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Double-Stage PV based Grid-Tie Inverter using Fuzzy Logic as MPPT technique with Flyback Converter

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Abstract —*The present paper focuses on the development of a topology for single-phase grid connected inverter based on Photovoltaic generation. The work initiates with mathematically modeling a PV solar cell and studying its performance under varying environmental and physical conditions through P-V and I-V characteristics. Fuzzy Logic is developed as maximum power point tracking to overcome the drawback of poor efficiency of PV cells. Thus, implementing fuzzy logic, maximum power is extracted to revamp the PV cell efficiency. For grid connections, unregulated DC output of PV module needs to be regulated and elevated using DC-DC flyback converter. Finally, single-phase inverter will be synchronizing with grid using SPWM switching technique. The simulation work is performed using MATLAB/SIMULINK tool and results are presented.*

Keywords*-Photovoltaic; Maximum Power Point Tracking; Fuzzy Logic; Flyback Converter; Grid-Tie Inverter; Sinusoidal Pulse Width Modulation(SPWM).*

I. INTRODUCTION

RENEWABLE ENERGY SOURCES are emerging out as one of the best alternatives to conventional sources for electricity production, thus overcoming the ever increasing demand of electricity with growing population and tackles the menace of global warming. As per the survey, deployment of PV has gained momentum in recent years globally. PV capacity increased atleast by 75GW, with 50% year-on-year growth of new installations. Cumulative installed capacity ramped to 302GW at the end of year, and it is sufficient enough to supply 1.8% of world's total electricity consumption. Photovoltaic power systems are becoming increasingly important in modern electrical grids that will be transforming into Smart Grids in near future. In recent years, PV power systems are the centre of research, addressing the challenges like existing grid integration, infrastructure and reducing regulatory uncertainties. Thus, contributing in economic and overall development.

DOUBLE-STAGE PV BASED GRID-TIE INVERTER represents an inverter topology for a single-phase, grid connected photovoltaic systems based on two stages of power conversion [4] – 1st stage involves flyback(isolated, high step-up) DC-DC converter to achieve high efficiency as well as voltage gain and 2nd stage involves DC-AC inverter controlled by soft switching techniques such as Sinusoidal Pulse Width Modulation(SPWM). Based on equivalent circuit of a solar cell, mathematical model is developed using MATLAB/SIMULINK tool to simulate P-V and I-V characteristics to analyze its performance under varying environmental and physical conditions [1],[3]. The PV panel produces unregulated DC output due to continuously varying environmental conditions.

Scrutinizing the high initial capital cost of a PV module and its low energy conversion efficiency, it becomes imperative to operate the PV module at maximum power point (MPP) to extract maximum output power. This is done using MPPT (Maximum Power Point Tracking). Literatures are available on numerous MPPT techniques, but amongst the all traditional methods Fuzzy Logic is adopted as a part of Artificial Intelligence to perform maximum power point tracking by controlling the duty cycle of DC-DC converter. Unregulated DC output of PV panel is regulated by using Flyback converter. It is an isolated, high step-up converter with one controllable switch MOSFET having switching frequency in the range of 20 kHz - 100 kHz. Inverter that converts DC into AC consists of a power circuit and a control circuit. The power circuit consists of IGBT or MOSFET as switch. Using SPWM strategy, gating pulses are provided to the switches. But the inverter output with the PWM waveform will be filtered out using LCL filter. Lastly, inverter output is synchronized to the grid, fulfilling the requirements for the synchronization of grid.

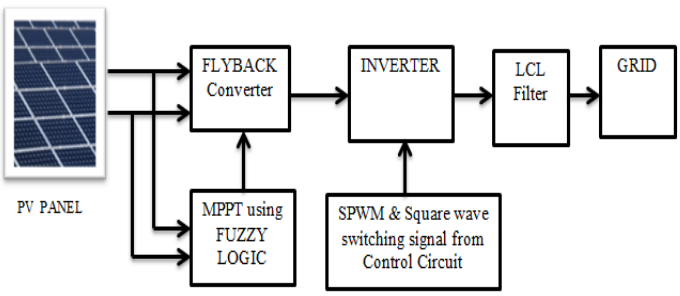

Figure 1. Block diagram of PV Grid-Tie Inverter

II. PHOTOVOLTAIC MODULE

PHOTOVOLTAICS (PV) word was derived from Greek word 'phos' meaning light and 'volt' being the unit of electromotive force. Solar cells convert light energy of sun into a flow of electrons using "Photovoltaic Effect". Using photovoltaic effect, solar cells were developed using different semiconductors like silicon. Integrating multiple solar cells in a group and orienting in on plane, a complete solar photovoltaic panel is formed. Connecting number of solar cells in series and parallel configuration will yield additive voltage and higher current respectively.

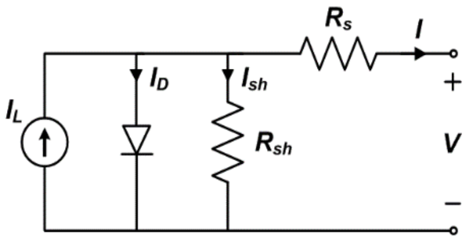

Figure 2. Equivalent circuit of solar cell

The equivalent circuit of a solar cell is modeled as a current source with a diode connected in parallel, shunt and series resistance [2]. Solar cell is modeled as a current source because it is observed from its I-V characteristics that for a given range of voltage, current is approximately constant.

The equations governing mathematical model of a solar cell are [1]:

1. $I_{ph} = I_{rr}[I_{sc} + K(T_{op} - T_{ref})]$
2. $I = I_{ph} - I_s[e^{\frac{q(V+IR_{se})}{KnT}} - 1] - \frac{V+IR_{se}}{R_{sh}}$
3. $I_s = I_{rs}(\frac{T_{op}}{T_{ref}})^3\{(\frac{qE_g}{Kn})[(\frac{1}{T_{op}}) - (\frac{1}{T_{ref}})]\}$
4. $I_{rs} = I_{sc}[e^{\frac{qV_{oc}}{KCnT_{op}}} - 1]$

Where,

I_{ph} = photo diode current
I_{sc} = short circuit current
I_d = Diode current
I = Load current
I_s = Diode Saturation current
I_{rs} = Reverse Saturation current
T_{op} = Operating Temperature
T_{ref} = Reference Temperature
V_{oc} = Open circuit voltage
K = Boltzmann's constant (1.38×10^{-23} J/K)
q = Electron charge (1.602×10^{-19} C)
n = Diode ideality factor
C = Number of cells in module
I_{rr} = Solar irradiations (W/m^2)

All the above equations form subsystem for a solar panel in MATLAB/SIMULINK which is shown in figure 3.

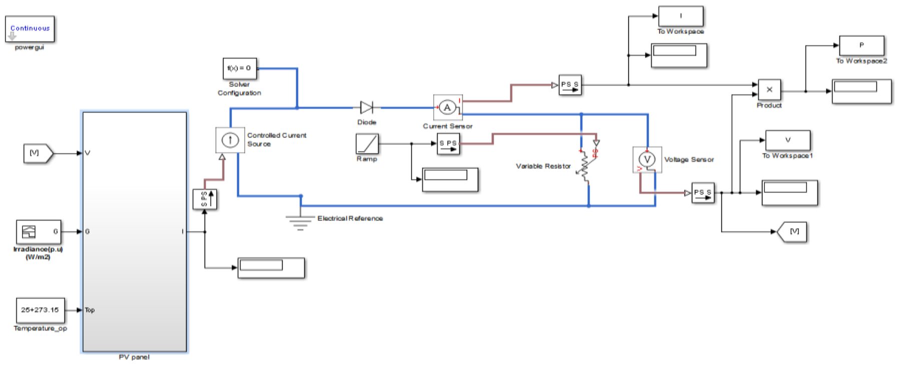

Figure 3. MATLAB model of a solar cell

The final model takes irradiations, operating temperature and module voltage as input to give output current I_{PV} and voltage V_{PV}. The above model is developed using reference datasheet of BE75S12 – SOLAR PANEL from Bharat Electronics Ltd.

Table 1. BE75S12 Datasheet

STC Rated Power	75W
Voltage at Maximum power (V_{mp})	17 V
Current at Maximum power (I_{mp})	4.40 A
Open circuit voltage (V_{oc})	21.5 V
Short circuit current (I_{sc})	4.7 A
Total number of cells in series (N_s)	9
Total number of cells in parallel (N_p)	4
Temperature Coefficient of I_{sc}	0.070%/℃
Temperature Coefficient of V_{oc}	-0.33%/℃

P-V and I-V characteristics are obtained at STC for solar irradiations of 1000 W/m^2 and temperature of 25ºC.

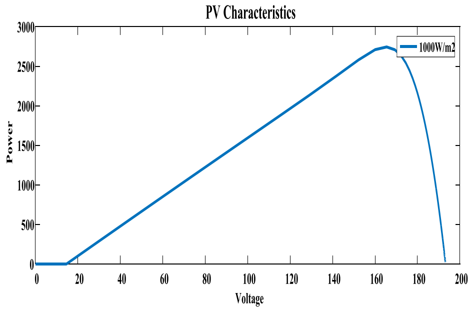

Figure 4. P-V characteristics

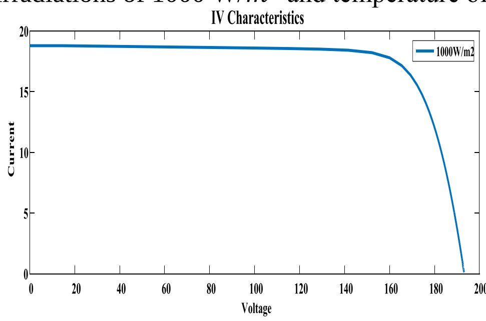

Figure 5. I-V characteristics

III. Implementing Fuzzy Logic based MPPT with Flyback Converter

A. FUZZY LOGIC: A major challenge in use of PV is posed by its nonlinear I-V characteristics, which result in a unique maximum power point on its P-V characteristics. With varying solar irradiations and temperature, MPP also varies. To improve efficiency of a solar cell, maximum power point tracking is done. There are many MPPT methods like Perturb & Observe, Incremental Conductance, Fuzzy Logic, Neural Networks. But Fuzzy Logic Control is used due to its advantages like fast convergence speed, can work with imprecise inputs, easy to implement etc. A Fuzzy Logic Controller consists of 3 blocks [5],[6] – Fuzzification, Inference and Defuzzification.

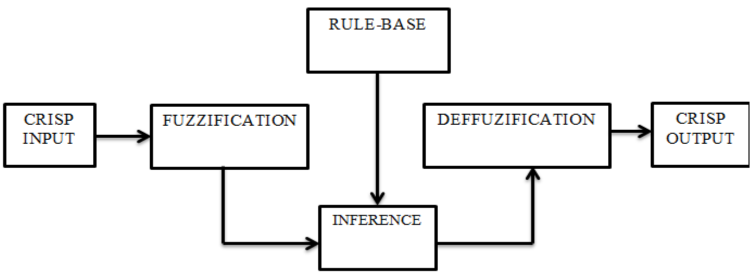

Figure 6. Block diagram of Fuzzy Logic

The fuzzy logic controller takes each input/output variable defining a control surface which are expressed in fuzzy set notation using linguistic variables. The process of converting real world variables into linguistic variable is called Fuzzification. The behaviour of control surface relating input to output variable are governed by set of rules in Inference process using Mamdani Method. As the output of the fuzzy controller is a fuzzy set, it is required to convert into real world variable using Defuzzification. The input to fuzzy logic controller is error E(k) and change in error CE(k) for k^{th} sample time.

$$E(k) = \frac{dP}{dv} = [P_{PV}(k) - P_{PV}(k-1)]/[V_{PV}(k) - V_{PV}(k-1)]$$

$$CE(k) = E(k) – E(k-1)$$

Where I_{PV} and V_{PV} are PV panel current and voltage respectively.

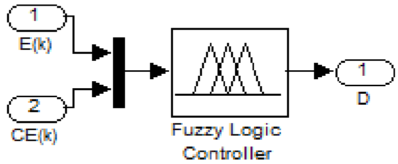

Figure ***7. Fuzzy Logic Controller***

The input and output variables uses 7 fuzzy sets which are- PL (Positive Large), PM (Positive Medium), PS (Positive Small), Z (Zero), NS (Negative Small), NM (Negative Medium), NL (Negative Large). The rules for fuzzy logic controller are:

Table 2. Rules

CE/E	**NL**	**NM**	**NS**	**Z**	**PS**	**PM**	**PL**
NL	PL	PL	PL	PL	NM	Z	Z
NM	PL	PL	PL	PM	PS	Z	Z
NS	PL	PM	PS	PS	PS	Z	Z
Z	PL	PM	PS	Z	NS	NM	NL
PS	Z	Z	NM	NS	NS	NM	NL
PM	Z	Z	NS	NM	NL	NL	NL
PL	Z	Z	NM	NL	NL	NL	NL

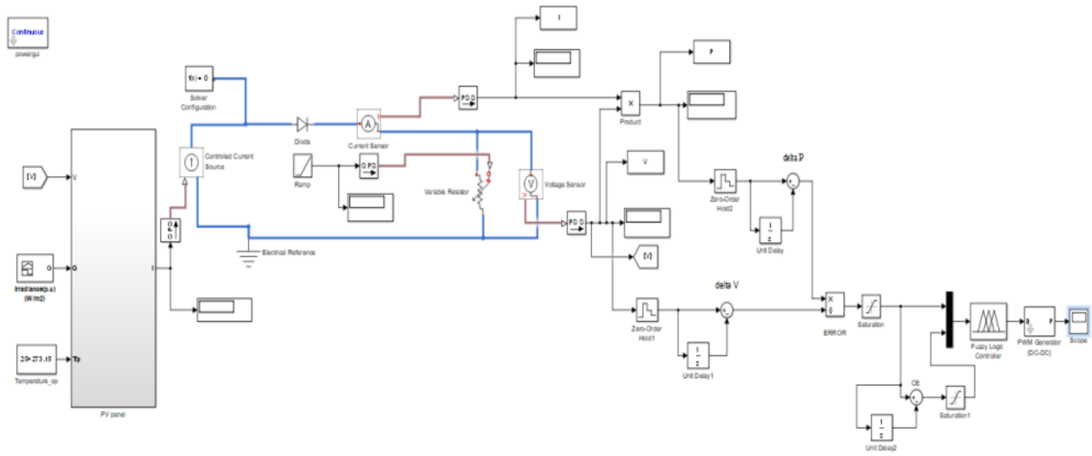

Figure 8. MATLAB model of Fuzzy logic with PV panel

B. FLYBACK CONVERTER: Flyback converter converts unregulated DC output of PV panel into regulated DC voltage as well as increases output upto certain level for grid integration. It is a simple buck-boost converter whose inductor splits into a transformer, thus multiplying voltage ratios and providing galvanic isolation between PV panel and the grid to avoid faults. No separate inductor is used to store energy, thus making circuit simple, cost effective as well as popular topology [8].
The circuit configuration is made up of a power MOSFET, diode D, transformer, capacitor C and a load as shown in the figure 9.

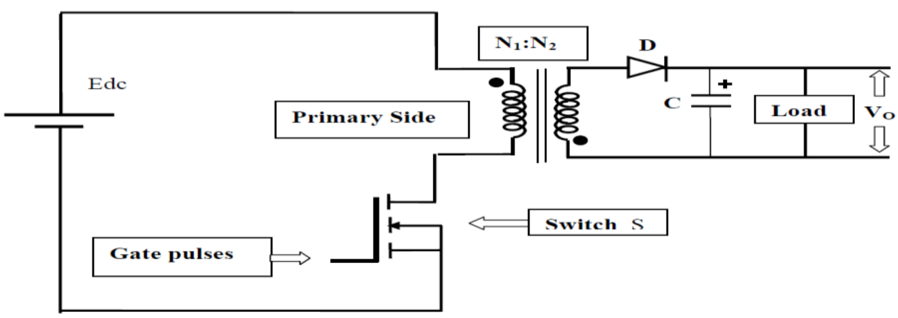

Figure 9. Circuit diagram of Flyback Converter

In steady state, the equations governing the operation of the flyback converter are:

$$\frac{V_{out}}{V_{in}} = (\frac{N_1}{N_2})(\frac{D}{1-D})$$

$$\frac{I_{in}}{I_{out}} = (\frac{N_1}{N_2})(\frac{D}{1-D})$$

Where, D is the duty cycle, N_1 and $N_2$are number of turns of primary and secondary windings, V_{in} and V_{out} are the input and output voltage to the converter, $I_{in}$and I_{out} are the input and output current respectively.
The duty cycle provided by the fuzzy logic controller will control the switching of the power MOSFET whose switching frequency is selected to be 20 kHz, and produces constant output voltage.

IV. GRID TIE INVERTER

Design of the grid connected inverter slightly differs from the stand-alone traditional inverter topology. For grid synchronization, the necessary conditions to be satisfied are [10]- voltage magnitude and the phase of the inverter output should match with the voltage magnitude and the phase of the grid; inverter output frequency must be the same as that of the grid frequency. The schematic diagram of inverter in the grid-tie inverter [10]:

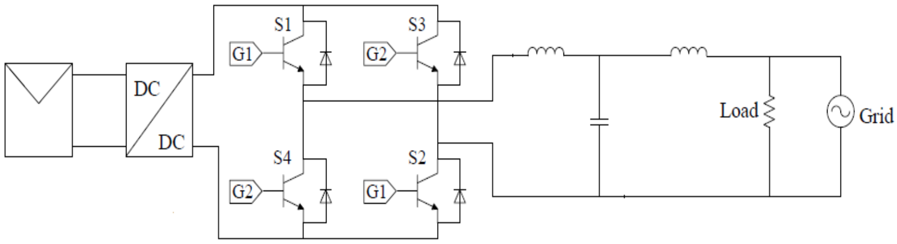

Figure ***10. Inverter in GTI***

The inverter uses four switches S1, S2, S3, S4 which can either IGBT or MOSFET. To drive the gate of switches, gating signals are generated using SPWM (Sinusoidal Pulse Width Modulation). SPWM produces controlled inverter output, characterized by generating a pulse of varying width with constant amplitude, by modulating the duty cycle. The switching control circuit of the grid-tie inverter involves combining SPWM and a square wave signal with an aim of reducing switching losses [2]. This requires taking the sample of a sine wave from the grid (230V), which will be stepped down to 5V using transformer. The SPWM signal is generated using the sampled sine wave to ensure that the output voltage of the GTI has same frequency as the grid. a precision rectifier rectifies the sine wave, after sampling. As a carrier signal, triangular wave of much higher frequency (10 kHz) is used. These two signals are compared to generate unipolar SPWM signal. Using PWM generator, square wave signals of line frequency (50 Hz) and in phase with the SPWM are employed. To produce 180˚ phase shift, square wave is transmitted through a NOT gate [11]. Using AND gate operation between SPWM signals and the two square waves, gate pulses are provided to S1, S2, S3, S4 accordingly.

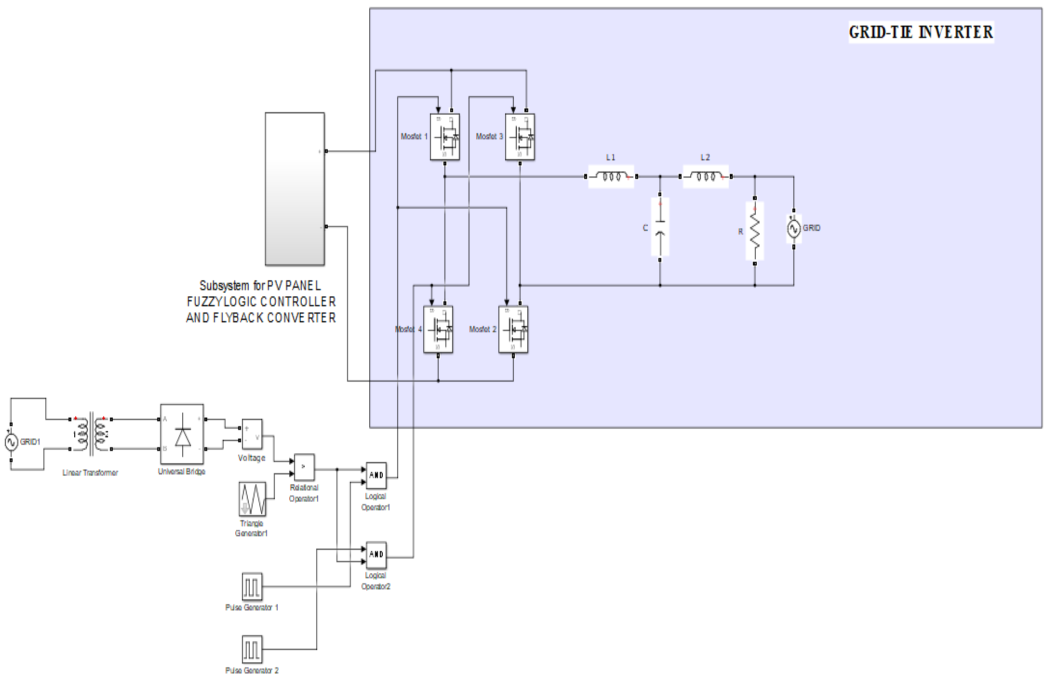

Figure 11. MATLAB model of GTI with switching circuit

The gate pulses to the switches S1, S2, S3, and S4 are as shown in figure 12.

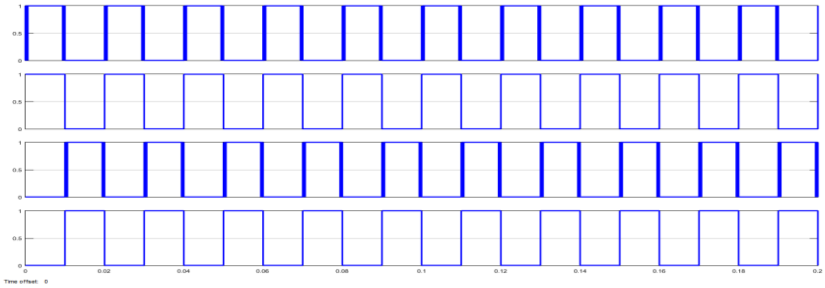

Figure 12. Gate pulse to the switches S1, S2, S3, S4

V. SIMULATION RESULTS

The simulation is performed for the proposed model of the Grid-Tie Inverter. The unregulated DC output of PV panel with varying maximum power point can be regulated and boosted upto 310V DC by using flyback converter and applying fuzzy logic as MPPT technique.

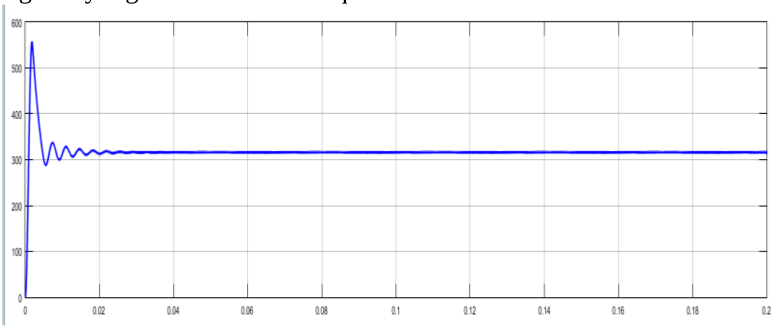

Figure 13. Output voltage of Flyback converter

Using SPWM switching control strategy, 310 V DC is converted to 230 V AC through inverter. But the output of inverter without filter, contains harmonic content and is non sinusoidal. Implementing LCL filter, the harmonic influence can be minimized to great extent. Thus, to produce pure sine wave output, LCL filter is used that reduces voltage THD level and hence improves efficiency of the inverter output [9].

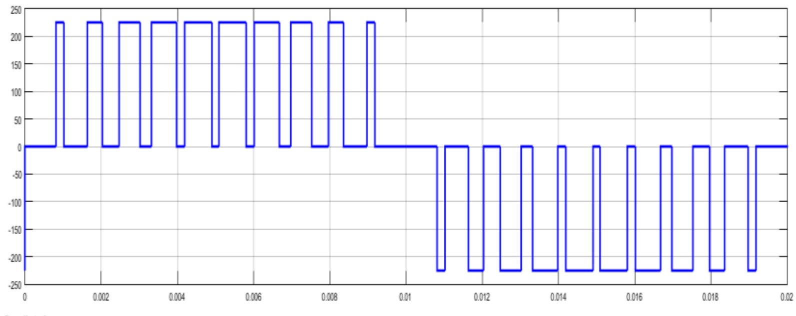

Figure 14. Output voltage of inverter without LCL filter

After using LCL filter, harmonic content is minimized and almost sinusoidal AC output voltage is generated. Thus 230V AC at 50Hz is obtained at output with reduced THD level.

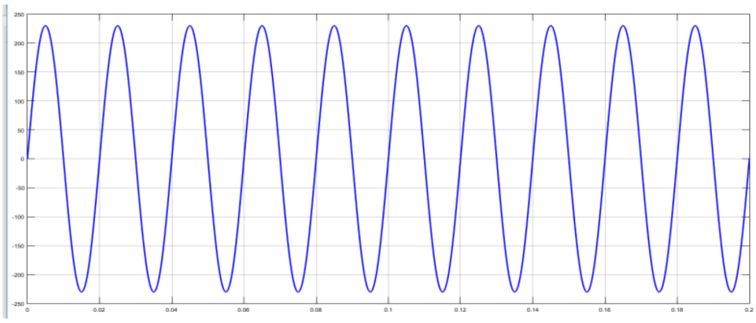

Figure 15. Output voltage of inverter with LCL filter

VI. CONCLUSION

From the above presented work, it was concluded that using MATLAB tool we can easily perform simulation of Grid-Tie Inverter addressing various difficulties for grid synchronization. Also using renewable energy resources like PV as a source of electricity generation, we can contribute to reduce environmental degradation. Mathematical model of PV panel helps us to analyze its performance under varying conditions through P-V and I-V characteristics. Further to improve solar cell efficiency, out of several MPPT techniques, study is done to implement fuzzy logic. Recently, many efforts are made to implement new topology for DC-DC converter, thus flyback converter is used to produce constant DC voltage. Lastly, grid synchronization of inverter through appropriate switching technique and use of LCL filter is done to generate pure sinusoidal AC output voltage.

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