Modeling and implementation of Conventional Power Grid-Tied Solar Photovoltaic System using Constant Current Controller

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A B S T R A C T

Interconnection of dynamically variable renewable electricity sources like sun, tidal and geothermal, etc. interfacing with the conventional power grid needs awareness to make sure the electrical power system is consistent and reliable. Sun energy can be converted into electrical energy via photovoltaic cells. Running characteristics of such solar photovoltaic cells to be well known to the power system designers. This can be achieved with device modeling, simulation, and experimental studies. This paper develops a 1kW solar photovoltaic power plant which consists of a solar photovoltaic array, DC-DC step-up converter, 3-Φ Pulse Width Modulated Voltage Source Inverter (PWM-VSI) integrated with conventional power grid using Constant Current Controller (CCC). This proposed controller uses inverse Park's transformation, Park's transformation and Phase Locked Loop (PLL) to track the traditional power grid frequency and phase. The LC filter is used to remove the high-frequency harmonics from the output potential, it appears to be efficient in supplying to load with a consistent voltage without phase disturbances. The entire mathematical version of the conventional power grid-tied solar system is designed and simulated using MATLAB Simulink. Experimentally, CCC is developed using ATmega2560 microcontroller-based control system that provides the control to tune the MPP (Maximum Power Point) from a solar photovoltaic array using modified P&O method, DC bus voltage regulation, control of 3-ϕ PWM-VSI and system synchronization is also applied. The proposed controller can be validated through simulation and experimental outcomes with improved power quality features in conventional power grid-tied PV systems.

Keywords- Constant Current Controller (CCC), Phase Locked Loop (PLL), Conventional power grid, LC filter, Proportional-integral, 3-Φ PWM-VSI.

1. Introduction

As the world, electrical energy consumption swiftly increases with the growth in population new power era capacities are required to cover that demand. In a recent study, the total electricity generation of the world is anticipated to increase from 18 trillion kWh in 2009 to 29 trillion kWh in 2022 and 37 trillion kWh in 2040 [2-3]. Electrical power generation relies on multiple fuel sources coal, oil, and gas to cover electricity needs. Coal is the most used fuel because plenty of coal is available at a low cost. A major disadvantage of fossil fuels is the production of a large amount of CO_2 emissions, which causes harmful effects on the environment. Renewable electrical sources are the fastest-growing source of electrical power generation with a growth rate of 4%. The main driven renewable electrical sources are hydro, wind energy & sun energy [15]. In a major renewable power generation, almost 85% proportion is dominated by hydro & wind power, while solar and geothermal power generation is contributed by using 2% each. Among all the renewable electricity sources, solar energy is a prime renewable source of energy as it's far considerable in nature and its conversion to electrical power via photovoltaic (PV) process is pollution-free.

Solar PV array is interconnection of PV modules; each PV module is made of interconnected solar cells. Solar PV arrays can be operated in two modes of operation "islanding connected mode" and "conventional power network associated approach". In islanding connected mode of operation, solar PV array output is directly connected to the Load [4-7]. In real time applications of solar photovoltaic array integrated with the grid, single-stage and two-stage adoption arrangements can be used. In single stage conversion system, multilevel inverters are used to convert variable DC voltage into AC voltage [1]. In this proposed work two-stage conversion system is used. One power electronic converter is used to convert variable DC to fixed DC Voltage and another power electronic converter is used to invert fixed DC to AC voltage. Two stage or multiple stage conversion system distributes the control into two separate responsibilities to achieve greater effective energy harvesting [8].

The principle attention in this paper is to incorporate the conventional power grid with a solar photovoltaic array using different controllers. Since solar is a nonlinear source there is a need for power electronic converters to be interfaced between the solar source and load/conventional power grid. The modest form of a conventional power grid-tied solar system consists of a single-stage conversion which includes a solar photovoltaic array & 3-Φ PWM-VSI. In this PV array, the output voltage must be more than the conventional power grid peak voltage. To conquer this limitation in this paper two-stage energy conversion is proposed which consists of a solar array, DC-DC step-up converter, and 3-Φ PWM-VSI integrated with a conventional power grid using Constant Current Controller (CCC) [13]. Solar PV array output relies upon solar irradiation & temperature of the solar array. The maximum power output from the solar photovoltaic array can be achieved through the MPPT algorithm under varying load conditions [16-17]. One of the usual algorithms recycled to path away the maximum energy from a solar photovoltaic array is the modified P&O method [2]. To track the maximum energy point from solar array different conventional strategies are available.

Those are 1) P&O technique 2) INC technique (Incremental conductance) 3) FSCC (Fractional Short circuit current) Technique 4) FOCV (Fractional Open circuit Voltage) Technique 5) modified P&O Technique.

P&O Technique is simple, economical and can be easily developed with Analog & Digital elements in both islanding and conventional solar grid connected systems. But in this strategy, MEP (Maximum Energy point) fluctuates around the operating point continuously even though temperature and radiation are constant. This technique will not be able to track MEP under the fast change in atmospheric conditions.

INC technique can track the MEP under the fast change in environmental conditions as well as it provides better accuracy in comparison with P&O technique. The main disadvantages of this technique are tedious, complex and not economical.

FSCC technique works on the principle of relation between short circuit current (I_{sc}) and current corresponds to MEP. This technique is very simple, lower in cost and provides medium convergence speed under transient environmental conditions. But the efficiency of FSCC is very low as compared with P&O, INC techniques.

FOCV MPPT method works on the principle of voltage at MEP (V_{MEP}) is directly proportional to Open Circuit Voltage (V_{OC}). Measurement of Open circuit Voltage is difficult in this technique. Both FSCC, FOCV strategies don't provide true MPP values.

Amongst all the above mentioned strategies conventional P&O is commonly used strategy, because of its simplicity and accuracy under steady-state conditions. But this strategy doesn't provide exact value of MEP under transient conditions. To overcome the disadvantages of conventional P&O, modified P&O or variable step-size P&O is proposed in this work. In modified P&O, initially larger step-size is provided to improve the tracking convergence speed and step-size is gradually decreased to reduce the fluctuations around MEP.

Different current controller strategies are available in the integration of solar PV array with conventional power grid. Mainly current controller strategies can be classified as linear & Nonlinear methods. Linear current control techniques are PI (Proportional Integral), PR controller (Proportional Resonant) and RC controller (Repetitive controller). Nonlinear control strategies are Predictive controller, Dead-beat, Hysteresis controller, PSO, GA & Constant Current Controller (CCC).

Mathematical modelling of PV array can be done using single diode model and two diode models. Both the models have the same ability to extract the unknown parameters. But single diode model is simple, accurate and requires less computation time. Hence mathematical modelling of single diode model of PV array is proposed in this work.

In this proposed work, a DC-DC step-up converter is used to enhance the solar array voltage to 600V irrespective of sun irradiation & temperature. This paper proposes modelling, layout, and hardware implementation of the conventional power grid-tied solar photovoltaic system using CCC, which controls the 3-Φ 2 level PWM-VSI for interfacing the conventional power grid [17-18]. DC voltage generated via the solar photovoltaic array is increased with the usage of a DC-DC step-up converter and then given as input to the 3-Φ 2 level PWM-VSI. Control of the 3-Φ 2 level PWM-VSI is provided through the CCC. This controller uses the Phase Locked Loop (PLL), to follow the phase angle and conventional power grid voltage. This controller also uses a proportional-integral controller, the proportional & integral gains are selected such that CCC generates pulses for PWM-VSI according to the requirements of conventional power grid potential & phase. The proposed model is capable of delivering energy to local linear & nonlinear loads [11-14]. Advantages of CCC are

- This CCC uses PLL (phase locked loop) to track the voltage magnitude and phase angle of the three phase conventional power grid.
- CCC in combination with LC filter eliminates all higher order harmonic components of inverter output voltages.

But CCC without LC filter is less efficient, produces lower power factor and higher value of THD of inverter output voltages

Objectives of the proposed work are

- Mathematical modelling of single diode model of PV array/.
- Design and implementation of modified P&O method to track the MEP of PV array.
- Modelling, design & hardware implementation of three phase conventional grid connected PV system with proposed CCC .

Section 2 explains the proposed system description, section 3 describes complete mathematical version of a photovoltaic array, section 4 explains DC-DC step-up converter operation and its control, section 5 gives the simulation and experimental results of conventional power grid-tied solar photovoltaic system using CCC, section 6 gives the conclusion of proposed work.

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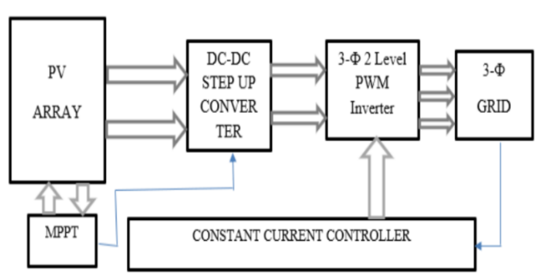

Fig 1. Block diagram of 3-Φ conventional power grid-tied solar system

2. Proposed system description

Configuration of 3-Φ conventional power grid-tied solar photovoltaic system using CCC is shown in fig 1. A solar photovoltaic array is a combination of the series and parallel connected photovoltaic modules. Each solar photovoltaic module accommodates a series combination of solar photovoltaic cells as per the requirements of voltage & the parallel combination of solar photovoltaic cells according to the requirements of current. The output power generated by photovoltaic array depends on many factors such as solar irradiation, temperature, the air mass coefficient, and cloudy weather etc. Photovoltaic array output power has non-linear operating characteristics with single maximum power point. There are many techniques to extract the maximum power point from solar photovoltaic array. The Perturb & Observe algorithm is commonly used method to extract the maximum power point from solar photovoltaic array. This algorithm has major drawback that maximum power point oscillates under steady state conditions. To avoid this disadvantage modified Perturb & Observe technique is proposed to tune the MPP from solar photovoltaic cells. Modified P&O method perturbs the duty cycle, which controls the DC-DC step-up converter, in this way it causes steps over the p-v characteristic to find the maximum energy point of a solar array. This perturbation causes a new operating point with exceptional output power, in case this output power is greater than the previous output power, this point is set as the new operating point. In case it is lower, the same power point is adjusted to a lower or higher working voltage, relying on the preceding step direction. This type of arrangement controls the duty ratio of a DC-DC step-up converter. The 3-Φ 2 level PWM-VSI inverts the available 600 V DC voltage into 3-Φ 400 V, 50Hz AC. A CCC is provided to produce gate pulses to 3-Φ PWM-VSI by providing a PLL to track the conventional power grid voltage and phase angle under varying load conditions. If there are disturbances in the conventional power grid potential and phase angle, this CCC can track the disturbed phase, voltages and controls the solar DC-AC Converter to give the same voltage as conventional power grid voltage. The harmonics generated by the inverter can be reduced further using a 3-phase LC filter.

3. Complete mathematical version of solar photovoltaic array

Photovoltaic cells are the medium to convert available solar power to electricity. Crystalline silicon (c-Si) is a semiconducting material used in photovoltaic technology for the production of solar cells. A usual silicon solar crystalline cell generates typically 0.5 V. The output current varies depending on the size of the cell.

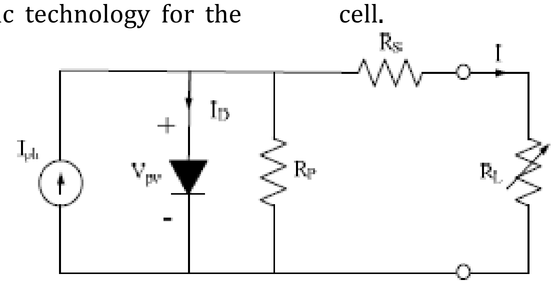

Fig 2. Equivalent circuit of a solar photovoltaic cell

In general, the commercially available silicon cell produces a current between 28 mA/cm^2 to 35 mA/cm^2. When cells are connected in series & parallel, then current and voltage ratings can be increased. This group of cells is known as a PV array. Fig 2. Shows the single diode model of a solar photovoltaic cell.

$$I= N_P I_{ph} - N_P I_D[\exp (\frac{q}{KT_A} - \frac{V_{pv}}{N_s})\text{-}1] \qquad (1)$$

Where
I_{ph} is the current generated by the solar irradiation
N_p -Number of PV modules connected in parallel
N_s -Number of PV modules connected in series
R_p-Shunt resistance
Rs-Series resistance
The current generated by a solar cell depends upon the level of solar irradiation and temperature

$$I_{ph=}[I_{scr} + K_i(T - T_r)\frac{S}{100}] \quad (2)$$

The power generated by solar photovoltaic array can be calculated
using the eq (3).

$$P=IV=N_P I_{ph}[\left(\frac{q}{KA_T} * \frac{V}{N_S}\right) - 1] \quad (3)$$

Solar irradiation and temperature perform a significant role to predict the functioning of a solar photovoltaic array. Solar irradiation affects the amount of current produced by PV Cell and temperature results in the terminal voltage.

Table 1. Technical specifications of IP65 100W photovoltaic module

Type of Module	100W
Maximum power	100W
Tolerance	±3%
Open circuit voltage	22V
Short circuit current	6.06A
Maximum power voltage	18V
Module efficiency	14.9%
Solar cell efficiency	17.2%
Series fuse rating	15A
Dimensions	1005mm×670mm×30mm

4. DC-DC step-up converter operation and its control

The output voltage of a solar photovoltaic cell is very low, even the series and parallel combination of solar photovoltaic cells do not produce the desired output power. Hence DC-DC step-up converter is a circuit that produces output potential at a higher level than the input potential to provide the required output.

DC-DC step-up converter is a class of SMPC contains at least two semiconductor devices and at least one energy storage element such as inductor, capacitor or combination of inductor and capacitor. An inductor is connected to input PV source and a MOSFET is connected across the input source. losed loop control of the DC-DC step-up converter circuit is shown in fig 3.

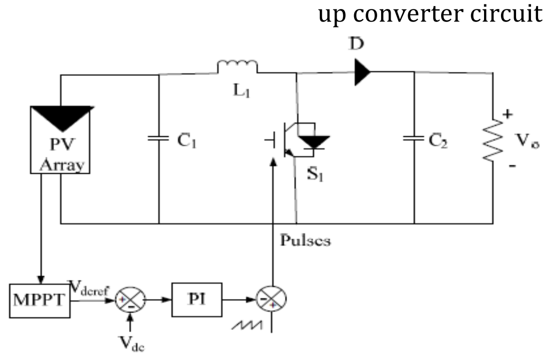

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Fig 3. Closed loop control of DC-DC step-up converter

When the gate drive signal is given to switch S_1, then it becomes ON. Inductor L_1 stores the energy from the solar PV array voltage (V_{pv}) and capacitor C_2 discharges through the load. Boost converter operates with a duty cycle $\delta=\frac{T_{ON}}{T}$, Where T_{on} is the ON Time period & $T=\frac{1}{f}$. When switch S_1 becomes OFF, stored energy in the inductor will be delivered to the Load. In this proposed work, a large capacitor C_2 is provided across the load to operate the DC-DC step-up converter in continuous conduction mode along with ripple-free output voltage (V_0). A control signal is provided to switch through the PWM Signal. The proportional-integral controller is provided to decrease the error in the output. This signal is in comparison with the sawtooth waveform to produce the gate drive signal to S_1.

5. Controller for 3-Φ 2 level PWM-VSI inverter for interfacing the conventional power grid

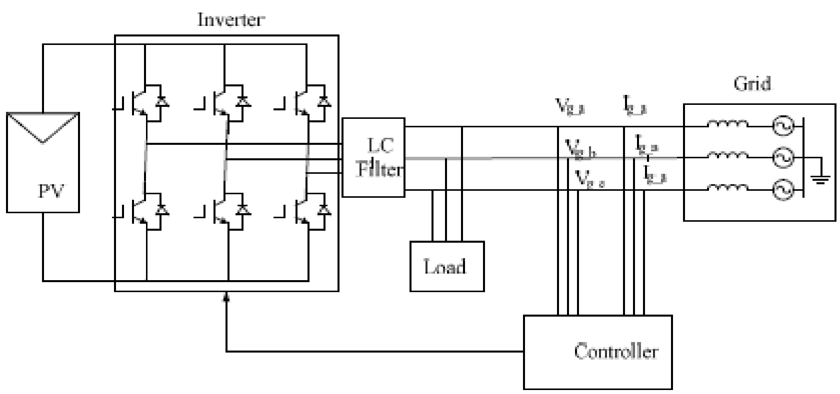

Fig 4. Proposed circuit diagram of 3-Φ conventional power grid connected PV system

A 3-Φ 2 level PWM-VSI is provided for interfacing the utility conventional power grid and solar PV array. This solar inverter converts variable DC voltage of solar photovoltaic panels into an alternating voltage that can be fed to the conventional power grid. There are two different types of controllers "constant power controller" and "constant current controller". In this proposed work, a constant current controller along with 3-Φ PLL is provided to control the solar inverter. PLL is provided to track the phase voltages and phase angle of the conventional power grid and also gives the information regarding variations in the frequency of the utility conventional power grid. Detailed Constant Current Controller block diagram is shown in fig 5, which generates controlled pulses for the solar inverter. 3-Φ Conventional power Grid Voltage Vg_{abc} is sensed by using a voltage sensor and gives information to the PLL. To simplify the control and design process of 3-ϕ conventional power grid connected clarke's transformation can be used. Conventional power grid current Ig_{abc} is converted into αβ variables using Clarke's transformation

Clarke's transformation can be obtained with the following equations.

$$I_{\propto} = \frac{2}{3}\left(I_{ga}\right) - \frac{1}{3}\left(I_{gb} - I_{gc}\right) \quad (4)$$

$$I_{\beta} = \frac{2}{\sqrt{3}}\left(I_{gb} - I_{gc}\right) \quad (5)$$

Further αβ current variables can be converted into dq variables using park's transformation. Currents I_d and I_q are compared with the reference values I_{dref} & I_{qref} for processing the proportional-integral Controller to reduce the errors. Output signals of proportional-integral controllers are transformed into 3-Φ abc signals using inverse Park's transformation. These signals are compared with triangular waveforms to generate the pulses for a solar inverter. Where V_{dc} is the DC Link voltage and V_{dcref} is the predicted DC voltage from the PV array.

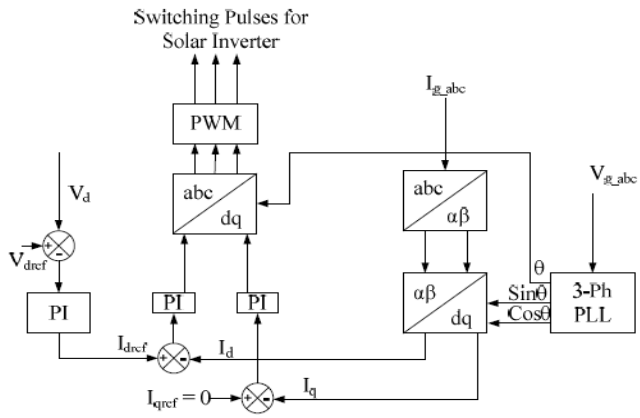

Fig 5. Representation of Constant Current Controller

6. Simulation & experimental results of the proposed controller

6.1. Simulation circuit & results

To demonstrate the behavior and overall performance of the proposed controller, a simulation study is conducted in MATLAB Simulink software before the experimental investigation. In this paper simulation model of a 1 kW solar photovoltaic system integrated with the conventional power grid is developed. The number of PV modules connected in series is 10 & the number of PV modules connected in parallel is 1. The solar PV array produces variable DC output voltage of 220V at Solar irradiation of 1000W/m^2 & temperature levels of PV array are 30^{0}C. This voltage is boosted to 600 V Maximum by using a DC-DC step-up converter. DC Voltage delivered by the DC-DC step-up converter from MATLAB Simulink is shown in fig 7. Boosted DC Voltage is given to the 3-Φ 2 level PWM inverter. 3-phase LC Filter is provided at the output of inverter with an inductance of 50mH & capacitance of 2.5μF, 400V. The combination of 3-Φ PWM-VSI & LC filter converts fixed 600 V DC voltage into 3-Φ 400V, 50Hz pure sinusoidal AC with the reduced value of THD. The constant current controller simulation circuit diagram using MATLAB Simulink is shown in fig 8.

Fig 9 & fig 10. shows the simulated inverter output voltages without & with filtering respectively. The Fast Fourier Transform (FFT) investigation of the inverter final voltage gives the value of Total Harmonic Distortion (THD). THD Spectrum of inverter output voltage with the combination of CCC & LC filter from MATLAB Simulink is shown in fig 11.

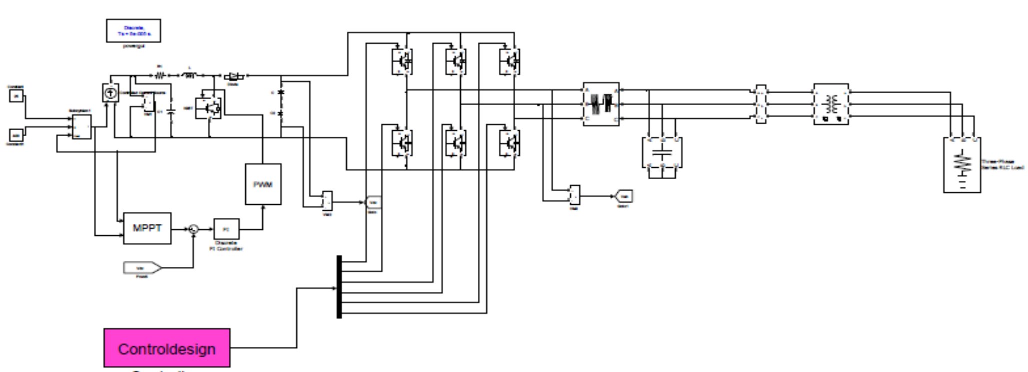

Fig 6. Simulation circuit illustration of the suggested solar grid integrated system

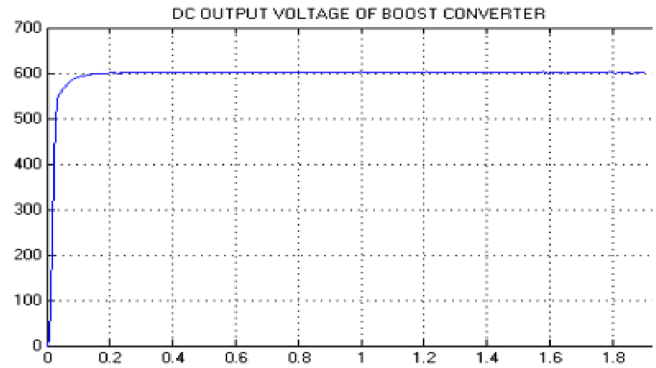

Fig 7. DC Output Voltage of the step-up converter

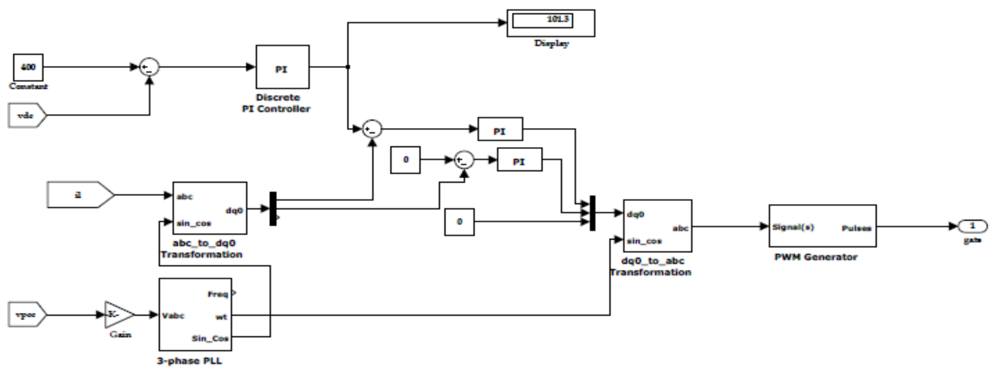

Fig 8. Simulation circuit diagram of constant current controller

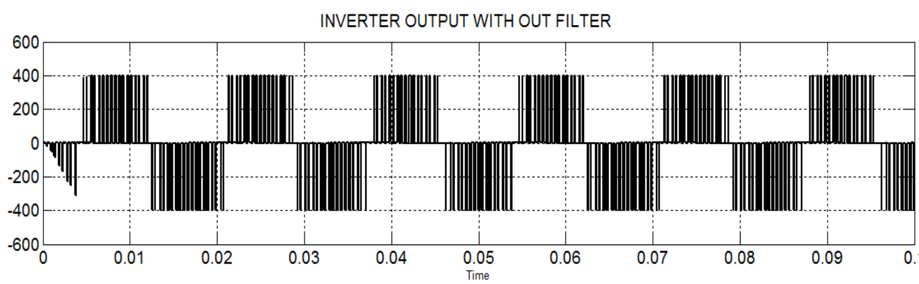

Fig 9. 3-Φ inverter output voltages without filter

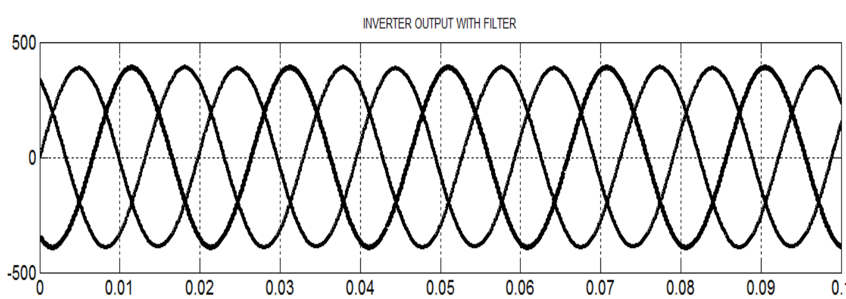

Fig 10. 3-Φ inverter output voltages with LC filter

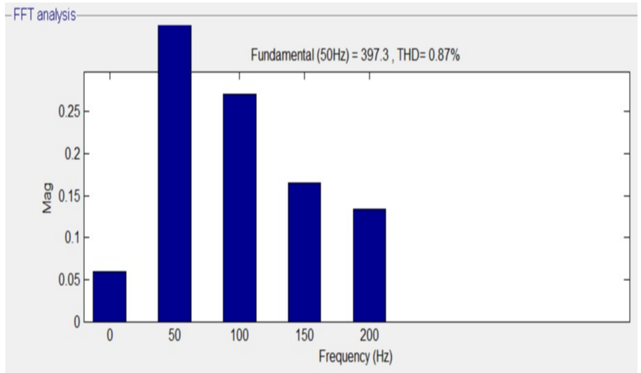

Fig 11. THD spectrum of 3-Φ inverter output voltage with LC filter

THD gives information regarding the deviation or distortion of voltages or currents due to presence of harmonics.

From Fig 11.It can be seen that the combination of the CCC & LC filter effectively eliminates the high-frequency harmonics from the inverter output voltage.

6.2. Experimental results & discussion

In this proposed paper, for the validation of simulation results an experimental prototype of the 1kW solar PV array integrated with a conventional power grid using CCC is developed & experimental prototype is shown in fig 12.

Table 2. Parameters considered in the design of Experimental prototype

S.No.	Parameters	Value	Unit
1	Solar photovoltaic panel rating	100	W
2	Number of PV modules connected in series	10	No.
3	Number of PV modules connected in parallel	1	No.
4	Maximum voltage rating of each module	22	V
5	Maximum current rating of each module	6.06	A
6	Filter inductance per phase	50	mH
7	Filter capacitance per phase	2.5	μF
8	Grid RMS voltage (Line to Line)	400	V
9	Grid frequency	50	Hz

This system is designed by using 100W IP65 PV silicon polycrystalline modules. The maximum voltage & current ratings of each photovoltaic module are 22V & 6.06A respectively. DC-DC step-up power electronic converter constructed with a IGBT switch (CT60AM-18B, 900V, 60A, N - CHANNEL) together with a gate driver circuit (HCPL-3100-000E). The 3-Φ 2 level PWM-VSI is developed with six MOSFET switches (IRFZ44NPBF Channel, 800V, 10A). This 3-Φ 2 level PWM-VSI receives a constant DC voltage of 600 V from the DC-DC step-up converter and produces an output voltage of 3-Φ 400V, 50Hz and is fed to the conventional power grid. Voltage sensor (ZMPT101B) & current sensor (PMCS1100A2QDR) are provided near the conventional power grid to sense the 3-Φ voltages & currents and then fed to the 3-phase PLL (CD4046BK3). The proposed CCC is developed using ATmega2560 microcontroller. This controller provides the control to tune the MPP (Maximum Power Point) from a solar photovoltaic array using modified P&O method, DC bus voltage regulation, control of 3-ϕ PWM-VSI and system synchronization. Inverter Output voltages with and without LC filter are shown in fig 13 & fig 14.

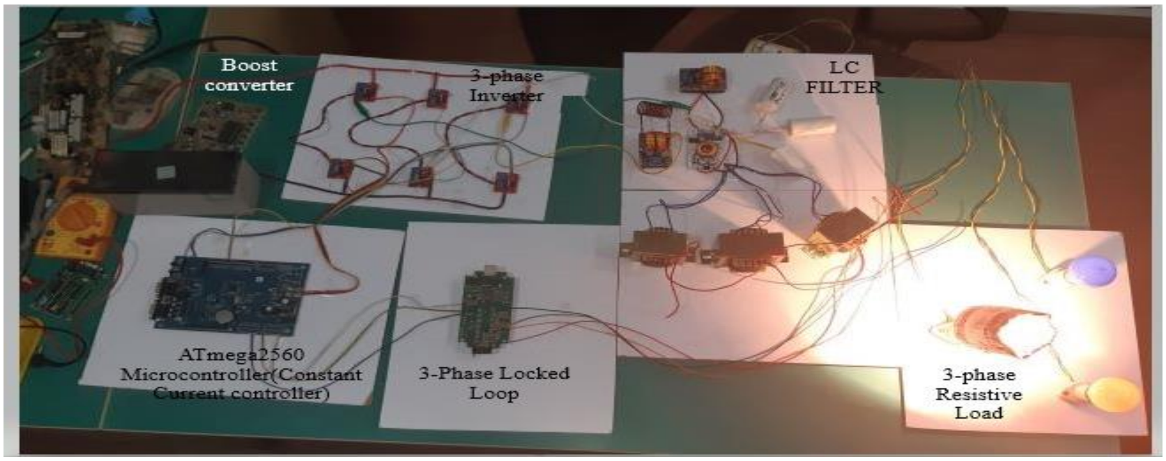

Fig 12. Experimental setup for the proposed conventional power grid connected PV System using a constant current controller

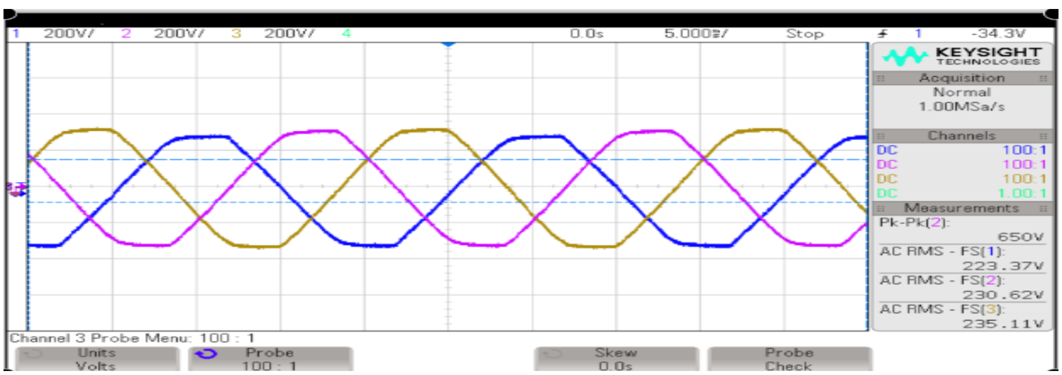

Fig 13. 3-Φ inverter output voltages with LC filter

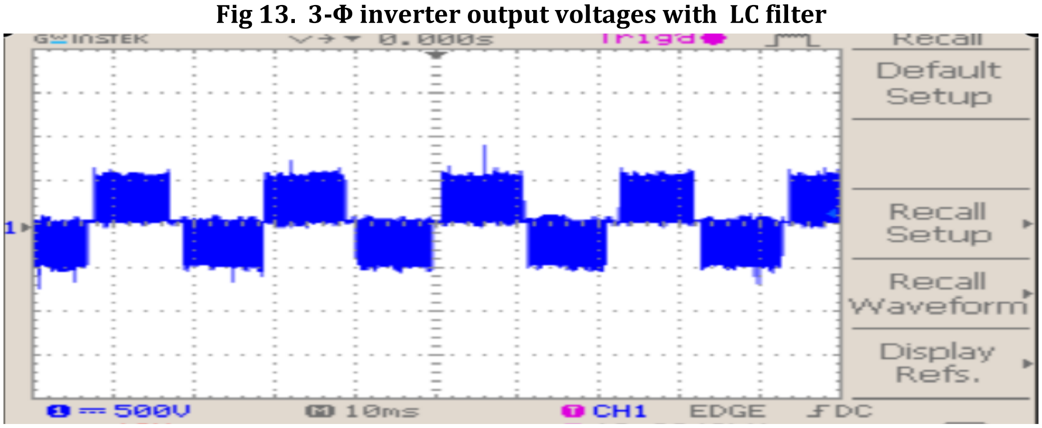

Fig 14. Inverter 3-Φ output voltages without LC filter

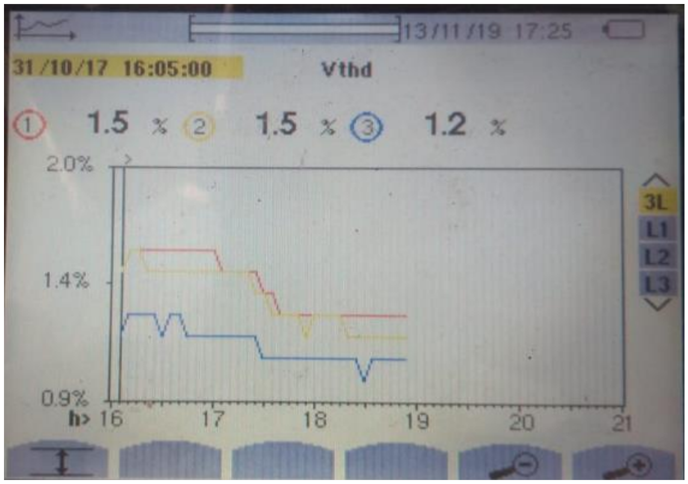

Fig 15. Total Harmonic distortion spectrum of inverter output voltage with LC filter

Table 3. Comparison of simulation results & experimental results

S.No.	Parameter	Simulation	Experimental
1	Inverter output voltage (Phase voltage RMS)	230V	223.7V
2	THD of Inverter output voltage with LC filter	0.87%	1.5%
3	Boost converter DC-DC output voltage	600V	582V

7. Conclusion

In this proposed work, an experimental prototype of 1kW solar photovoltaic power plant which comprises a photovoltaic array, step-up power electronic DC-DC converter, 3-Φ PWM-VSI is incorporated with conventional power grid using CCC (Constant Current controller) is developed using ATmega2560 microcontroller. The conventional power grid-tied 1kW solar photovoltaic system modeling and simulation is also done using MATLAB Simulink. The solar photovoltaic system produces an output DC voltage of 220V. Closed loop step-up power electronic DC-DC converter is used to produce the Maximum Energy from the solar photovoltaic power plant, as well as to increase the 220V variable DC voltage to fixed 600 V DC. A 3-Φ 2 level PWM-VSI in conjunction with LC filer converts 600V DC into 3-Φ, 400V,50Hz Sinusoidal AC Voltage. Control of 3-Φ 2 level PWM-VSI is maintained through CCC. This follows the conventional power grid phase and frequency. Using CCC, 3-Φ PWM-VSI output voltages & traditional power grid voltages are in the same phase. Experimentally CCC together with low pass LC filter gets rid of the inverter output voltage harmonics and produces an output voltage to the low value of THD i.e. 1.2 %. To validate the effectiveness of the proposed controller both simulation & experimental effects are presented in this paper. But the main disadvantage of proposed controller is CCC without LC filter is less efficient, produces lower power factor and higher value of THD of inverter output voltages. Hence renewable electricity sources can be incorporated with the traditional power grid by using the proposed controller with the improved features of power quality.

Future work: Hysteresis controller in combination with CCC may eliminate the usage of passive LC filter to improve the inverter output voltage.

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