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Modeling and Simulation of Grid-connected PV System Using Harmonic-Reduction Techniques

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Abstract—*The PV system produces electric power without hampering the environment by directly converting the solar radiation into electric power. However, the solar radiation never remains constant. It keeps on varying throughout the day. The need of the hour is to deliver a constant voltage and frequency to the grid irrespective of the variation in temperatures and solar isolation. The user wants to operate the photovoltaic (PV) array at its highest energy conversion output by continuously utilizing the maximum available solar power of the array. This paper gives report on the role of smart grids in addressing the problems associated with the efficient and reliable delivery and use of electricity with the integration of renewable sources. Different power quality issues are addressed and a device STATIC COMPENSATOR (STATCOM) is connected at PCC to reduce the power quality problems like harmonics and power factor correction in the grid current by injecting superior reactive power into the grid and also an active power filter implemented with a four-leg voltage-source inverter using DQ (Synchronous Reference Frame) based Current Reference Generator scheme is presented for renewable based distributed generation system of PV cell. This paper presents modeling and simulation of the grid-connected PV generation system on MATLAB/Simulink. In this paper, different cases are simulated and the results have verified the validity of models and control schemes.*

Keywords*: Photovoltaic array, Modeling, Grid-connected photovoltaic system, MPPT control, Power inverter.*

1. INTRODUCTION

The trend of reducing cost of PV modules and the good support of government in enhancing the technology have increased the use of PV and solar thermal energy as important factors in the present and future renewable energy's growth scenario, Grid-connected solar PV systems can provide some relief towards future energy demands. Solar PV is the technology that offers a solution to a number of issues associated with fossil fuels. It is clean decentralized, indigenous and environmentally friendly. On top of that, India has among the highest solar irradiance in the world which makes solar PV more attractive for India. Renewable Energy integration is the one of the massive challenges in the present power scenario. However, looking to the future perspective, it is the ultimately need in power sector.

As the worlds electrical power demand increases, more environmental constraints are given to conventional energy sources such as fossil or nuclear energy. Declining of fossil fuel supplies, Environmental issues, increasing cost of fossil fuels, business opportunities, energy security, energy independence are the reasons for increasing renewable energy sources. A PV system converts the solar energy into electricity and feeds into the grid. A plant of 1 MW can displace 1500 tons of CO_2, 6.5 tons of SO_2 and 3.2 tons of NO_x. in one year. (A report, Washington July 2003). In PV generation PV cell converts solar energy into electrical energy. In grid-connected applications, the power is supplied directly to the grid Large scale power generations are connected to transmission systems where as small scale distributed power generation is connected to distribution systems.

2. POWER QUALITY ISSUES IN GRID CONNECTED PV SYSTEM:

There are certain challenges in the integration of wind and solar systems with grid directly. Grid Integration – Grid-tie Inverter is used. The use of Inverter is to take energy from grid when renewable energy is insufficient and supply energy when surplus power is generated. The block diagram for grid connected PV array is shown in Fig. 1. The main function of converter is to correct the magnitude and phase of the output of PV system by taking the feedback from utility grid.

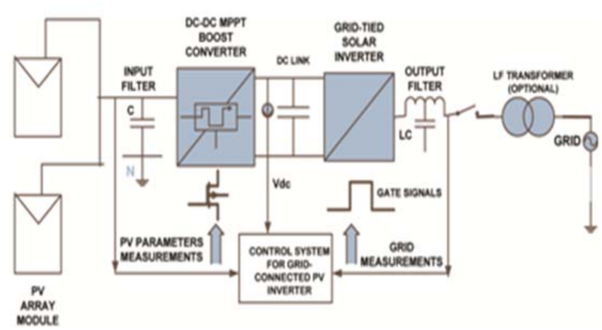


Fig. 1: Block Diagram for Grid connected PV Array.

There are several technical issues associated with grid connected PV systems like Power Quality Issues, Power and voltage fluctuations, Storage, Protection issues, Islanding.Power Quality issues are harmonics and voltage and frequency fluctuations.

2.1. Harmonics:

Harmonic currents generated by electronic equipment cause power system heating and add to consumer power bills. A common source of harmonic currents in power systems is electronic equipments and non linear loads connected with power system. Eliminating harmonic technique at their source provides most effective option. The rated KW capacity of PV plant increases about 1.3% due to additional harmonic generated losses The cost of these losses is compared to the cost of reducing harmonics in the equipment design. The boost-converter built- in circuit technology is the best and economical to be cost-effective option, yielding a 3-year pay back, based on energy savings alone.

2.2 Over/under voltage and over/under frequency:

The abnormal utility situations such as faults etc. result in frequency and/or voltage excursions at the point of common coupling (PCC). The PV grid integration standards define the permissible PCC voltage variation range and the permissible grid frequency variation range under which, the PV generation should continue to operate. The normal operation zone defined by the standard IEC61727 is shown in Fig.2.

The standard recommends that a PV generation should continue to operate normally if a PCC voltage variation is between -15% to +10% from the nominal value. Similarly, a PV plant should not be disconnected from a grid if a grid frequency variation is 2% from the nominal value. There should be a PV plant disconnection if either of these bands of the PCC voltage or the frequency is violated. The standard further also prescribes the time interval within which disconnection of the PV plant should occur if the grid frequency or the PCC voltage violation.

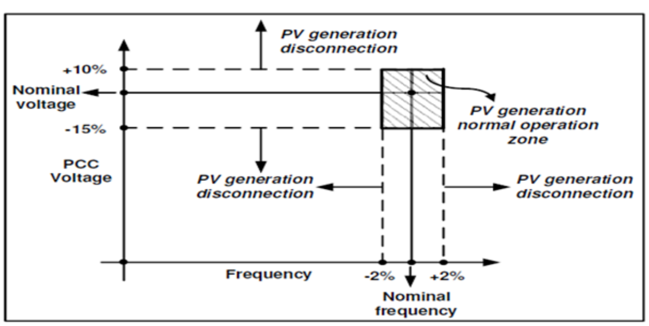


Fig. 2: IEC61727 : Permissible PCC voltage and frequency variation

The recommended time delay for the disconnection, if the frequency band is violated, is 0.2 sec. The recommended time interval for the disconnection if the voltage band is violated depends upon the magnitude of the PCC voltage. The recommended disconnection should occur within 2 sec if the PCC voltage magnitude is less than 85% of the nominal. The slandered IEC61727 is applicable to a PV generation getting integrated at the LV distribution system

- Inverters operating in voltage-regulating mode help boost network voltage by injecting reactive power during voltage sags, as well as reduce network voltage by drawing reactive power during voltage rise.
- Standards need to be developed to incorporate and allow inverters to provide reactive power where appropriate and other options to provide voltage regulation - such as SVCs (Static VAr Compensator) or STATCOMS (static synchronous compensators).
- Due to increase in voltage, power flow can be reversed that affects the network and other plants connected with the network.

2.3 Power Factor Correction:

Indian grid prescribes 0.95 lag/lead Power factor range for PV plants having apparent power between 3 KVA to 6 KVA and above 0.9 lead/leg is recommended. Most of the standard expect a reactive power support through following different ways [12], [13].

1. constant power factor (p.f)

2. Constant reactive power (Q)

3 Variable reactive power as voltage varies [Q(U)]

Poor power factor on the grid increases line losses and makes voltage regulation more difficult. Inverters in voltage-regulating mode provide current that is out of phase with the grid voltage. A number of factors are to be taken into consideration when using inverters to provide power factor correction.

- To provide reactive power injection while supplying maximum active power, the inverter size must be increased.
- The provision of reactive power support comes at an energy cost, Simple reactive power support can be provided cost-effectively by SVCs or STATCOMS [1,2], which have lower energy losses,
- Reactive power compensation is effective for voltage control, Var-compensation is less effective for voltage control.

3. GRID CONNECTED PV GENERATION SYSTEM:

Fig. 3.shows the configuration of the grid-connected PV /Battery generation system. PV array and battery are connected to the common dc bus via a DC/DC converter respectively, and then interconnected to the ac grid via a common DC/AC inverter. Battery energy storage can charge and discharge to help balance the power between PV generation and loads demand.

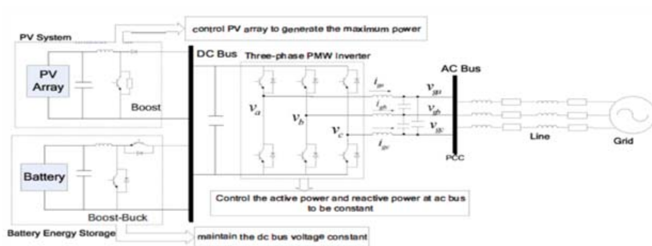


Fig. 3: Block diagram for Grid connected PV system.

3.1. Incremental Conductance Algorithm:

Different kinds of MPPT algorithms have been developed and put into application. The most popular ones are: constant voltage tracking (CVT), perturbation and observation method (P&O), incremental conductance method (IncCond). The IncCond shows some advantages over others, like high tracking accuracy and no oscillation around MPP. The flowchart of IncCond is depicted in Fig. 5.

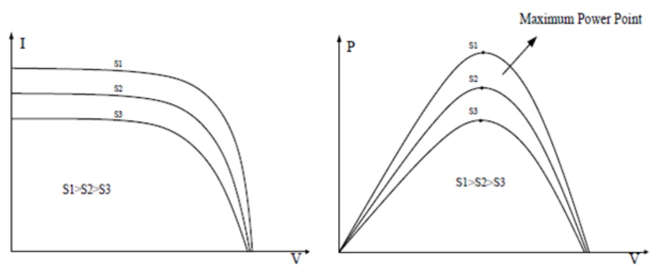


Fig. 4: I-V and P-V characteristics of PV arrays under different solar irradiation

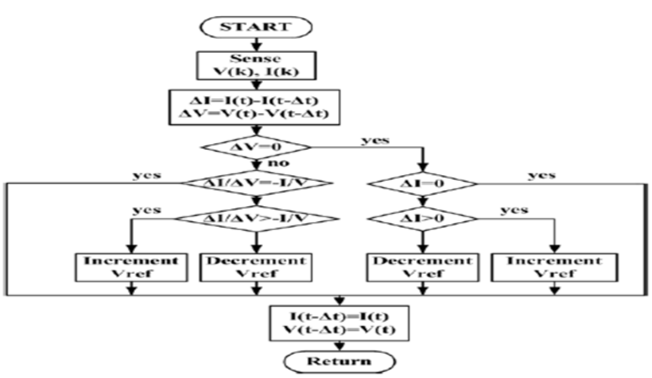


Fig. 5: Incremental Conductance algorithm

As shown in fig 5, the flow chart above, the MPP can be tracked by comparing the instantaneous conductance (I/V) to the incremental conductance (ΔI/ΔV). Vref is the reference voltage and equals to VMPP at MPP. Once the MPP is reached, the operation of the PV array is maintained at this point unless there is change in ΔI, which indicates a change in solar irradiation or weather condition. The algorithm decreases or increases Vref to track the new MPP [5].

3.2 Boost circuit and its control

In two-stage PV generation system, boost chopper circuit is always used as the DC/DC converter. The DC-DC converter rises the low solar voltage to a suitable level corresponding to the optimal PV power. A capacitor is generally connected between PV array and the boost circuit, which is used to reduce high frequency harmonics. The duty cycle of the boost converter is determined by MPPT control system When the IGBT is closed, the inductance voltage and capacitor voltage meet the following relationship:

$$\begin{cases} L_{pv}\dfrac{dI_{pv}}{dt} = V_{pv} = v_{L(on)} \\ C_{dc}\dfrac{dV_{dc}}{dt} = I_{dc} = i_{C(on)} \end{cases} \qquad (1)$$

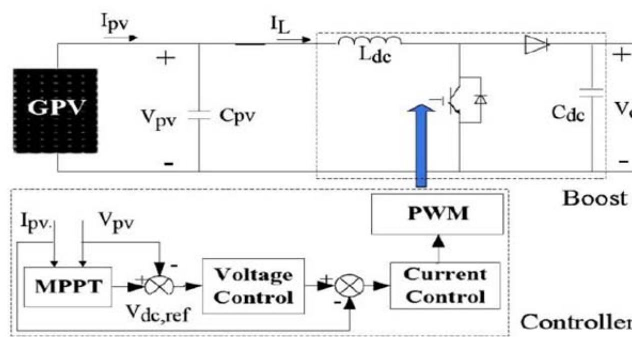
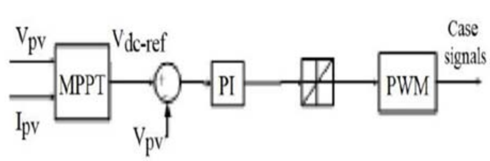


Fig. 6: Boost circuit and its control

Similarly, when the IGBT is open, the equations of inductance voltage and capacitor voltage are described as:

$$\begin{cases} L_{pv}\dfrac{dI_{pv}}{dt} = V_{pv} - V_{dc} = v_{L(off)} \\ C_{dc}\dfrac{dV_{dc}}{dt} = I_{dc} - I_{pv} = i_{C(off)} \end{cases} \qquad (2)$$

The maximum power point by regulating the duty cycle is used to control the boost converter as shown in Fig. 7 (a)



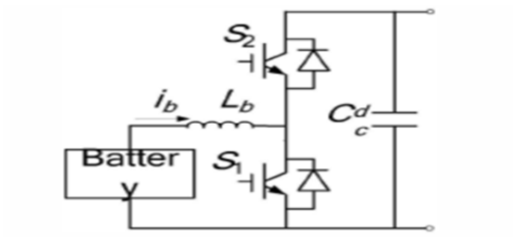


Fig. 7: (a) Control structures of boost converter (b) Battery energy storage system *PV array.*

Fig.7(b) shows the Battery energy storage system (BESS). The BESS is composed of a battery bank, a bi-directional DC/DC converter and control system [10]. The system should be able to operating in two directions: the battery can be charged to store the extra energy and also can discharge the energy to loads[4]. The grid is considered as a backup source and the battery bank serves as a short-duration power source to meet the load demands which cannot be fully met by the PV system, during fluctuations or transient periods.

The objective of the battery converter is to maintain the common dc link voltage constant. In this way, no matter the battery is charging or discharging, the voltage of the dc bus can be stable and thus the ripple in the capacitor voltage is much less. When charging, switch Sf is activated and the converter works as a boost circuit. otherwise. When discharging, switch S2 is activated and the converter works as a buck circuit.

3.3 Shunt Power Filter:

The APF can compensate harmonics and reactive power requirement of the nonlinear load effectively. Presently, APFs are designed to absorb all of the harmonics generated and/or reactive power required by the load and make source current sinusoidal. By using APF the reactive power is completely compensated, and unity power factor operation can be achieved.

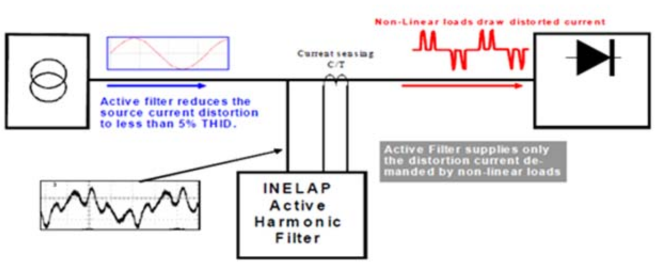


Fig. 8: Typical connection and performance of active filters.

The latest technology available for mitigation of harmonics is the active filter. Typically, active filters will monitor the load currents, filter out the fundamental frequency currents, analyze the frequency and magnitude content of the remainder, and then inject the appropriate inverse currents to cancel the individual harmonics. Active filters will normally cancel harmonics up to about the 50th harmonic and can achieve harmonic distortion levels as low as 5% THD-I or less

3.4. Advances in PV Inverter :

The idleness of solar farm in night leads poor asset management. In [6] a new approach on power inverter as PV-STATCOM, which uses solar farm at night time for the regulation of voltage variations at the point of common coupling. STATCOM control functionality is implemented in PV inverter during night time for enhancing the transient stability of the system. It is also noted that the recent grid code recommend the solar PV farm to help the voltage regulation of grids by supplying / absorbing appropriate reactive power. This operation makes revenues to the investors. However, this is achieved by appropriate agreements between regulators, changes in grid code and inverter manufacturers.

4. CONTROL OF GRID-CONNECTED INVERTER:

Fig 9 Shows the proposed control block diagram for the inverter. The inverter is used in current control method with PWM switching mechanism to make the inductance current track the sinusoidal reference current command closely and to obtain a low THD injected current. The control strategy mainly consists of two cascaded loops, namely a fast internal current loop and an external voltage loop. The proposed control scheme is based on the concept of instantaneous power on the synchronous-rotating dq reference frame.

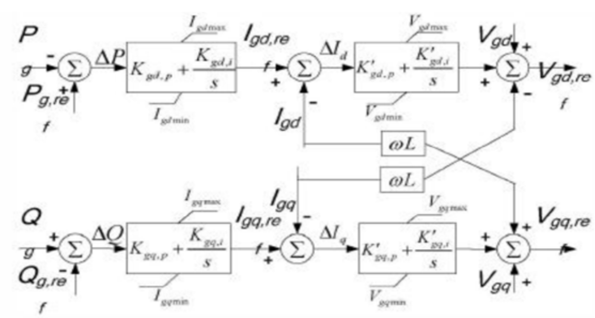


Fig. 9: Multi Level Control circuit block diagram of PV connected Inverter.

4.1 Control Strategy of Grid-Connected Inverter:

The control strategy of the DC/AC converter is designed to supply current into the utility by regulating the bus voltage to 400V. The power flow control to the grid, is based on the control of active and reactive power. The primary objective of the active and reactive power is to control the power factor/voltage at PCC. Active and reactive power from the grid-side inverter can be given by:

$$\begin{cases} P_g = v_{ga} \times i_{ga} + v_{gb} \times i_{gb} + v_{gc} \times i_{gc} \\ Q_g = \frac{1}{\sqrt{3}} \times \left(v_{gab} \times i_{gc} + v_{gbc} \times i_{ga} + v_{gca} \times i_{gb} \right) \end{cases} \quad (3)$$

Where, Pg is active power and Qg is reactive power and Vga, Vgb, Vgc are three-phase voltages at the AC bus bar and iga , igb , igc are three-phase currents injected into the grid.

Applying Park transformation, Eq. (3}, in reference frame can be written as:

$$\begin{cases} P_g = 1.5 \times \left(v_{gd} \times i_{gd} + v_{gq} \times i_{gq} \right) \\ Q_g = 1.5 \times \left(v_{gq} \times i_{gd} - v_{gd} \times i_{gq} \right) \end{cases} \quad (4)$$

Where, vgd , vgq, represent the d,q components of the voltage at PCC. and igd , igq represent d,q components of the line current. In the reference frame synchronized with the grid voltage, PLL always set vgq components to zero and vgd = vg that satisfy

$$\begin{cases} P_g = 1.5 \times v_{gd} \times i_{gd} \\ Q_g = -1.5 \times v_{gd} \times i_{gq} \end{cases} \quad (5)$$

The active power at the PCC can be controlled by controlling *Igd* and the reactive power can be controlled by controlling *Igq*. The active power reference value is set by the DC link voltage control. The errors in the direct and quadrature currents are processed by the compensator. The compensator calculates the VSC duty ratios required to track the reference values. The inverter uses hysteresis switching and controls active power by manipulation of direct-axis current while holding reactive power at 0 VAr.

$$\begin{cases} i_{gd,ref} = \left(K_{gd,p} + \frac{K_{gd,i}}{S} \right) \times \left(V_{dc,ref} - V_{dc} \right) \\ i_{gq,ef} = -\left(K_{gq,p} + \frac{K_{gq,i}}{S} \right) \times \left(Q_{dc,ref} - Q_g \right) \end{cases} \quad (6)$$

The electrical model presented by three-phase voltages at the AC side of the inverter at Fig. 1, is given by:

$$\begin{cases} i_{gd,ref} = \left(K_{gd,p} + \frac{K_{gd,i}}{S} \right) \times \left(V_{dc,ref} - V_{dc} \right) \\ i_{gq,ef} = -\left(K_{gq,p} + \frac{K_{gq,i}}{S} \right) \times \left(Q_{dc,ref} - Q_g \right) \end{cases} \quad (7)$$

Where, va , vb , vc are three-phase voltages at the AC side of the inverter, Lf , Rf are the filter inductance and resistance. Applying Park transformation, {Eq. (11)} represents the electrical model of the grid side inverter in the d,q referential axis. It is given by:

$$\begin{cases} v_{gd} = v_d - \left(L_f \times \frac{di_d}{dt} + R_f \times i_d \right) + \omega \times L_f \times i_q \\ v_{gq} = v_q - \left(L_f \times \frac{di_q}{dt} + R_f \times i_q \right) - \omega \times L_f \times i_d \end{cases} \quad (8)$$

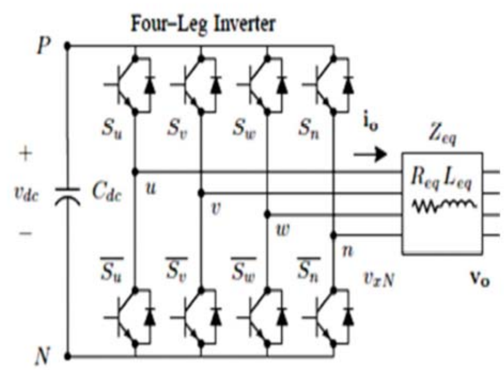
Where, ω , is the grid frequency.

The current controller still uses PI regulator, described by:

$$\begin{cases} v_{gd,ref} = v_d + \left(K'_{gd,p} + \frac{K'_{gd,i}}{S} \right) \times \left(i_{d,ref} - i_d \right) - \omega \times L \times i_q \\ v_{gq,ref} = v_q + \left(K'_{gq,p} + \frac{K'_{gq,i}}{S} \right) \times \left(i_{q,ref} - i_q \right) - \omega \times L \times i_d \end{cases} \quad (9)$$

4.2. Control circuit for the four leg VSI:

A dq-based current reference generator scheme is used to obtain the active power filter current reference signals. Four leg VSI Schematic Diagram is shown in Fig.10. The current reference signals are obtained from the corresponding load currents as shown in Fig11. The dq-based scheme operated in a rotating reference frame. Therefore, the measured currents must be multiplied by the sin ωt and cosωt signals. By using *dq* transformation, the *d* current component is synchronized with the corresponding phase-to-neutral system voltage and the *q* current components are phase-shifted by 90°. The sinωt and cosωt synchronized reference signals are obtained from a Synchronous Reference Frame (SRF) PLL. The SRF-PLL generates a pure sinusoidal waveform even when the system voltage is severely distorted.



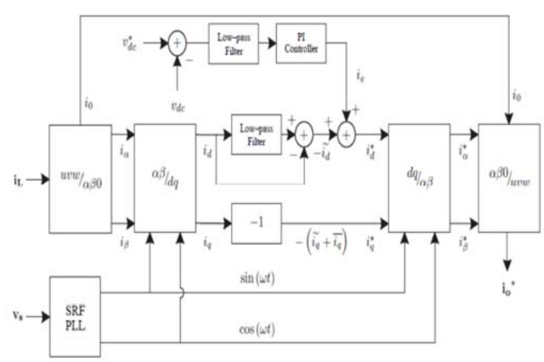


Fig. 10 Four leg VSI Schematic Diagram Fig. 11. Block Diagram for control circuit of four Leg based VSI.

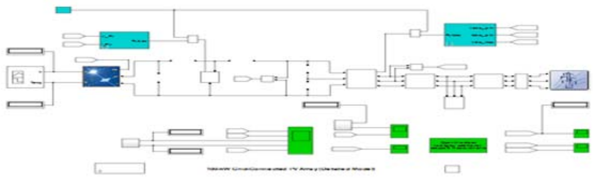


Fig. 12: Control scheme of the grid-side inverter in Simpower - systems

5. SIMULATION RESULTS AND DISCUSSION :

The objective is to verify the effectiveness of current harmonic compensation of the proposed control scheme under different operating conditions**:** A six pulse rectifier was used as a non-linear load

Matlab/Simulink simulation of the grid connected PV System:

Active and reactive control of the grid-side inverter has been carried out with the following parameters as,.

The PV System is composed of 15 series and 2 parallel Sun Power SPR 305E-WHT-D modules. Each module is composed of 58 series cell, presents the following characteristics:

- Nominal peak power: 200 W, Nominal voltage: 26,3 V,
- Short-circuit current: 8.12 A , Open-circuit voltage: 31.8 V,
- Maximum current: 7.52 A , The grid voltage: 400/50 Hz ,
  - Fig. 13 shows simulation results of characteristic of the PV generator in irradiation at 1000 W/m2 and temperature of 25°C with MPPT control systems. The active power and reactive powers at AC bus are considered to be constants in three phase PWM inverter control. The input power rapidly and accurately reaches the maximum power corresponding to, after 0.2 s. It shows the importance of the MPPT algorithm performance in resolution of the issues of the degradation of the climatic factors.
  - Fig. 14 shows simulation results of active and reactive powers at the AC bus for compare with the reference values by inverter DC-AC. The maximum output power of PV system is 6000 W. Set the power demands to be 1800W at the Є [0, 4.2 sec] after 4.2 sec it is equal to 6000 W. This variation of the active power demands are controlled by the PI regulator with reactive power reference equal to zero. The simulation results present the performance of the control systems.

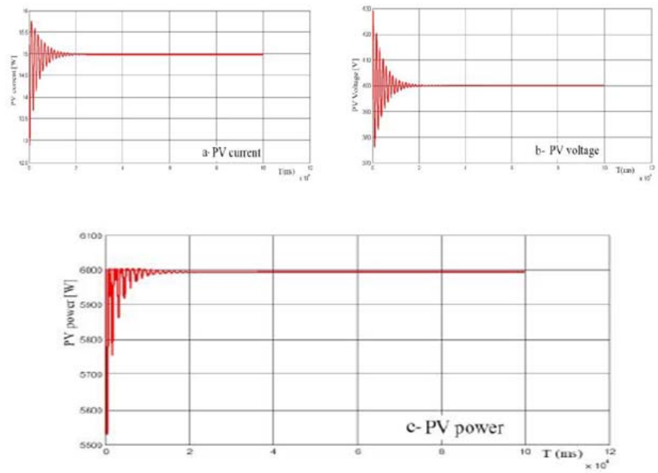


Fig. 13: characteristics of the PV System at irradiation 1000 W/m2 and temperature 25℃

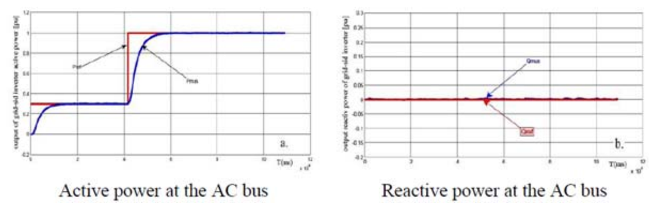


Fig. 14: Active power and reactive power at the AC bus

- Fig. 15 shows the current injected into the main utility and the grid side voltage. As it can be noted, the voltage and current are in phase which means that the MP extracted from the PV array can pass into the DC-AC grid-side inverter as the whole system operates at unity power factor (Q=0) with no reactive power exchange.

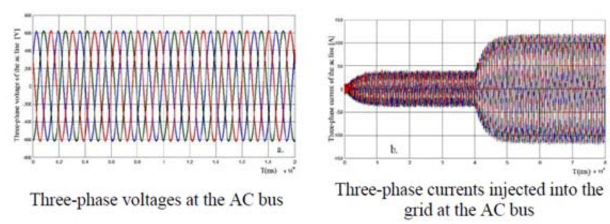


Fig. 15: (a) Grid side voltage (b) Injected current

- By applying the inverse Park transformation to d, q current vector components, the phase current references are obtained. These are passed to a PI controller, which outputs the pulses to drive the inverter switches. The output line voltage of the inverter is shown in Fig. 16.

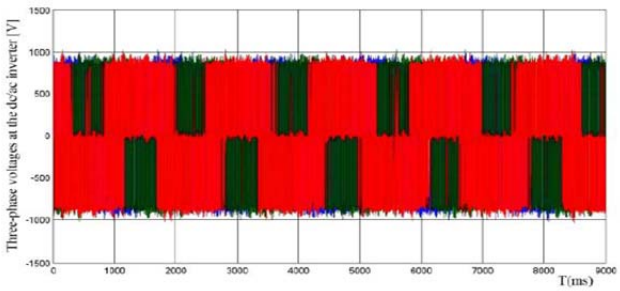


Fig. 16: Inverter line three-phase voltage

Simulation Results with active power filter:

A simulation model with three phase voltage of 55V, 50 Hz, dc capacitor of 2000µF and filter inductor of 6.0 mH with a sampling time of 20 micro seconds has been developed using MATLAB. In the simulated results as shown in Figures 13-19, the active filter starts to compensate at t =0.2. At this time, the active power filter injects an output current i to compensate harmonic currents During compensation, the system currents show sinusoidal waveform, with low THD. At t =0.4, a three-phase balanced load step change is generated from 0.6 to 1.0 p.u.

The compensated system currents remain sinusoidal despite the change in the magnitude of load current. Finally, at t=0.6, a single-phase load step change is introduced in phase from 1.0 to 1.3 p.u. which is equivalent to an 12% current imbalance. A neutral current flow through the neutral conductor, but on the source side, no neutral current is observed (isn). Simulated results show that the proposed control scheme effectively eliminates unbalanced currents. Additionally, results represents that the dc-voltage remains stable throughout the operation of active power filter.

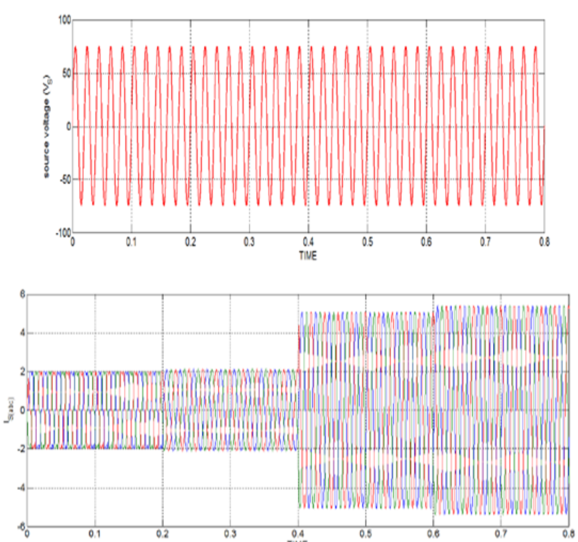


Fig. 13. Phase to neutral system voltages. Fig. 14 System Currents.

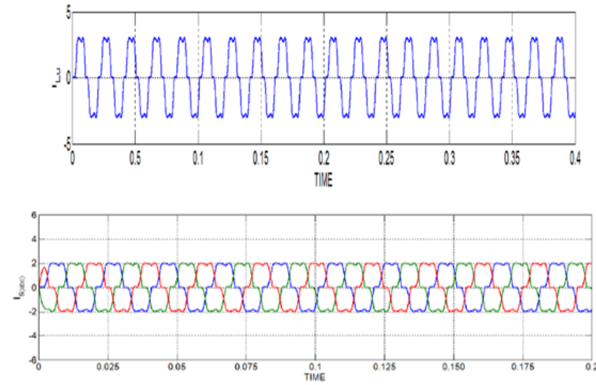


Fig.15 Load current at 0<t<0.4sec. Fig. 16. System current at 0<t<0.2 Sec

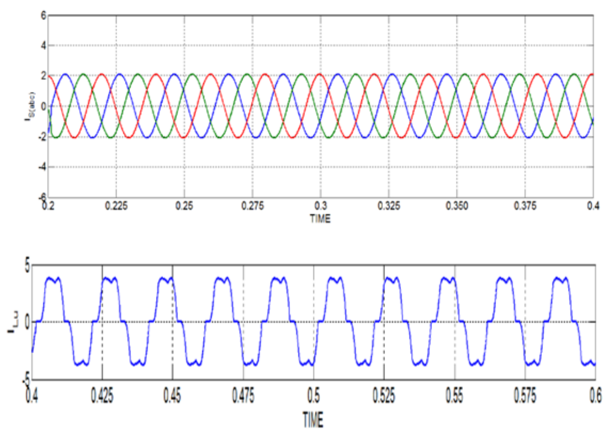


Fig. 17 System current at 0.2 <t<0.4sec. Fig. 18. Load current due to step change 0.4<*t<0.6 sec.*

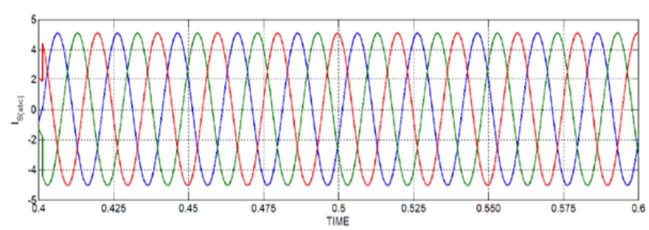


Fig. 19. Compensated load current 0.4<t<0.6 sec.

Simulation Results with STATCOM:

This reactive support is given by the STATCOM. STATCOM operates in two different modes. One is voltage regulation and the other is VAR control mode. In voltage regulation mode the STATCOM regulates the amount of reactive power that is absorbed from or injecting into the power system through VSC. When the system voltage is high the STATCOM will absorb the reactive power (inductive behavior). When the system voltage is low the STATCOM will generate and inject reactive power into the system.

A battery energy storage system with STATCOM is also connected at the PCC to control the distortions caused by the nonlinear load. The BESS is used as an energy storage element for the purpose of voltage regulation and to maintain dc capacitor voltage constant The BESS is best suited in STATCOM since it rapidly injects or absorbed reactive power to stabilize the grid system. The system is connected with grid having the nonlinear load. It is observed that due to the effects of nonlinear load , the purity of waveform is lost on both sides in the system. The three phase injected current into the grid from STATCOM will cancel out the distortion caused by the nonlinear load and system.

Fig. 20(a) shows the source current waveform of the test system without STATCOM and the Fig. 20 (b) shows the corresponding FFT analysis waveform. From FFT analysis, it is observed that the Total Harmonic Distortion (THD) of the source current waveform of the test system without STATCOM is 28.54%

Fundamental (50Hz) =73.28, THD=28.54 %

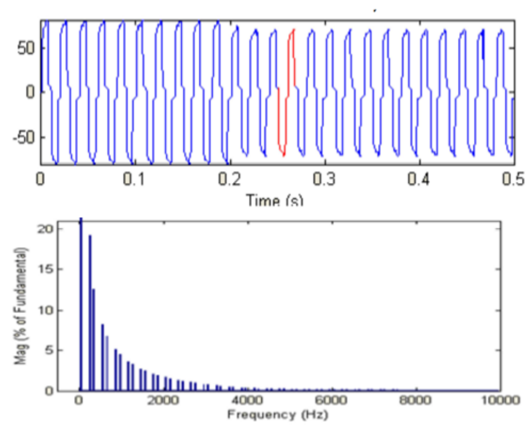


Fig. 20(a) Source current without STATCOM. Fig. 20(b). FFT analysis of source current for without STATCOM

Fundamental (50 Hz)=144.4, THD=0.25%

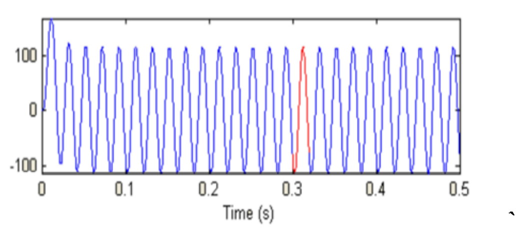


Fig. 21 (a). Source current wave form with STATCOM Compensation.

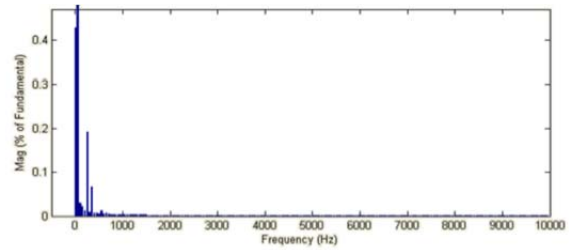


Fig. 21(b). THD for the source current wave form with STATCOM.

- Fig. 21(a) shows the source current waveform of the test system with Hybrid Fuzzy Logic Controller based STATCOM and the Fig.21(b) shows the corresponding FFT analysis waveform. From FFT analysis, it is observed that the THD of the source current waveform of the test system with Hybrid FLC based STATCOM is 0.25%. Thus, it is observed that there is a further reduction in the THD value of the source current waveform.

6. CONCLUSIONS

This paper presents a technique to design and control of grid-connected PV generation system, identify its components, and describe how it works. In order to convert the solar energy efficiently, the MPPT algorithm for photovoltaic systems based on Incremental Conductance algorithm has been presented. It should be tracked to ensure the PV array to generate maximum power to grid, and describe the following control algorithms used for the inverter DC-AC to regulate amount of active and reactive power that is absorbed into the system through VSC. All simulation results, obtained under Matlab/Simulink environment, show the control performance and dynamic behavior of grid connected PV system provides good results and show that the control system is robust and provides superior quality of power to grid.

This paper also presents a technical review of causes of Power quality issues associated with renewable based DG system Simulation study has done on PV based grid connected system with four leg VSI to enhance the power quality. It has been shown that the grid connected inverter can be effectively utilized for power conditioning without affecting its normal operating of real power transfer. A hybrid fuzzy logic controller based STATCOM is presented for grid. The proposed Hybrid FLC based STATCOM have improved the power quality of source current significantly by reducing the THD from 28..54% to 0.25%.

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