

Design and Analysis of PV Based Micro-inverter Using INC MPPT Controller and Fuzzy Logic Controller

Aabir Dasgupta^{1,*}, Piyush Saxena²

Abstract

The reserve of conventional energy sources such as coal, natural gas, and crude oil are rapidly decreasing with increasing demand of electricity in the world. Also, the fossil fuels cause air pollution, global warming and similar environmental problems. Therefore, recent studies have become widespread about renewable energy sources (RESs) such as biomass, hydropower, geothermal, wind and solar which are the most popular worldwide. Among other RESs, solar energy is assumed as the best alternative to conventional sources of energy. In this study, a micro inverter (MI) is designed by using isolated boost converter on dc-dc side and Full Bridge Inverter for dc-ac conversion. The power capacity of designed MI is rated at 10kW where the input voltage is 55 V while output voltage is converted to 230 Vrms at 50 Hz frequency. Two different controllers are used against changing irradiation conditions in this work. The boost converter is controlled by an INC MPPT controller. The PI controller and Fuzzy Logic Controller are used to control the Bridge Inverter and the result of both the control methods have been compared.

Keywords: Micro inverter, Renewable energy sources, MPPT controller, Fuzzy logic controller

INTRODUCTION

Electricity is mostly generated by using conventional sources of energy such as coal, natural gas, crude oil etc. around the globe. Recently, the reserves of conventional sources have gradually decreased while electricity demand has been increased. The use of conventional energy sources causes environmental pollution and global climate change. Hence, research work on RESs have increased rapidly. It is obvious that renewable energy sources (RESs) are abundant, clean, environment friendly and sustainable. Solar energy is most preferred among all others. Among all solar technologies, photovoltaic (PV) module that is comprised by PV cells is the most significant device in terms of generation electricity. The desired output voltage (V), current (I) and power (P) values of PV modules are obtained by connecting solar cells in series and parallel. Central inverter, string inverter and MI are

the major types of inverter configurations in commercial use. The central (CI) and string inverter (SI) are used for household and commercial applications where PV modules are connected in series or parallel to generate higher DC voltage [1–3]. Hence partial shading can affect PV systems with CI or SI. The central and string inverter systems have some disadvantages such as no expandability, safety problems etc. The MIs are designed to be used for individual PV modules with low power rates. Thus, the MI has individual MPPT which is used to acquire maximum power from PV module and so it overcomes partial shading condition of PV system. The PV systems consist of single or more MI. When a MI in the PV system does not function, other units continue working. The MI has advantages such as

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suitability for residential applications, better efficiency and noncomplex structure. However, the cost of MI is the highest among other types of inverters. In this paper, a MI has been modelled with Isolated boost converter and Full Bridge inverter topologies. The Boost converter & the HF transformer are used to increase the input DC voltage to generate appropriate output voltage. The converter is controlled to obtain maximum power of PV module using Incremental Conductance MPPT algorithm with integral regulator which tracks MPP in changing irradiation situations. Firstly, the PI controller is used to control the single-phase bridge inverter. Then the FLC has been used to control the inverter. Although the output of MI is set to 230 Vrms at 50 Hz line voltage, it is not connected to utility grid and is used as a standalone inverter configuration for supplying light domestic loads. This paper is organized in following order: 2nd section introduces the circuit configuration of designed MI while the MI design studies have been presented in 3rd section. The MI simulation and analysis studies are given in 4th section and conclusions are presented in the last section.

CIRCUIT CONFIGURATION OF DESIGNED MI

Figure 1 shows the schematic diagram of designed MI which is comprised of isolated boost converter, Full Bridge inverter and filter circuit. The converter section includes high frequency (HF) transformer which ensures galvanic isolation between the source and load, switch S, diode D1 and capacitor C1. The duty cycle of S which is an IGBT is determined by MPPT algorithm. The single-phase Bridge inverter is comprised of four IGBTs and is controlled, firstly by PI controller and next by Fuzzy Logic Controller. The switching pulses for inverter switches are generated via sinusoidal pulse width modulation (SPWM). LC filter is used to eliminate harmonics and to obtain pure sinusoidal waveform at the output of MI.

In this study, the output voltage of PV module is around 55.75V DC and the output of designed MI is 230 Vrms at 50 Hz. The output maximum power capacity of MI is set to 10kW. The Incremental Conductance MPPT algorithm is used to define duty cycle of switch S in dc-dc conversion. The output voltage of PV module is amplified up to 59 to 60 V DC with boost converter. The HF transformer used has 1:3 transformation ratio. The output voltage of the converter and HF transformer provides input voltage of single-phase bridge inverter where dc-ac conversion is performed. Table I presents the parameters of the PV module that is arranged according to a commercial PV module used in the modelled system [4–7].

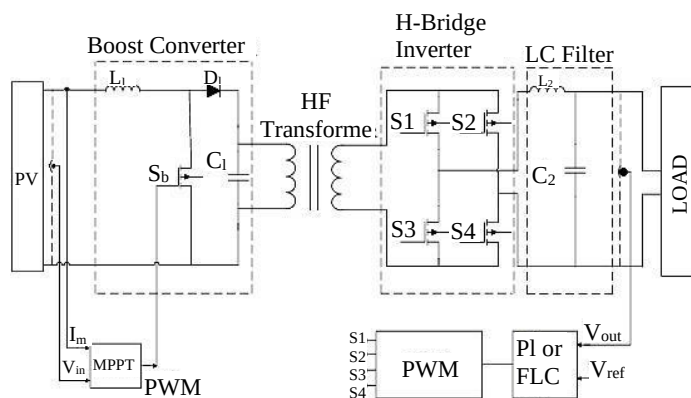


Figure 1. The structure of designed MI.

Table 1. PV module parameters.

Parameters	Value
Maximum power	305.226W
Voc, Open circuit voltage	55.75V
Vpm, Maximum power voltage	54.7V
Isc, Short circuit current	6.14A
Ipm, Maximum power current	5.76A

DESIGNED MICRO-INVERTER

Boost Converter

The dc to dc converter is quite important in PV system since the generated voltage from PV panel is not adequate to meet the load demand itself. The boost converter is also called step-up converter since value of input dc voltage is increased to a higher level [8]. It temporarily stores the input energy and then releases it into the output as a higher voltage level. This storage is performed in inductors or capacitors [9]. The capacitor is used to reduce oscillation in the output voltage wave form. For minimizing the switching power losses, a switching device is used with switching pulse that is generated by the MPPT controller [10]. Figure 2 shows circuit diagram of boost converter where the design parameters are given below.

$$V_{out} = \frac{V_{in}}{1-D}$$

$$C \geq \frac{I_{o.D.Ts}}{\Delta V_{max}}$$

$$L = \frac{V_{in.D}}{\Delta I.f_s}$$

The step-up converter is operated in two mode that are based on charge and discharge of the reactive components. In the first operation mode, the switching device is turned to the "on" position and the inductor is charged to an energy level. In the next step, the switch is turned to the "off" position, and the reactive energy is discharged to the output to supply the load. The operation modes are illustrated in Figures 3–4, respectively.

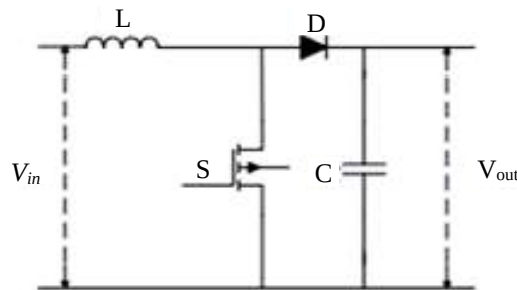


Figure 2. Structure of boost converter.

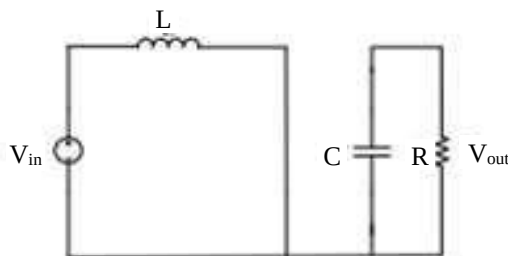


Figure 3. Structure of boost converter while the switch is "on".

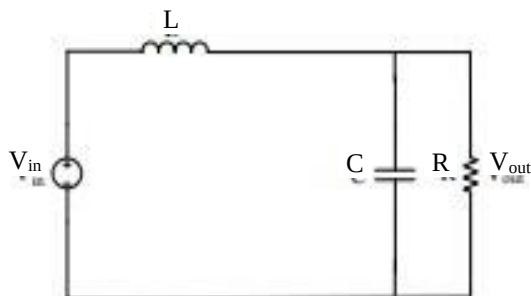


Figure 4. Structure of boost converter while the switch is "off".

First Operation Mode ($0 < t < t_{off}$)

Figure 3 shows the equivalent circuit while the switching device is conducting. At this interval, the switch is in "on" position and the diode is reverse biased. The inductor current is increased from the minimum value to the maximum value throughout t_{on} interval until the switch is turned off. As the switch is turned off, the second operation mode starts.

Second Operation Mode ($t_{off} < t < T$)

The circuit of second operation mode is shown in Figure 4. The accumulated energy in the inductor is added to the source voltage, thus it forward biases the power diode, and charges the capacitor to supply the load. Therefore, the voltage at output is increased as compared to the input voltage.

This continues until the IGBT is switched on again. The current through the inductor *decreases from its maximum value to the minimum value*. In case the inductor current is less than the required current to supply the output while the switch is in the "off" condition, the output of the converter will not be stepped up to the desired value. The inductor and capacitor values should be calculated in order to prevent the converter to operate in DCM. The calculated values of the modelled boost converter are given in Table 2.

Table 2. Parameters of boost converter.

Parameters	Value
Input Capacitor	47 microF
Inductor	520 microH
fsw, Switching frequency	10 kHz
Vin, Input voltage of boost converter	55.75V
Vout, Output voltage of boost converter	50-59V

MPPT Controller

The MPPT algorithm is required for obtaining maximum power from the PV panel in changing solar irradiance conditions and varying panel temperature [11]. Many MPPT algorithms for PV systems are studied such as fractional SC current, fractional OC voltage, P&O, incremental conductance and others. The incremental conductance technique has been used in this model as its performance is better in changing environmental conditions. The V and I measurement units are used to obtain output voltage and current value of PV panel. The slope of the PV array should be zero at MPP as shown in Figure 5. If the slope is positive, it means that the tracking point is on the left of MPP.

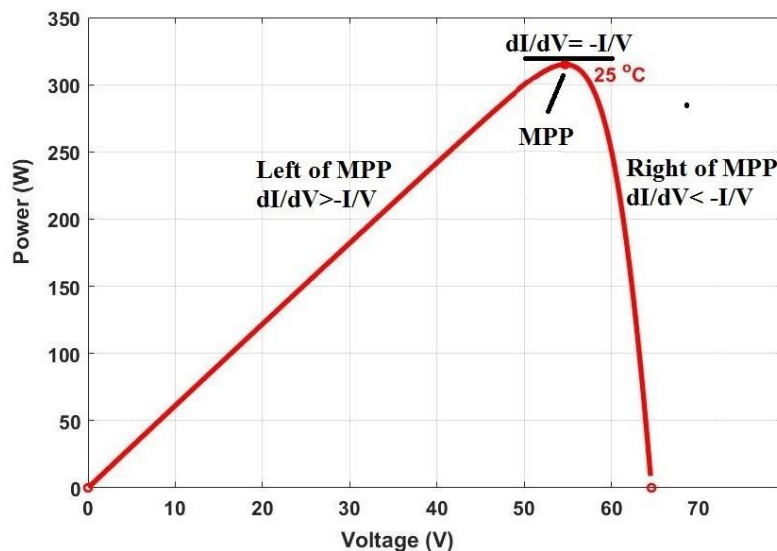


Figure 5. PV curve with INC MPPT controller.

Otherwise if slope is negative, it means that the tracking point is on the right of MPP. The base equations of this algorithm are given below.

$$P = V.I$$

$$\frac{dP}{dV} = I + V \frac{dI}{dV}$$

$$\frac{dP}{dV} = I + V \frac{dI}{dV} = 0$$

$$\frac{dI}{dV} = -\frac{I}{V} \quad (dP = 0)$$

$$\frac{dI}{dV} > -\frac{I}{V} \quad (dP > 0)$$

$$\frac{dI}{dV} < -\frac{I}{V} \quad (dP < 0)$$

Figure 6 shows flowchart of incremental conductance algorithm. Although incremental conductance algorithm is complex, but it ensures better control under changing atmospheric conditions and tracks MPP faster than other techniques.

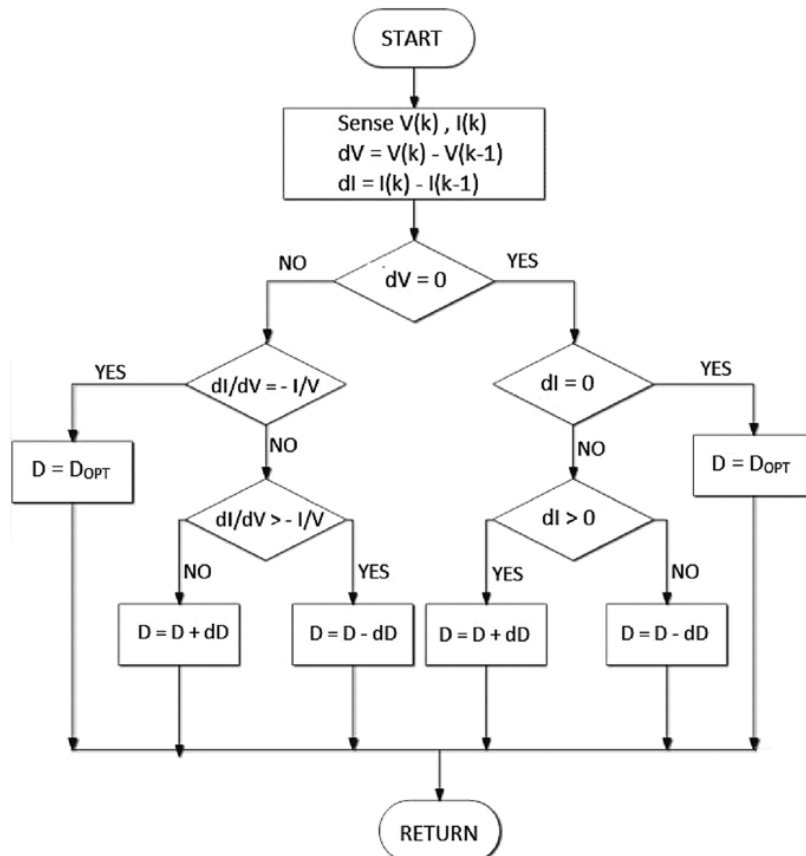


Figure 6. Algorithm of the incremental conductance.

H-Bridge Inverter with PI Controller

The bridge inverter performs the dc-ac conversion by alternative switching of the IGBTs. The output voltage of inverter is a periodic waveform, but its not sinusoidal. The H bridge circuit topology containing four switching components and dc source has been shown in Figure 7 [12–14].

The switching situations are shown in Table 3. There are four different switching situations to generate the output voltage waveform.

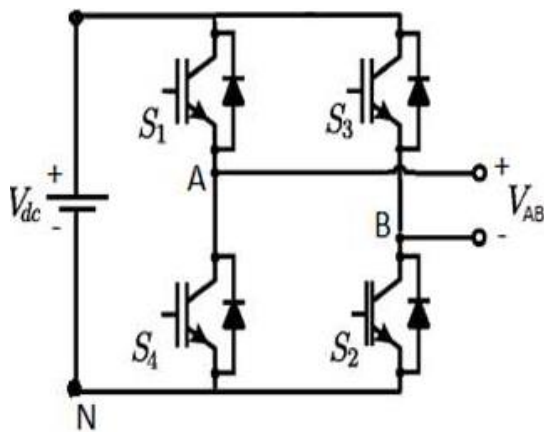


Figure 7. Circuit of H-bridge inverter.

Table 3. Switching situations of H-bridge.

Switching Conditions	Conducting Switches	Va	Vb	Vout
1	S1 and S2	$V/2$	$-V/2$	V
2	S3 and S4	$-V/2$	$V/2$	$-V$
3	S1 and S4	$V/2$	$V/2$	0
4	S3 and S2	$-V/2$	$-V/2$	0

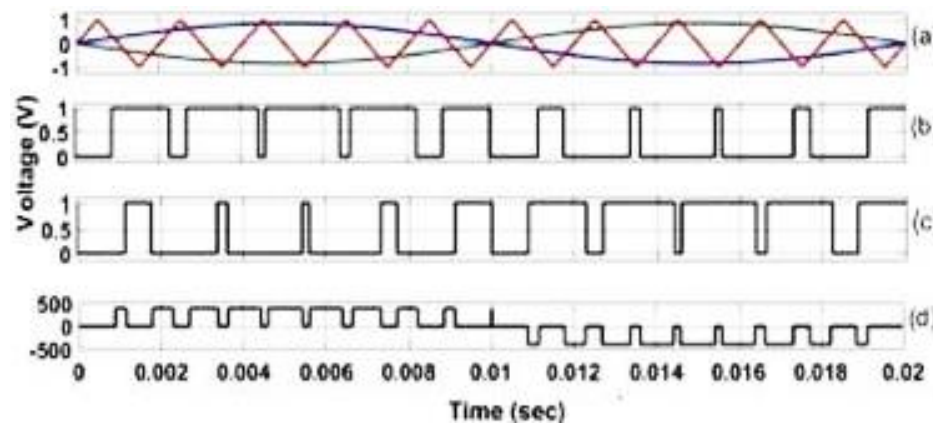


Figure 8. SPWM generation (a) Comparison between triangular waveform and sinusoidal reference waveform (b) Switching pulse of S1 and S2 (c) Switching pulse of S3 and S4 (d) Output voltage waveform.

The first two situations are used to generate AC output voltage in the table. In order to acquire these situations, pulse width modulation (PWM) is commonly used as a switching technique. There are more than one PWM techniques. The SPWM is the most preferred technique that operates by comparing the sinusoidal reference wave and triangular waveform. The triangular waveform determines switching frequency of inverter. The Frequency of reference waveform determines the frequency of inverter o/p voltage. Figure 8. shows generation of SPWM [15].

PI controller is used to reduce the error between the reference voltage and actual o/p voltage values. The reference voltage signal is compared with output voltage signal which is used as feedback signal. Then the error between the two signals is determined for input of PI controller and modulation index value is obtained. The modulation index is multiplied with the sinusoidal reference wave and this is compared with the triangular wave. Thus, switching pulse is generated for H-bridge inverter, as shown in Figure 9. The Kp value is set to 3.5 and Ki value is set to 0.0023 in this study where these values are determined by using Ziegler-Nichols method [16].

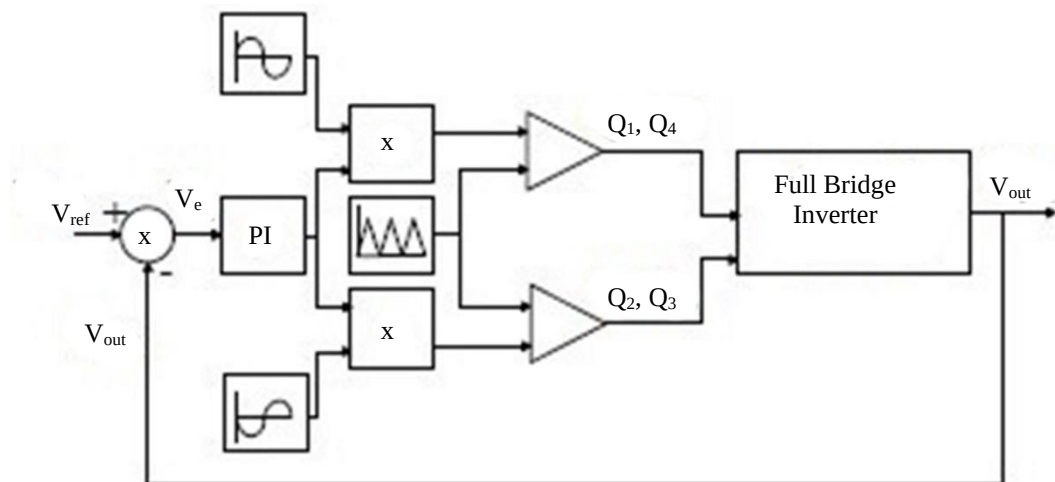


Figure 9. SPWM switching pulse generation with PI controller.

Fuzzy Logic Controller

The fuzzy logic controller performs the task of assigning the outputs based on the fuzzy if-then conditions and user provided information. The controller has been built with the knowledge base and the FI engine. The knowledge base has the membership functions and the fuzzy rules, which are deduced by information of the system's operation [18].

The Fuzzy Logic Designer displays information about a fuzzy inference system. For using the Fuzzy Logic Designer, the following MATLAB command has to be written in the MATLAB command window.

Fuzzy Logic Designer

Figure 10 shows the FLD where the FIS is displayed with the input variable names on the left and those of each output variable on the right [19].

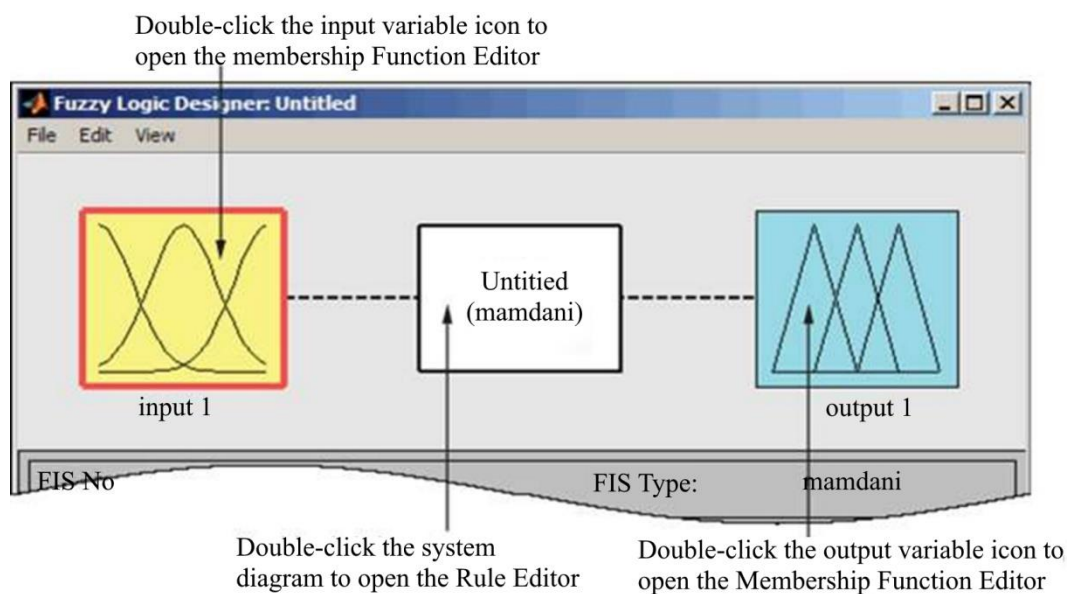


Figure 10. Fuzzy logic designer.

The Mamdani Inference system has been used in the model. The fuzzy inference system program is created, and it is then first imported to MATLAB and then exported to our MATLAB workspace (Figure 11).

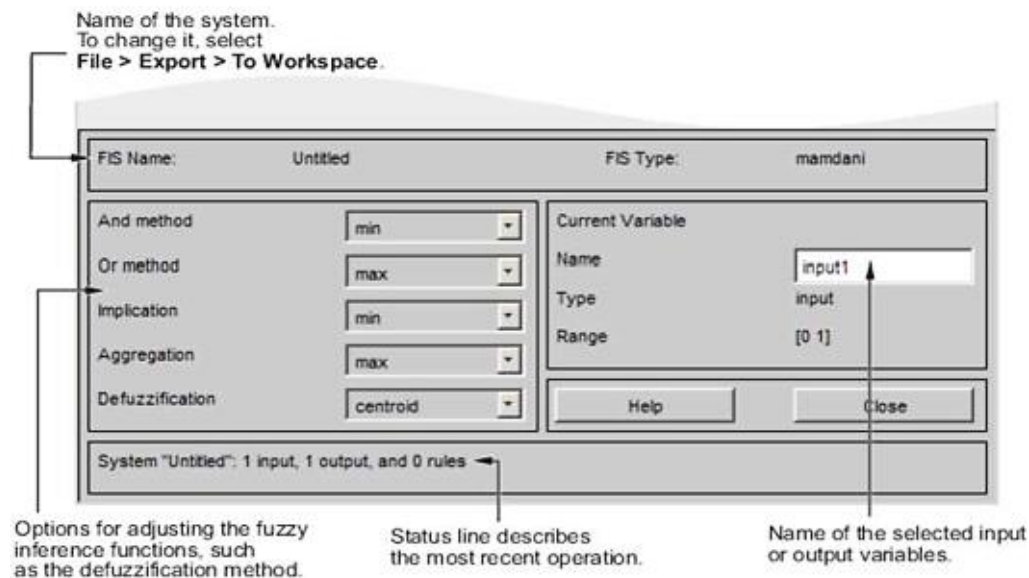


Figure 11. Type of inference used.

LC Filter

The output voltage harmonics of inverter are reduced by using LC filter in the inverter system. The output voltage harmonics can cause low power quality. The LC filter reduces harmonics present in the output and extracts high quality output voltage from the inverter generated output. The circuit diagram of LC filter is shown in Figure 12.

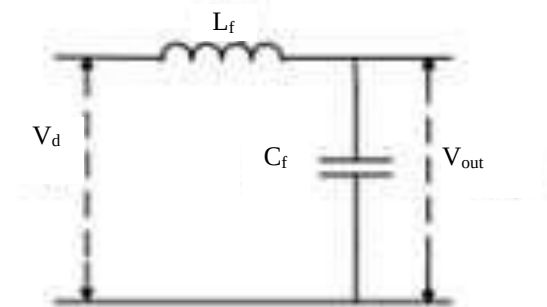


Figure 12. Structure of LC filter.

Filter Inductance and Capacitance Equations:

$$L_f = \frac{V_d}{4f_s \Delta i}$$

$$C_f = \frac{\Delta i}{8f_s \Delta V_o}$$

where V_d is dc bus voltage, Δi is ripple ratio of current, f_s is the switching frequency of H-bridge inverter and Δv is ripple ratio of output voltage (Table 4) [20–23].

Table 4. Calculated parameters of LC Filter.

xParameters	Value
C_f , Capacitor	7.5 μF
L_f , Inductor	259 mH
Switching frequency	10 kHz
Δi and Δv	3% and 5%

MATLAB SIMULATION AND RESULTS

The PV based MI model designed by MATLAB Simulink Software is shown in Figure 17 where the PV panel is placed first then, the boost converter is connected to the PV panel and HF transformer is connected to the output of the step-up converter. The H-bridge inverter is connected to the HF transformer HV side. Then the LC filter is connected to the H-bridge inverter. The temperature is constant for the designed PV system. Figure 15 shows the output voltage of boost converter that is tracked around 50V-59V against the changing irradiation condition on PV module. The output voltage of the boost converter is increased further at the output of HF transformer, and then it is supplied to the H-bridge inverter.

PV Panel Voltage and Current characteristics are shown in Figures 13 and 14 respectively.

The Boost Converter output voltage and the HF transformer output voltage is shown in Figure 15 and Figure 16 respectively (Figures 17.–19).

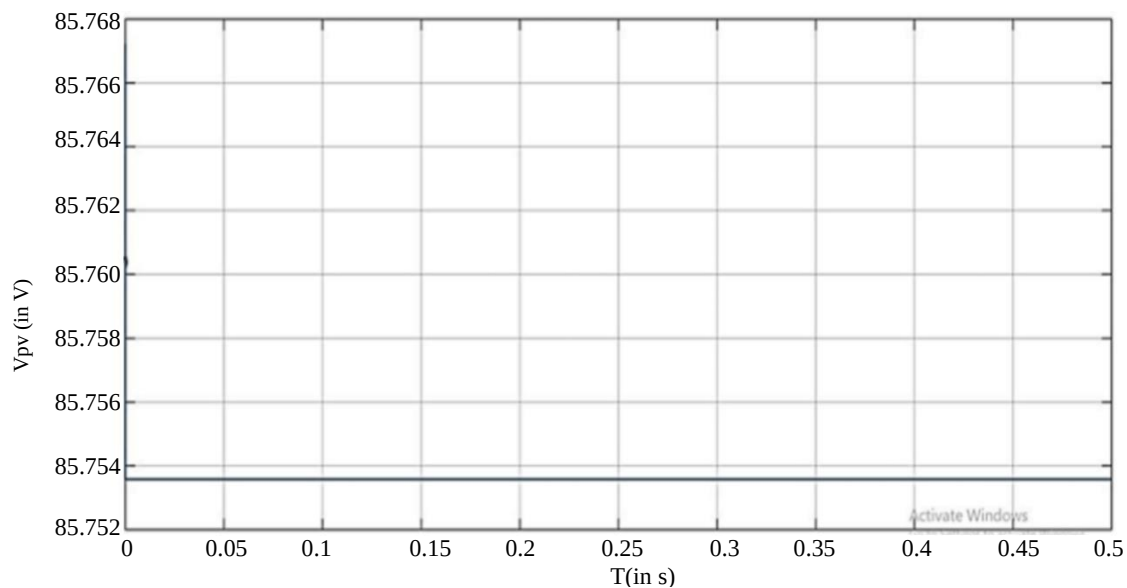


Figure 13. (PV panel Voltage vs Time):- Vpv values(y-axis values) are wrong. Inplace of (85.752,85.754,85.756,.....,85.768) values should be:(55.752,55.754,55.756,.....,55.768).

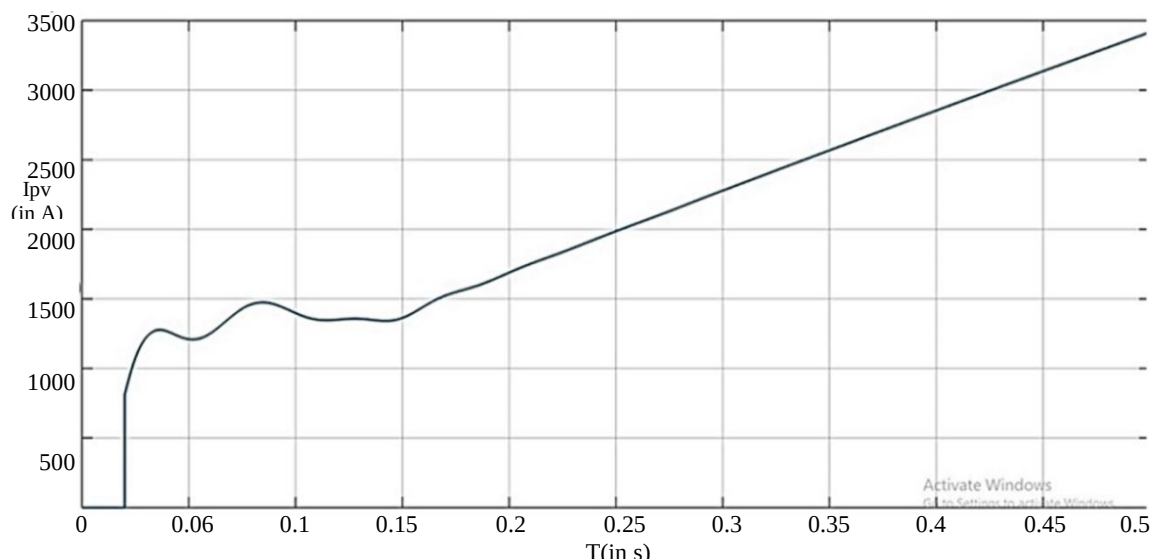


Figure 14. PV panel current vs. time.

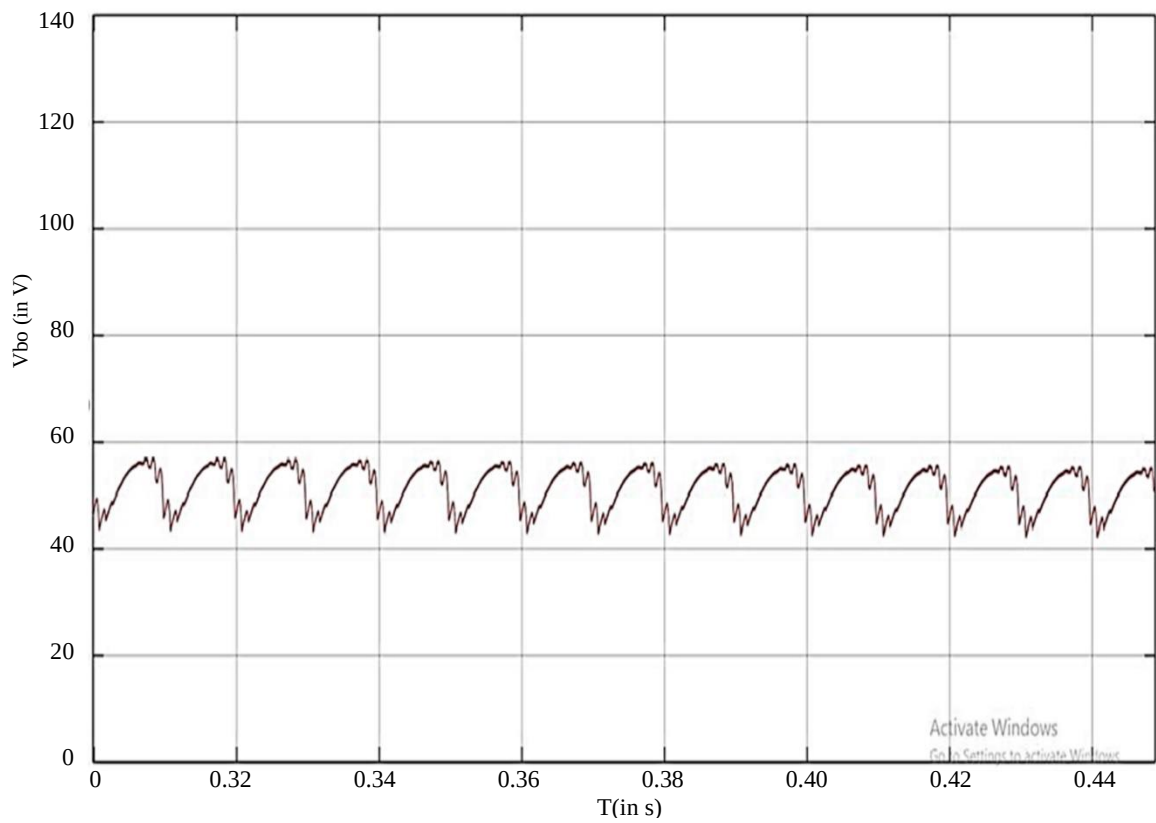


Figure 15. Step-up converter vout vs. time.

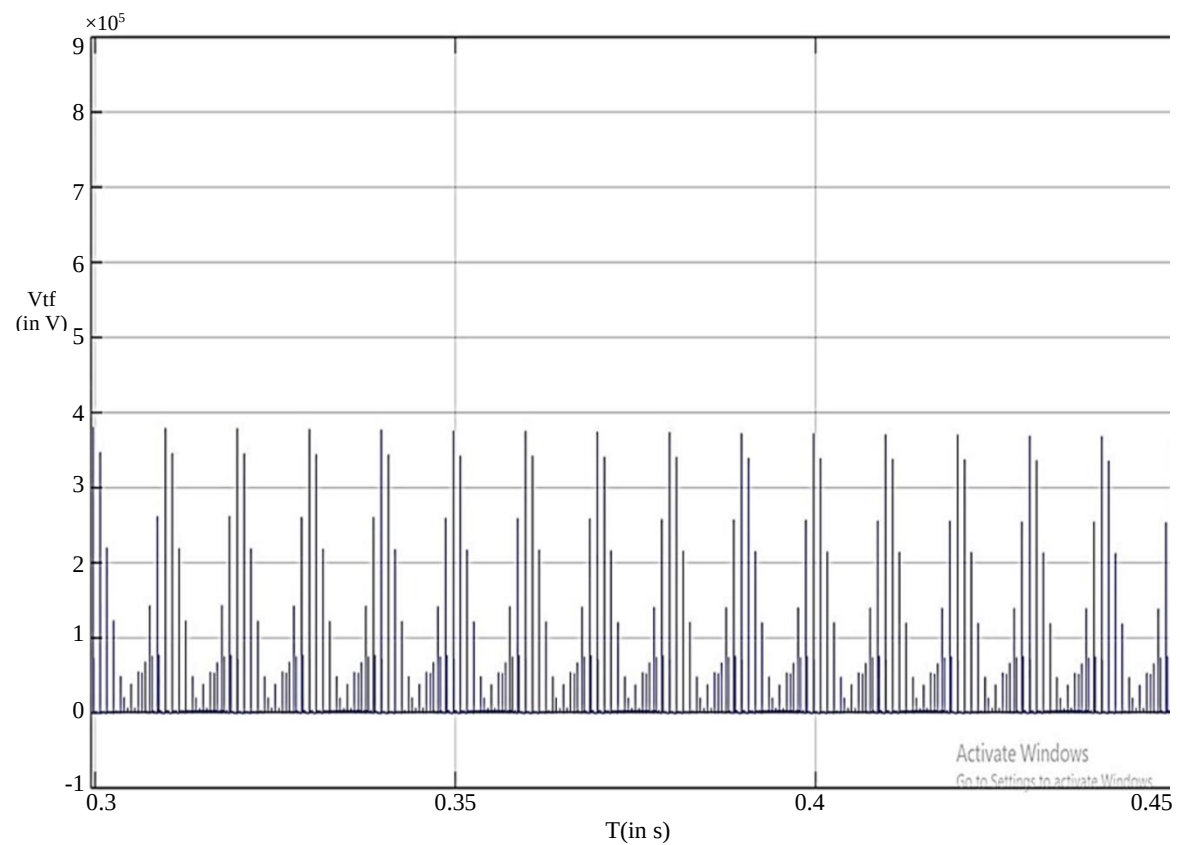


Figure 16. HF transformer HV side voltage vs. time.

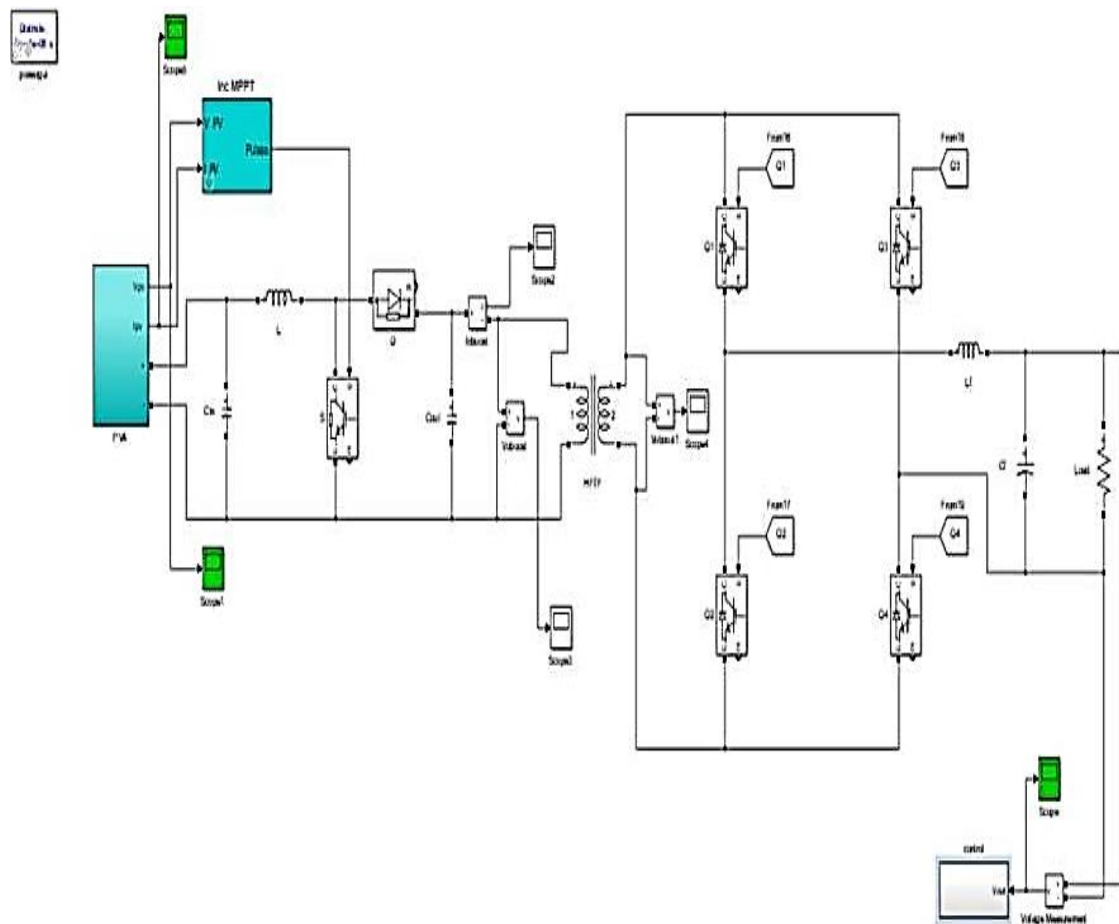


Figure 17. Structure of proposed Micro-Inverter.

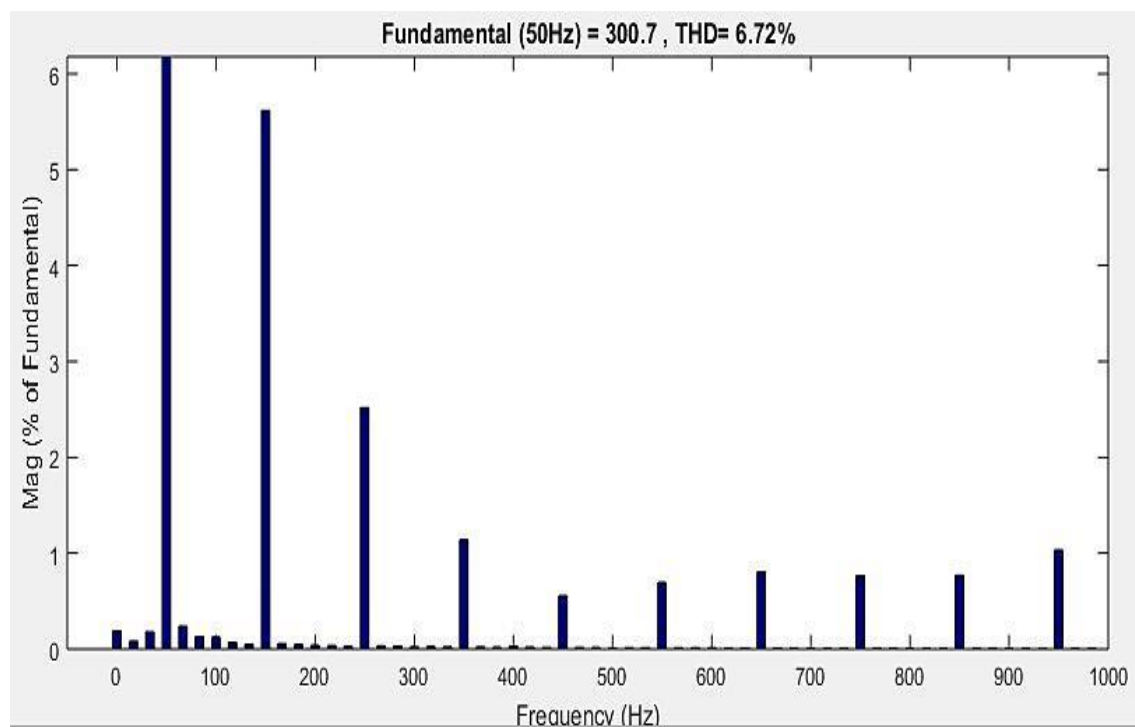


Figure 18. THD analyses using PI controller.

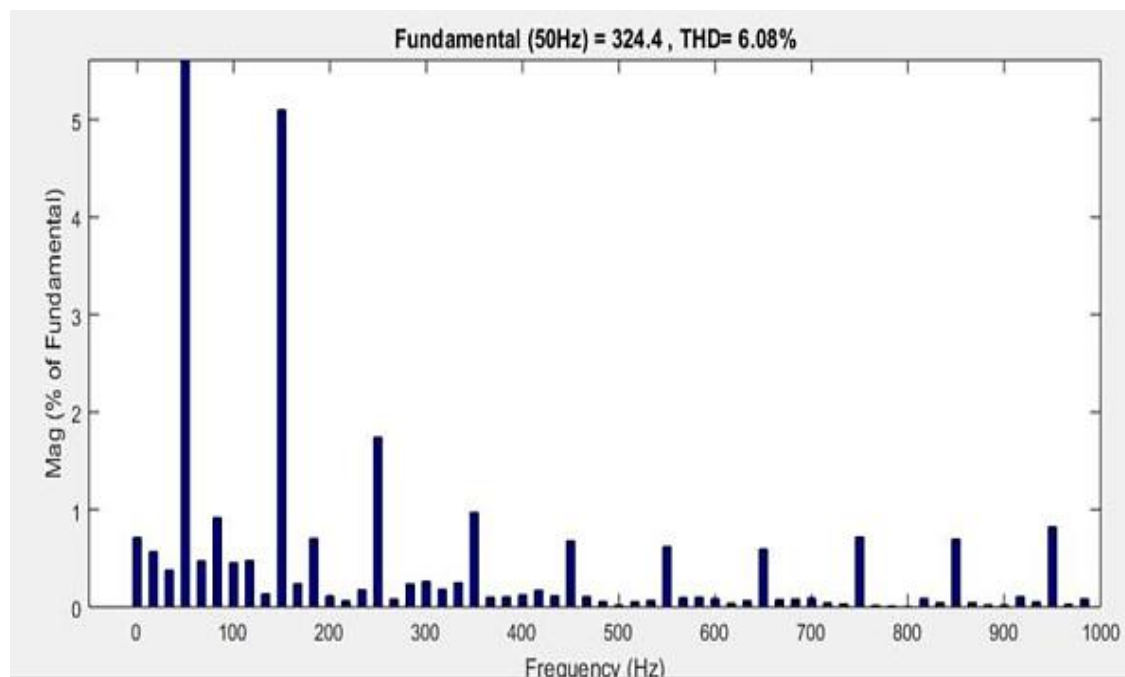


Figure 19. THD analyses using fuzzy logic controller.

CONCLUSIONS

This paper presents the analysis and design of a MI for single-phase PV energy system. The PV system is analyzed by simulating with MATLAB Simulink software under changing solar irradiation. The dc voltage of PV panel has been converted to ac voltage at the output of MI. Despite of increasing or decreasing solar irradiance, voltage output of the inverter does not change and is acquired as pure sine waveform. The terminal voltage is tracked at the reference value and it remains constant at desired value owing to controller operated H-bridge inverter. The output power and harmonic analysis is done using both the PI and Fuzzy Logic Controller and we can approve that the proposed inverter is capable to provide the power conversion at the required power rate and power quality. The THD analyses for the PI controller output gives 6.72% THD ratio, whereas with Fuzzy Logic Controller the THD ratio reduces to 6.08%. Hence it can be concluded that using the Fuzzy Logic controller provides better tracking of reference voltage of 230V rms and also reduces harmonic distortion value considerably in comparison with the PI controller.

In future studies, the proposed MI would use the fuzzy logic controller and its performance will be improved by adding Phase Locked Loop (PLL) for grid-tied applications.

REFERENCES

1. Kabalci E, Boyar A, Kabalci Y. Design and analysis of a MI for PV plants. Comput Artif Intell (ECAI), Targoviste, Romania 9th International Conference on Electronics. Vol. 2017; 2017. p. 1–6. doi: 10.1109/ECAI.2017.8166459.
2. KABALCI E, BOYAR A. Design and analysis of a single phase flyback MI 6th International Conference on Control Engineering & Information Technology (CEIT), Istanbul, Turkey, 2018; 2018. p. 1–6. doi: 10.1109/CEIT.2018.8751843.
3. Mahela OP, Shaik AG. Comprehensive overview of grid interfaced solar photovoltaic systems. Ren. Rew. 2017;68(February):316–32. doi: 10.1016/j.rser.2016.09.096.
4. Bagher AM, Vahid MMA, Mohsen M. Types of solar cells and application. Am J Opt Photonics. August 21 2015:94–113.
5. Dhivya R, Jaiganesh K, Duraiswamy Dr. K. MATLAB simulation of photovoltaic MI system using MPPT algorithm. Int J Sci Res vol. 4. December 2013:2077–82.

6. Diaz-Bernabe JL, Morales-Acevedo A. Simulation of a double-stage micro-inverter for grid-connected photovoltaic modules, in 2016. Electrical engineering. Mexico: Com (Coca-Cola enterprises inc), September 26–30 2016.
7. Panel SP PV; 14.05.2017. Available from: http://www.solar-facts-and-advice.com/supportfiles/sp_315ewh_en_ltr_p_ds.pdf.
8. Prabakaran N, Palanisamy K. 'Analysis and integration of multilevel inverter configuration with boost converters in a photovoltaic system', en Con Man vol. 2016;128(15):327–42.
9. Forouzesh M, Siwakoti YP, Gorji SA, Blaabjerg F, Lehman B. Step-up DC–DC converters: A comprehensive review of voltage boosting techniques, topologies, and applications. IEEE Trans Power Electron. March 2017;32(12):9143–78. doi: 10.1109/TPEL.2017.2652318.
10. Fathabadi H. Novel high efficiency DC/DC boost converter for using in photovoltaic systems. Sol Energy. 2016;125(February):22–31. doi: 10.1016/j.solener.2015.11.047.
11. Colak I, Kabalci E, Bal G. Parallel DC-AC conversion system based on separate solar farms with MPPT control, IEEE 8th international conference on Power Electronics, 2011, Jeju, Korea. p. 1469–75.
12. Kabalci Y, Kabalci E. The low cost voltage and current measurement device design for power converters. ECAI. 8th ed International Conference. Ploiești: ROMÂNIA; 2016–. p. 1–6.
13. Devi ML, Chilambarasan M. Design and simulation of incremental conductance MPPT using self lift cuk converter. Vol. 2013. India: ICRESE; 2013. p. 105–11.
14. Abatan OA, Egunjobi AI, Musari AA, Oseni KJ, Edun AT, Sodunke MA. Design of 50-kVA single phase static inverter. Int J Adv Eng. 2014;4(August):319–24.
15. Colak I, Kabalci E. Developing a novel sinusoidal pulse width modulation (SPWM) technique to eliminate side band harmonics. IJEPES. 2013;44(1):861–71. doi: 10.1016/j.ijepes.2012.08.024.
16. Kahlane AEWH, Hassaine L, Kherchi M. LCL filter design for photovoltaic grid connected systems. Rev Energ Renouvelables SIENR. 2014;227–32.
17. Yong BH, Ramachandaramurthy VK. 'Harmonic Mitigation of grid connected 5MW solar PV using LCL filter,' 3rd CEAT. Kuching, Malaysia; 2014. p. 1–6.
18. IEEE recommended practice and requirements for harmonic control in electric power systems, IEEE Standard 519–2014. June 2014;19 EPSMA. IEC61000–3–2:1–29.
19. Kivimäki J, Kolesnik S, Sitbon M, Suntio T, Kuperman A. Revisited perturbation frequency design guideline for direct fixed-step maximum Power Point tracking algorithms. IEEE Trans Ind Electron. 2017;64(6):4601–9. doi: 10.1109/TIE.2017.2674589.
20. Elgendy MA, Zahawi B, Atkinson DJ. Operating characteristics of the P&O algorithm at high perturbation frequencies for standalone PV systems. IEEE Trans Energy Convers. 2015;30(1):189–98. doi: 10.1109/TEC.2014.2331391.
21. Kjaer SB. Evaluation of the Hill Climbing' and the incremental conductance maximum PowerPoint trackers for photovoltaic power systems. IEEE Trans Energy Convers. 2012;27:922–9.
22. Kuo C-L, Lin C-H, Yau H-T, Chen J-L. Using self synchronization error dynamics formulation based controller for maximum photovoltaic power tracking in micro-grid systems. IEEE J Emerg Sel Top Circuits Syst. 2013;3(3):459–67. doi: 10.1109/JETCAS.2013.2272839.
23. Lin W-M, Hong C-M, Chen C-H. Neural-network-based MPPT control of a stand-alone hybrid power generation system. IEEE Trans Power Electron. 2011;26(12):3571–81. doi: 10.1109/TPEL.2011.2161775.