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PV based DG Power Quality Improvement Using Integrated D-STATCOM under varying Insolation

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Abstract: The standalone grid connected Photovoltaic (PV) systems have been gradually increasing for generation of electrical energy due to ever increasing fuel and coal prices, as well as the environmental issues posed by conventional power plants. In this transition phase, power quality is at its expense, resulting in damage to equipment or appliances and lost in production. Inadequate power quality can be caused by network failures and switching operations, which primarily cause voltage dips, interruptions, transients, and network disturbances from loads which primarily produce flicker i.e., rapid voltage changes, harmonics and phase imbalance. In this paper PV is used as an external DC source for D-STATCOM (Distributed Static Synchronous Compensator) which is a FACTS device that can maintain and repair power quality limitations such as power factor correction, voltage control, load balancing and harmonic reduction. The PV-STATCOM system inverter is implemented by impending MPPT method using P&O algorithm so as to provide DC link voltage control and to improve transient response along with counteracting power quality issues. MATLAB/Simulink based simulation results are presented for the proposed PV-STATCOM model. The simulation results proves that the PV-STATCOM system has better Total Harmonic Distortion (THD) and good reactive power compensation at different irradiance levels.

Keywords: Photovoltaic (PV) systems, D-STATCOM (Distributed Static Synchronous Compensator), Total Harmonic Distortion (THD), MPPT (Maximum Power Point Tracking), FACTS (Flexible AC Transmission System)

I. INTRODUCTION

The major cause of pollution and deterioration of environment is due to large dependency on conventional energy. To build a sustainable future, mostly it depends on assimilation and control of renewable energy resources [3] in grid distribution generation which is a roof challenge. Power sector is the most acute component of infrastructure, growth of economic activity and for nation welfare. It is one of the most heterogeneous component in the world. It is a big challenge for power sector to meet the load demand during peak hours. To meet this demand some DGs are used to supply extra power during. Power which is generated at distribution voltage level by using renewable energy sources like solar photovoltaic cells, power generated by wind, biogas and fuel cell is called Distribution Generation (DG)[1],[6]. Besides power generation, major concern is power quality. The generated power is to be transmitted from the point of generation to the point of consumption via transmission lines. The two important parameters in power generation are reliability and power quality. These are affected by weather conditions, different conditions of loads, alterations in demand, etc. The major power quality problems are voltage sag, voltage swell, fluctuations, harmonic distortions, unbalances and transients which results failure or disoperation of devices which are used by customers. To resolve these power quality issues [5] STATCOM which is a FACTS device [8] is utilized as a shunt controller which inject current into the line to control voltage at and around point of connection, to maintain power flow along paths established and to increase transmission capacity of line. When only STATCOM is installed in a system, it cannot control temporary over voltages in an actual distribution and transmission system whereas D-STATCOM is an advanced version of STATCOM used at heavily loaded or at high power quality issues and provide active support using energy source connected to inverter. In this paper, we intended to use PV array as an energy source for D-STATCOM to provide active power and reactive power support to grid and reducing its burden. Very low power factor loads are connected at point of common coupling (PCC) to analyze efficacy of this combined PV-STATCOM system. To track maximum power and to provide temporary voltage support, MPPT control has been implemented using P&O algorithm for a smart inverter in PV-STATCOM system [2]. This provides control of DC link voltage and also improves transient response of the system.

II. MATHEMATICAL MODELLING & CONTROL METHODS

A. *Modelling of PV Cell and Its MPPT Control Logic*

1) *PV CELL:* PV cells are fundamental building blocks of PV systems. These cells are made up of semi-conductor materials and their important property is band gap. If the bandgap of semiconductor matches the wavelength of incident light on PV cell, then the energy will be used in an efficient way. The PV array is combination of number of series and parallel modules of PV cells which are connected electrically to produce higher voltages, currents and power levels. The equivalent circuit diagram of PV cell is shown in fig 1.

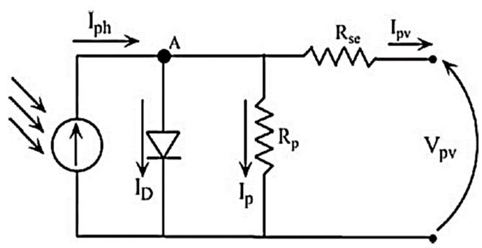

Fig 1: Equivalent circuit of PV cell

The output current Ipv is composed of generated light current Iph and diode current Id:
Ipv = Iph–Is{ exp[(q(Vpv+IRse))/(nkT)] – 1} – [(Vpv+IRse)/Rsh]

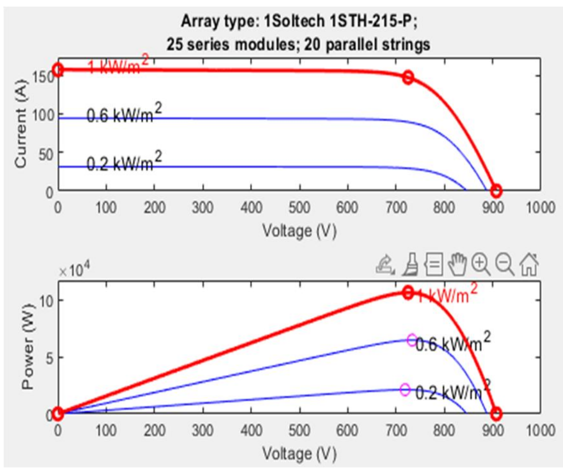

Fig 2: I – V & P-V characteristics of a practical PV cell

The I – V & P-V characteristics of practical PV cell is shown in fig 2 at different irradiances of 1000W/m^2, 600W/m^2 and 200W/m^2 respectively. Pm represents the maximum power obtained at that MPP. Vm is the voltage at maximum power point. Im is the current at maximum power point. Voc is the open circuit voltage and Isc is the short circuit current

Table 1: Voltage, Current and Power at different Irradiance values

Irradiance (W/m^2)	Vm (V)	Im (A)	Pm (W)	Voc (V)	Isc (A)
200	718.7	29.54	212.30	843.7	31.45
600	733.4	88.29	647.50	888.1	94.31
1000	725	147	1066	907.5	156.8

2) *P&O Algorithm:* For maximum power tracking (MPPT) [7], P&O algorithm is used. A minor perturbation is introduced for the power variation of PV module. The flowchart is shown in fig3. The MPPT controller is connected in between PV module and battery so as to measure PV voltage and battery voltage to determine whether it is fully charged or not fully charged. This controller calculates the existing new power (Pnew) at output by measuring voltage and current and compares to old power (Pold) which is previous measured power. If Pnew>Pold then to extract maximum power from the PV panel, PWM duty cycle is increased. If Pnew<Pold then to enable the system to move back to previous power, the duty cycle is reduced.

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B. STATCOM / Smart Inverter

STATCOM is a FACTS device and it is connected to Point of common coupling (PCC) to provide reactive power support along with mitigating power quality issues like voltage sag, total harmonic distortion, and power factor improvement. As solar PV system also needs to tie to grid via inverter, so same inverter has been used as STATCOM and PV inverter. Hence, it is called as Smart Inverter. In this control technique, dq0 control [2] which is also called as Synchronous reference frame control is used. By using park transformation it converts grid voltage (Vabc) and grid current (Iabc) into a dq0 reference frame that rotates synchronously with the grid vector so that the three-phase time-varying signals are transformed into DC signals. A phase-locked loop (PLL) block that detects the phase angle of the grid voltage which is generally used in this transformation. In this control, PI controllers are generally used by considering their capability of regulating DC signals without any steady state error. The transfer function of a PI controller in Laplace domain: GPI(S) = Kp + Ki/S Where Kp is Proportional gain and Ki is Integral gain.

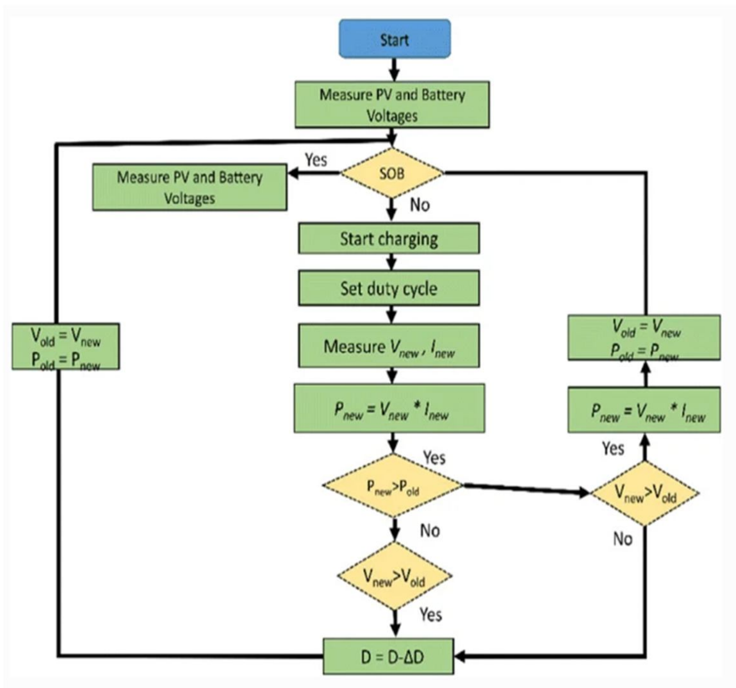

Fig 3: Flowchart of P&O Algorithm

1) *Parks Transformation:* Park transformation is used to convert three phase system time domain components in abc reference frame to dq0 components (direct, quadrature and zero) in rotating reference frame. Where a, b, and c represents three phase system components in abc reference frame. d and q represents two-axis system components in rotating reference frame. 0 is the zero component of two-axis system in stationary reference frame

For an a-phase to q-axis alignment park transformation can be represented as:

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

For an a-phase to d-axis alignment park transformation is represented as:

$$\begin{bmatrix} d \\ q \\ 0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ -\sin(\theta) & -\sin(\theta - \frac{2\pi}{3}) & -\sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$

III. PROPOSED MODEL

The Simulink model of PV-STATCOM system connected to grid is shown in fig4.

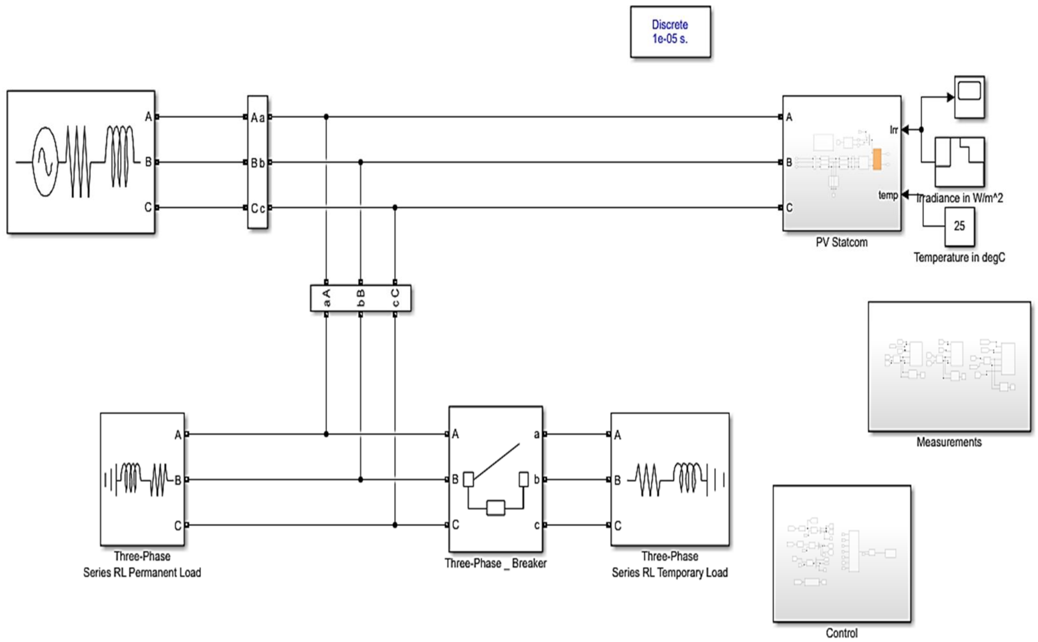

Fig 4: Simulink model of PV-STATCOM system connected to grid source

The PV-STATCOM system is connected to three-phase grid source. The series RL permanent load of active power 50 kW and reactive power of 100kVar and series RL temporary load of active power 20kW and reactive power of 15kVar are connected at Point of common coupling (PCC). The sub system and control block is shown in fig 5 & 6 respectively. , PV panel is connected to three-phase voltage source converter via DC link and non-linear loads are connected to network at PCC.

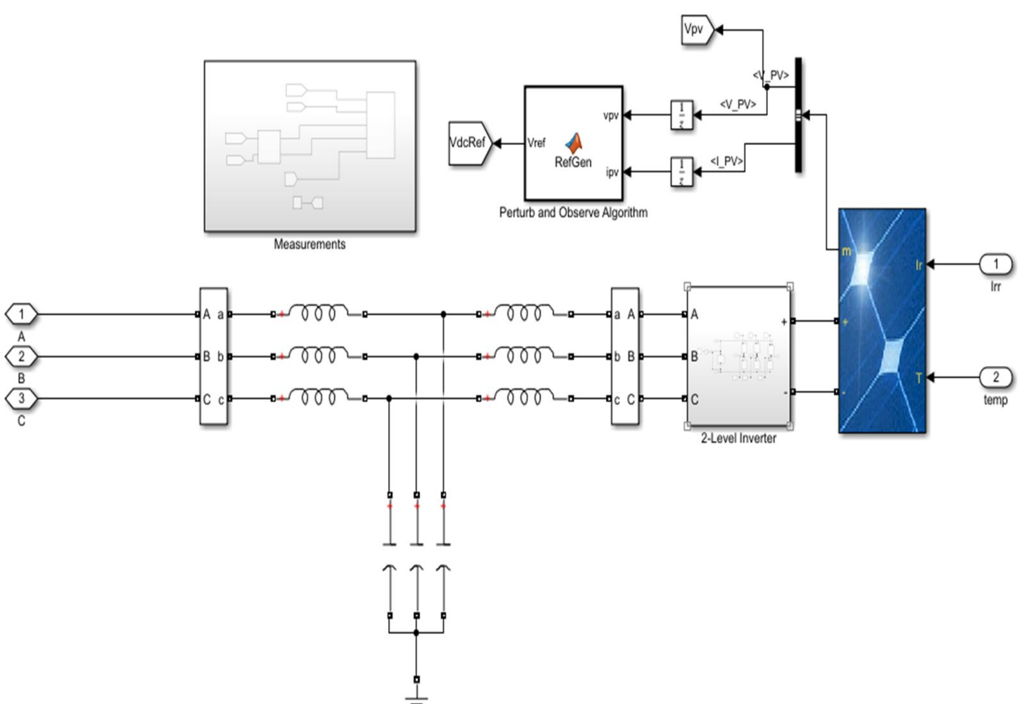

Fig 5: Simulink Model of PV array

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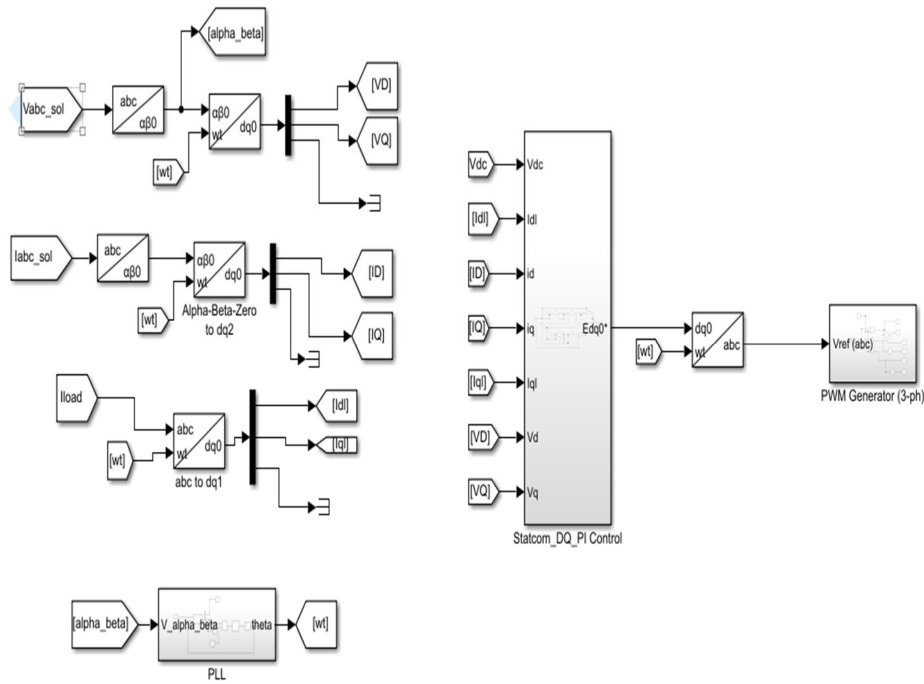

Fig 6: Control block of PV-STATCOM system

Fig 6 shows the control block of PV-STATCOM system. The sub blocks are conversion blocks, PLL generation block for phased locked loop control and PWM generation block and current control block. abc to αβ0 conversion block is used to transform three phase abc components to stationary αβ reference frame which is known as Clarke transformation. Vabc_sol and Iabc_sol which are voltage and current of PV array is transformed from three-phase quantities into components of αβ0 reference frame and from αβ0 components to dq0 orthogonal reference frame. The conversion of abc components to dq0 components in orthogonal reference frame is called Park Transformation. Load current Iload components are also transformed from abc quantities to dq0 orthogonal reference frame by using Park transformation.

These transformed dq0 signals are inputs to the respective PI controller in the dq PI control block which is the control logic of STATCOM. The outputs from STATCOM control block which are in dq0 reference frame are transformed into abc components of three-phase system reference frame. This transformation is known as Inverse Park transformation. Based on their values, reference wave is generated and applied to comparator. This modulated signal acts as second input to comparator and other input is fed with a non-sinusoidal wave or saw tooth wave. It operates at a carrier frequency and comparator compares two signals and generates a PWM signal. In this Simulink model PV-STATCOM system is designed to operate in three modes i.e. in full STATCOM mode [9], partial PV-STATCOM mode, full PV mode considering real time simulation environment.

IV. OPERATION OF PV-STATCOM SYSTEM

PV-STATCOM system determines the operation of system and gives precedence to generation of real power or exchange of reactive power based on system requirements, disturbances, time interval and capacity of inverter.

1) *Full STATCOM Mode:* During night time, this inverter operated completely in STATCOM mode due to unavailability of sun irradiation. During this time reference current of PV array is less than threshold value so, there will be no power flow from PV array. In this mode of operation only reactive power is supplied by inverter to grid and total power is kept constant. During day time also it is operated in this full STATCOM mode only when it is needed i.e. when disturbances or faults occur. During interval of faults or disturbances, for reactive power exchange it automatically discontinues generation of real power. The discontinuation of real power generation can be done by two ways:

a) By disconnecting solar panels
b) By increasing voltage of solar panels above the open circuit voltage

The full capacity of inverter is only to operate as STATCOM for reactive power exchange as long as grid needs.

2) *Partial PV-STATCOM Mode:* During daytime i.e. in early morning and in late afternoon the system is under partial PV-STATCOM mode of operation. The system is under this mode of operation when irradiance values are less or moderate and reference current of PV array is slightly greater than threshold value of PV array. Real power generation is sustained based on irradiation of sun and exchange of reactive power with grid is done which is operated as STATCOM when power generated by PV array is not up to the maximum. In this mode of operation smart inverter control utilizes small DC power from solar panels to keep capacitor charged and rest of the inverter capacity is injected into the grid.
3) *Full PV mode:* The PV-STATCOM undergoes full PV mode of operation during day time, when irradiance values are higher and reference current of PV array is much higher than the threshold value of PV array. Power generated by PV array is maximum of its irradiation limit which is generally 1000 w/m^2. Maximum irradiation of sun is observed generally in mid-afternoon. Only real power is generated without any reactive power exchange due to operation of only PV system.

V. RESULTS

Irradiance values of PV array are taken with respect to particular time interval and are tabulated in table 2. The Irradiance values are taken at particular time intervals considering real-time environment. Irradiance plot with respect to time shown in fig 7. The simulated results of the system at different irradiance at PV-STATCOM bus and grid bus are shown in fig 8, 9, and 10.

Table 2: Irradiance values at particular time interval

Time Interval (sec)	Irradiance (W/m^2)
0 to 1	600
1 to 2	1000
2 to 3	200

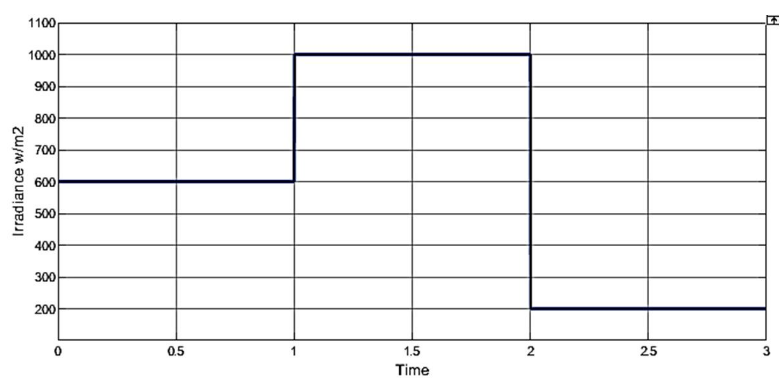

Fig 7: Irradiance plot with respect to time

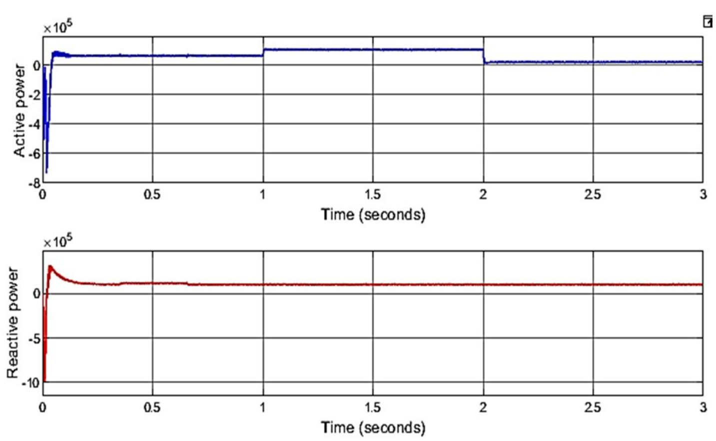

Fig 8: Active power & Reactive power of PV-STATCOM

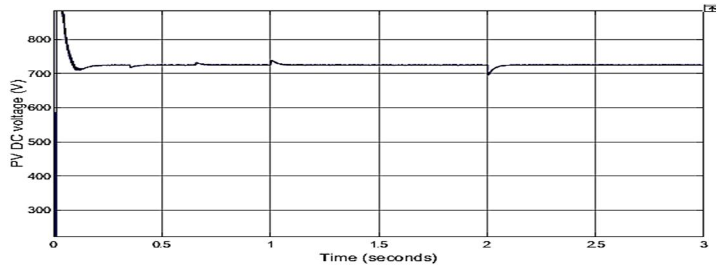

Fig 9: PV DC voltage with respect to time

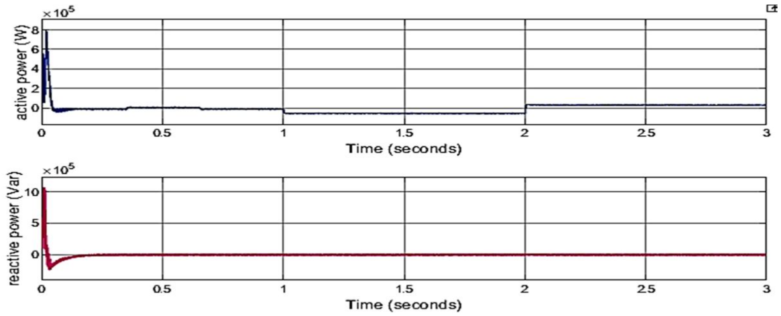

Fig 10: Active power and Reactive power of grid

At different irradiance values, active power and reactive power at PV-STATCOM bus and at grid bus are tabulated in table 3.

Table 3: Simulated Results at different Irradiances

Irradiance (W/m^2)	Time interval (sec)	At PV-STATCOM bus Active power (kW)	Reactive Power (kVar)	PV DC Voltage (V)	At Grid bus Active power (kW)	Reactive power (kVar)
600	0 to 1	52.45	109.2	730.7	-4.59	-10.49
1000	1 to 2	104.3	100.1	724.9	-56.09	-6.018
200	2 to 3	20.82	99.96	724.2	28.95	-5.801

1) At an irradiance of $600W/m^2$ in between the time interval from 0sec to 1sec considering as late mornings interval in real time environment, it operates in a partial PV-STATCOM mode and its active power at PV-STATCOM bus is 52.45 kW, which has optimally reached the maximum power point at its 88% tracking efficiency and also satisfied continuous reactive power requirements at load bus of 100kVAr thus, by aiding grid under very low power factor loads.
2) At an irradiance of $1000W/m^2$ in between the time interval from 1sec to 2sec considering as mid-afternoon interval in real time environment, it operates in a full PV mode and its active power at PV-STATCOM bus is 104.3 kW, which has optimally reached the maximum power point at its 98.4% tracking efficiency and minimum of 5% reactive power exchange (-6.018kVar) takes place with the grid. The active power of grid (-56.09 kW) is negative due to the power flow from grid to generator to keep it spinning. The small amount of DC power from solar panels of PV array is utilized for the capacitor to be charged at 724.9V and rest is injected into grid.
3) At an irradiance of $200W/m^2$ in between the time interval from 2sec to 3sec considering as early mornings and late evenings in a real time environment, it operates in a partial PV-STATCOM mode and its active power at PV-STATCOM bus is 20.82 kW, which has optimally reached the maximum power point at its 98% tracking efficiency. In this mode of operation inverter absorbs small real power from the grid and capacitor is charged to 724.2V through diodes of an inverter for an uninterrupted power supply. The reactive power which is supplied by PV-STATCOM system is well stored in capacitor bank and meets the load requirements. Due to some over compensation it is giving more than expected reactive power in which the remaining part is imported to grid (-5.801kVAr).

The THD analysis of Load current is done for this system and for the selected signal at fundamental frequency, the THD value is 3.73% which is improved as shown in fig 11.

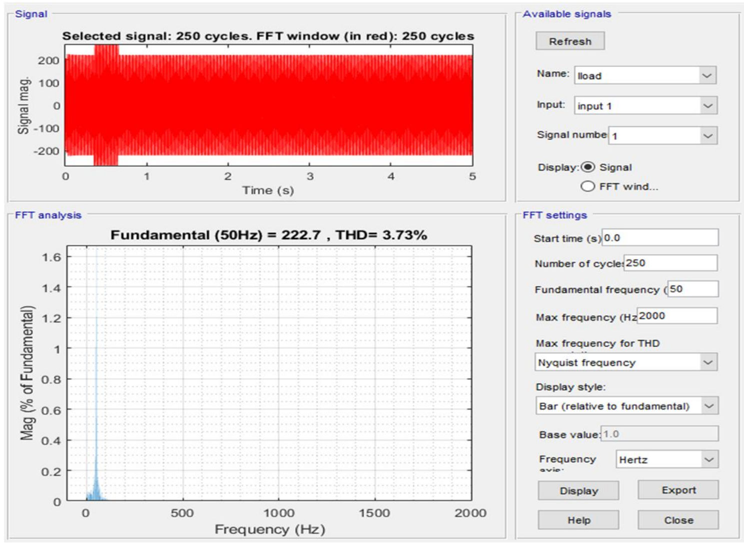

Fig 11: THD analysis of Load current

VI. CONCLUSION

An effective "PV-STATCOM" topology is used in this paper, which incorporates PV array linked to a single stage grid connected inverter that can also be used as STATCOM in the course of low irradiance. This "PV-STATCOM" model also incorporated with the features like DC link voltage control, improved transient response and a counteractive control strategy in advent of power quality issues. A mathematical study of the DQ0 control mechanism is performed in combination with P&O algorithm, to extract maximum power from the photovoltaic array and the current reference vectors are taken from the load center to provide constant reactive power support and to attenuate harmonics. The attained results in MATLAB/Simulink shows that the photovoltaic system with DSTATCOM can generate different active powers at different solar irradiances, carrying out reactive power compensation, maintaining the stable grid connection voltage and lowering the Total Harmonic Distortion (THD) of power current.

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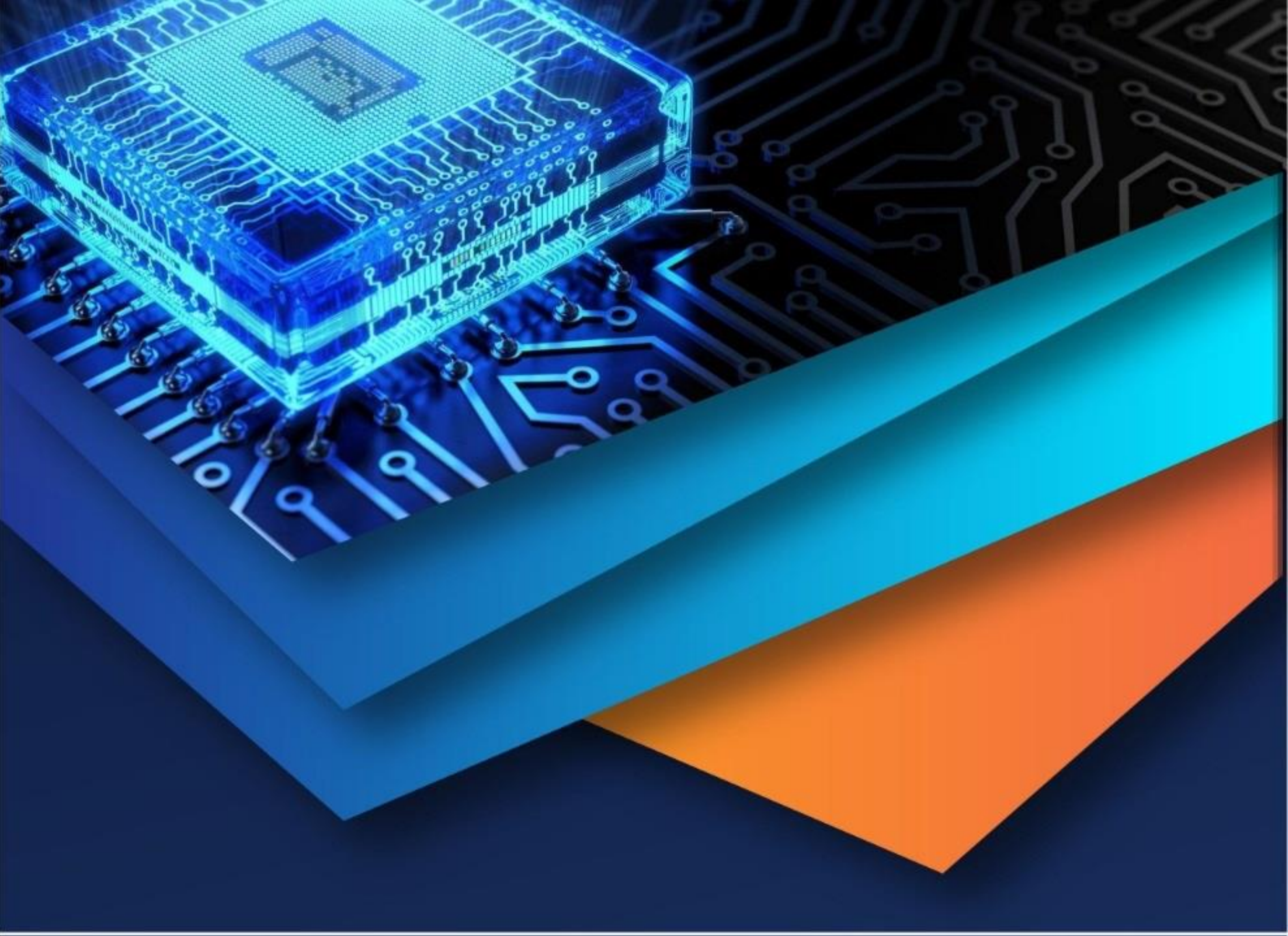

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