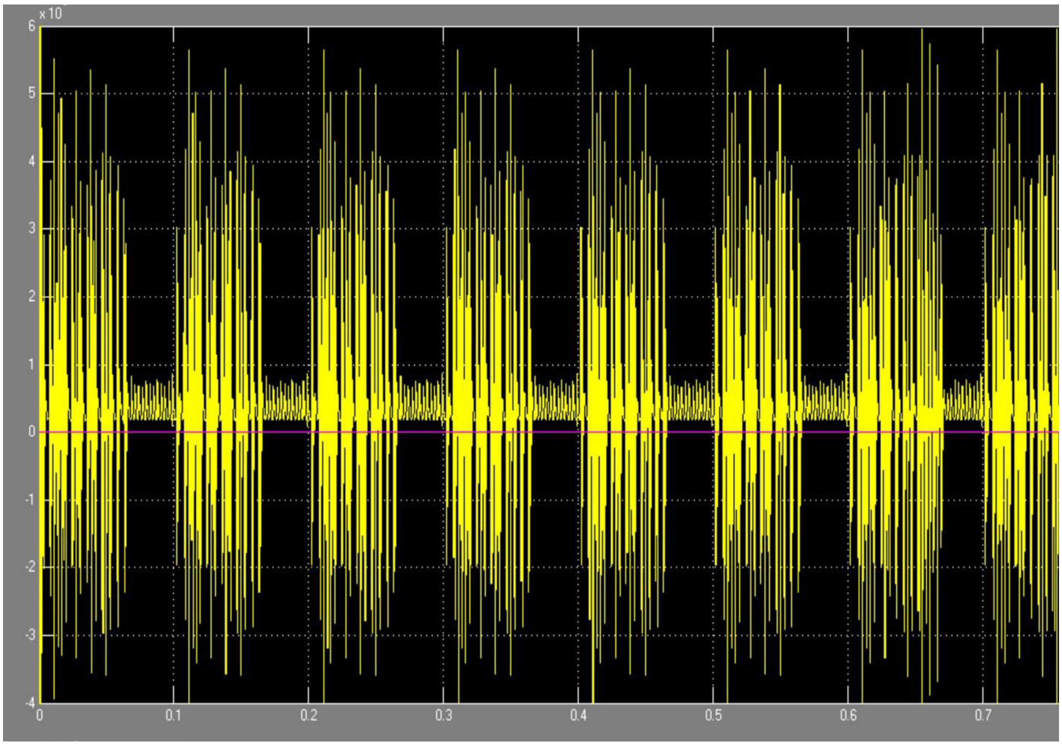
Fig: MATLAB Circuit Design

8.1 SIMULATION RESULTS

OUTPUT WITHOUT STATCOM



OUTPUT WITH STATCOM



CONCLUSIONS

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 EMTDC/PSCAD simulation 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

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