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Three-phase Inverter with Fuzzy Logic Control (FLC) based Maximum Power Point Tracking (MPPT) technique for Grid Connected Photovoltaic (GCPV) System

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Abstract

The performance of the Photovoltaic (PV) System is dependent upon the environment conditions due to the variation of the solar irradiance and cell temperature. This affects the quality of the output voltage that is generated by the photovoltaic modules. To overcome these challenges, an artificial intelligence approach is implemented into the system. The objective of the proposed work is to develop a boost converter to control the output power generated by the photovoltaic modules by increasing the output power. In order to adjust power factor and power for a three-phase grid inverter system, the boost converter is integrated with a three-phase inverter that uses the Pulse Width Modulation (PWM) control approach. Since it's the most important component of any grid-connected system and enables the source generated to feed into the grid, it evolved to control power to the grid. Therefore, the three-phase inverter with PWM control is proposed to optimize the performance of the PV system. A Fuzzy Logic Control (FLC) is implemented in the system as an artificial intelligence alternative for a PV system that works rapidly, accurately, and efficiently to track the Maximum Power Point (MPP) under varying weather conditions and solar irradiation. By using the FLC, the constraints that come from conventional technologies could be improved and a better grid-connected photovoltaic system be provided. The proposed PV system is modelled and simulated in MATLAB/Simulink. The simulations results are presented.

Keywords: Boost Converter, Three-phase Inverter, Pulse Width Modulation (PWM), Fuzzy Logic Control (FLC), Maximum Power Point Tracking (MPPT)

Introduction

Renewable energy is "clean" energy that originates from natural sources or processes that renew themselves on a regular basis. It is expected to be the primary energy source for future power generation (Jiang et. al., 2018). The renewable energy sources presently provide somewhere between 15% and 20% of world's total energy demand and in fact it also guarantee steady power supply. Figure 1 defines the annual growth for renewable electricity generation by source from 2018 to 2020. According to Figure 1, the most prominent technologies that ensure the increase of renewable energy production are wind power and solar technology (Ayadi et. al, 2020). Due to advancements in power electronic technology, solar photovoltaic (PV) energy has been recognised as an important natural energy resource since it is clean, affordable, and pollution-free (Kotha et. al., 2010).

Solar photovoltaic power generation is one of the widely used energy sources in recent years. Photovoltaic cells convert light energy into electrical energy, the photoelectric conversion efficiency influenced by light intensity and temperature, in order to get maximum power, the maximum power point tracking circuit or controller integrated between photovoltaic system and output load (Jiang et. al., 2018). PV system supplying DC power source so an inverter is required because many researchers have propose various inverter controllers since the ability to generate a good sinusoidal voltage waveform is the most crucial quality of a good inverter (Mutlag et. al., 2013). The development of grid-connected photovoltaic solar cells has increased in recent years due to the growing need for electricity. Grid-connected PV systems have a number of advantages, including the fact that they are pollution-free and do not affect the environment and they can meet the need for AC loads. As a result, the grid's load demand is lower (Hota et. al., 2020).

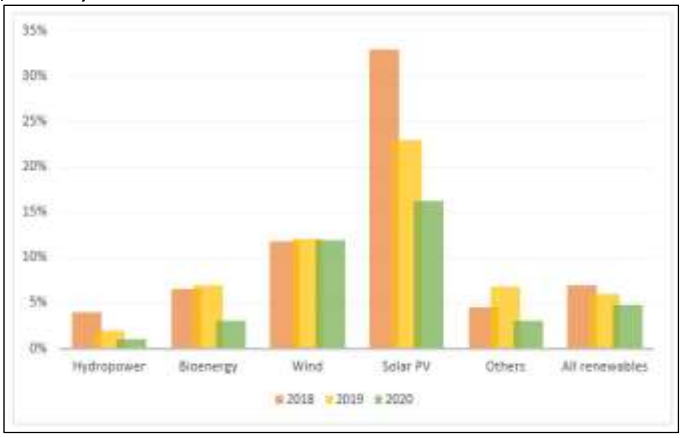

Figure 1. Annual growth for renewable electricity generation by sources in year 2018 until 2020 (Ayadi et. al., 2020)

Solar energy as an electrical power generator has been contributing some benefits to economic growth. It can generate electricity for your home and business without being concerned about hefty maintenance costs, so it will be a good investment. People who invest in solar energy have received a significantly reduced amount on their utility bill each month. Their money will be greatly saved as there is no longer a requirement for homeowners and business owners to depend only on electricity from electric companies. They also can avoid being affected by the rise in electricity rates (Verma et. al., 2017). Through solar energy systems, an employment opportunity is generated. An increase in energy workers is required to keep up with demand as more consumers express interest in installing solar panels. Jobs in manufacturing, installation, and maintenance are needed in this industry. Our local economy will be boosted by the investment in solar, which also creates new job opportunities. Besides, installing solar power at a house can increase the owner's home's resale value, as for the new homeowner, they will receive a lot of convenience provided by the solar power system. Natural disasters can interrupt the grid's ability to provide power, therefore solar power is beneficial in an emergency. Solar energy can still be used to generate electricity during a natural disaster since the sun still generates the energy required to run solar panels when other energy sources, like fossil fuels, aren't available. A further advantage of adding solar electricity is known as net metering, which lets you sell any excess solar energy you create to the utility provider. When the solar energy system generates more electricity than what is required for your home. You receive payment from your utility for the excess electricity that is transferred to the power grid. Rooftop solar panels are a good way to save money because of net metering.

The photovoltaic system must have to operate near MPP to obtain high efficiency for the PV output. This could be obtained by design and develop a suitable MPPT controller (Kotha et. al., 2010). In the past years, there are many MPPT algorithms that had been developed to give a great performance for the solar technology. Each of the MPPT algorithm varies in application, complexity, precision, sensors, cost, popularity, etc. (Khanaki et. al., 2013). Conventional MPPT algorithm provide a simplicity to design such as Perturb and Observe (P&O) and Hill Climbing. Perturb and Observe (P&O) method have to calculate dP/dV to determine the MPP. Though it is relatively simple to implement, it cannot track the MPP when the irradiance changes rapidly and it oscillates around the MPP instead of directly tracking it. Other existing conventional method that give similar problems are the incremental conductance method can track MPP rapidly but complexity of the algorithm is increases, which employs the calculation of dI/dV. Next, the constant voltage method, which uses 76% open circuit voltage as the MPP voltage and the short circuit current method are simple, but they do not always accurately track MPP (Kotha et. al., 2010). Therefore, conventional MPPT method resulting in low performance when working under rapidly changing of solar irradiation and oscillation also not be able to track the MPP effectively in cloudy weather conditions (Javed et. al., 2020). The reason to develop and integrate the best MPPT controller for photovoltaic system is required (Ayadi et. al., 2020). Therefore, the limitation of using the photovoltaic module as an electricity generator is that it is only able to produce a DC source, which is incompatible with supplying electricity to the grid system. An AC voltage source is needed to meet the requirements for the three-phase utility grid. The AC source also needs to be controlled in order to operate at the right voltage and frequency. Therefore, Artificial Intelligence based MPPT technique is proposed in this work.

There are three objectives that are focused on in this work are as followed.

- Modelling the DC-DC boost converter to extract the Maximum Power (MP) from PV modules under various solar irradiance and cell temperature values.
- Implement Grid connected Photovoltaic (GCPV) system with Fuzzy Logic Control (FLC) based Maximum Power Point Tracking (MPPT).
- Develop three-phase inverter to control power to the grid with unity power factor.

The MPPT is to track the PV modules' MPP and to keep the PV system's accuracy and efficiency high under all circumstances, particularly when the weather and solar irradiation are changing. As an artificially intelligent MPPT method, FLC is chosen for this work because it is robust, relatively simple to design, and does not require knowledge of a precise model (Subiyanto et. al., 2009). This method requires linguistic rules in the design; there is no mathematical model for the system; and expert qualitative control expression in fuzzy languages may be used to control it (Mutlag et. al., 2013). FLC also provides improved tracking performance compared with the conventional methods (Usmani et. al., 2017). By using FLC, we can overcome the disadvantages of conventional methods. Furthermore, the third objective is to develop the power converter for the system where it consists of a DC-DC boost converter and a three-phase inverter. A boost converter is used to increase the photovoltaic output voltage, and it can also extract the MPP from the PV module under different solar irradiance and cell temperature conditions. Output of the boost converter is transferred to the three-phase inverter, as it needs to convert the DC supply to the AC supply to meet the requirements needed for the three-phase utility grid.

Method

In this work, PV modules brand Yingli Energy (China) YL265C-30b is used for the power generation of the system. The DC-DC boost is developed as a support for the MPPT controller. It was utilized as a regulator of the PV module's output voltage to drive the PV modules to get maximum power when the solar irradiance and temperature level changed.

Overview of the System

The proposed Three-phase Inverter with FLC based MPPT technique for GCPV system is developed as shown in Figure 2.

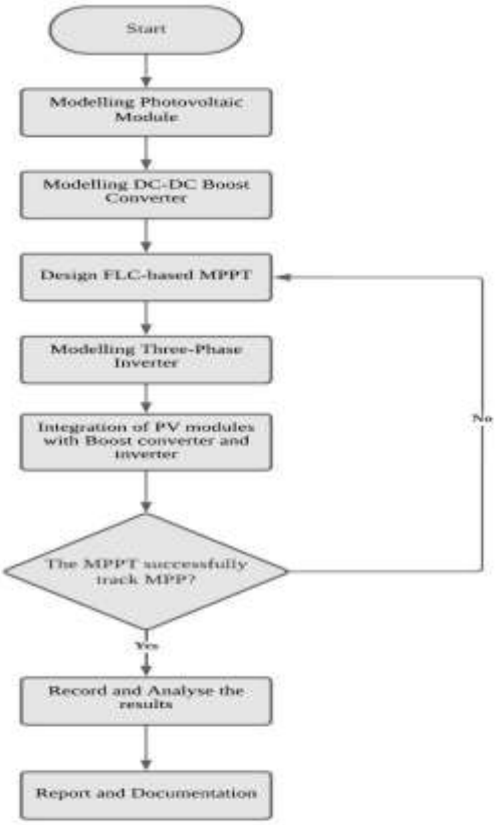

Figure 2. The prototype operation flowchart

The boost converter operate at output voltage bigger in magnitude than its input voltage. FLC designed as the MPPT to track the maximum power from the PV modules. The Three-phase inverter is used to convert DC to AC and fed to the grid. Then, the FLC is integrated with the

PV system. If the MPPT controller successfully tracks the maximum power point, the system is optimized the performance of the PV system.

Three-phase Grid Connected Photovoltaic System

Three-phase Inverter with FLC based MPPT technique for Grid Connected Photovoltaic System is developed as shown in Figure 3. The system consists of PV modules, DC-DC Boost Converter, Three-phase Inverter, FLC and the grid. The PV modules received the solar energy and transmits the generated power to the DC-DC boost converter. The basic function of a boost converter is to convert a DC voltage from one level to another. The output power changes according to temperature and irradiance intensity fluctuations.

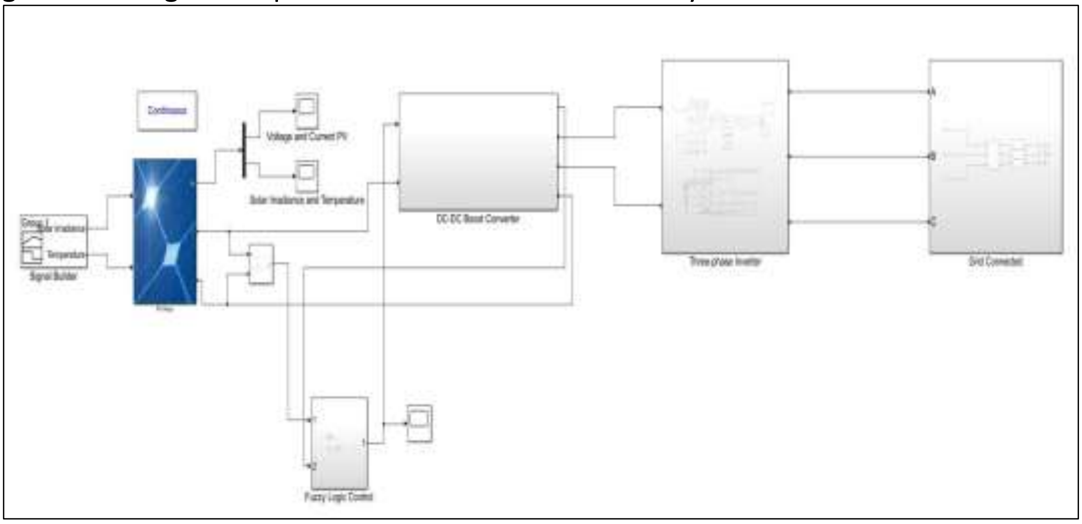

Figure 3. Three-phase Grid Connected Photovoltaic System

The three-phase inverter as shown in Figure 4, operates to convert the DC output to the AC output with the help of PWM. This three-phase inverter are capable of producing AC voltages of variable magnitude and frequency where it have been knowing as the most used power electronic circuits in practical applications. PWM generator controls the triangular wave and sine wave, then transfers the both waves to the gate pulses through 6 IGBT switches. The DC input supply connected to 6 IGBT switches is corresponds with triangular and sine waves. Three-phase AC source is generated and is transferred through LC filters to decrease the Total Harmonic Distortion (THD) in the waveform before being fed into the grid. The inverter extracts as much DC electricity as possible from the PV modules and converts it into AC electricity at the right voltage and frequency. At the grid, the step-up transformer is used as to step-up three-phase voltage to 415Vrms, to meet the requirement needed for the three-phase utility grid.

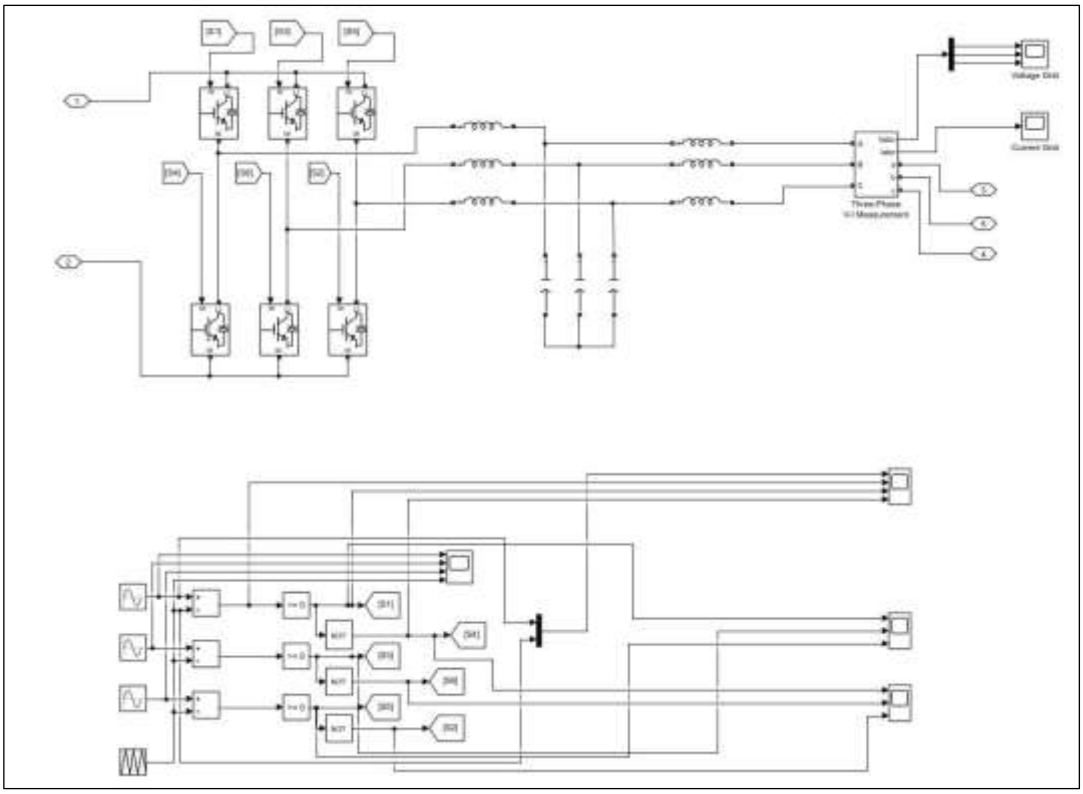

Figure 4. Three-phase Inverter

Fuzzy Logic Control (FLC) is implemented to track maximum power of a solar photovoltaic energy conversion system while at the same time the output power produced from the PV modules can be increased. A Fuzzy Logic control (FLC) which is one of Artificial Intelligence method would be used as its ability to track the maximum power point of PV panel under varying conditions such as temperature, solar irradiance, partial shading and load variation. This method will maintain high efficiency PV system in all conditions.

PV Module Parameter

In this work, PV modules Yingli Energy (China) YL265C-30b has been modelled in MATLAB/Simulink. The detailed specifications parameter of PV modules are given in Table 1.

Table 1

Parameters of Yingli Energy (China) YL265C-30b

Maximum Power (Pmax)	265.2174W
Volatge at at Pmax (Vmpp)	30.38V
Current at Pmax (Impp)	8.73A
Open Circuit Voltage(Voc)	38.28V
Short Circuit Current (Isc)	9.35A
Temperature coefficient of Isc	0.044%/ K
Temperature coefficient of Voc	-0.3%/ K
Temperature coefficient of Pmax	-0.45%/ K
Normal Working Cell Temperature	25°C

DC to DC Boost Converter

A boost converter is one of the simplest types of switch mode converter. As implied by the name, it boosts an input voltage. It is made up only of an inductor, an IGBT semiconductor switch, a diode, and a capacitor. Figure 5 below shows the boost converter developed in the system for this project. The voltage magnitude of the output boost bridge circuit needs to be almost constant to enable the inverter to convert the voltage to pure sine wave. The modulation index regulates the switching pattern of the boost converter. Therefore, the converter enables to track the MPP from the PV modules.

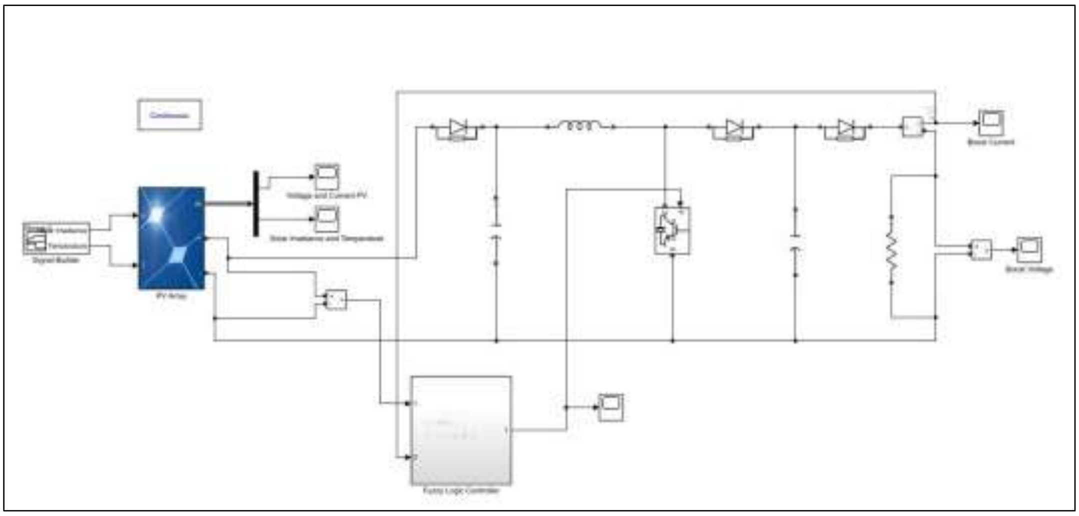

Figure 5. DC-DC Boost converter

MPPT using Fuzzy Logic Controller

The main components in a FLC are Fuzzification, Inference Unit, Rule Based and Defuzzification as shown in Figure 6.

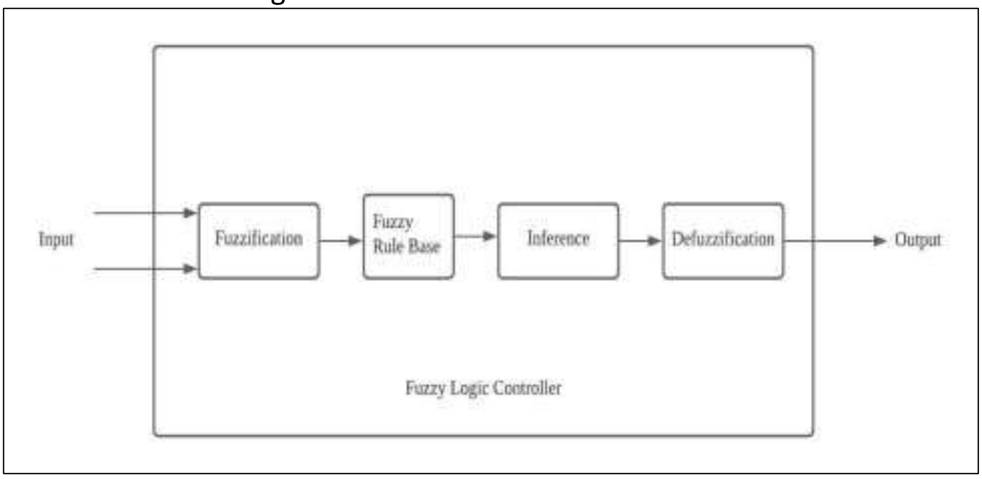

Figure 6. Structure of a Fuzzy Logic Control (FLC)

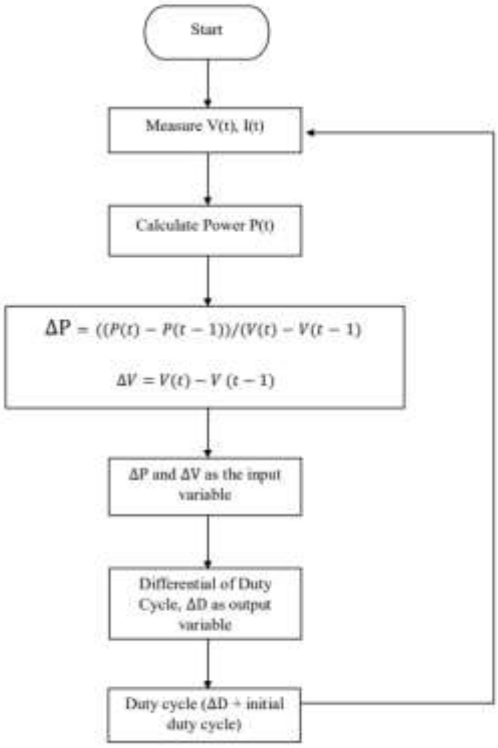

Figure 7. Flowchart of Fuzzy Logic Control (FLC) as MPPT

In Figure 7 shows a flowchart of FLC as MPPT operates in tracking the maximum power point (MPP) in the system. It starts with measure V(t) and I(t). Next, the power $P(t)$ is calculated by using the formula $P(t) = I(t) * V(t)$. Then, the ΔP and ΔV is calculated by using the formula in (1) and (2) respectively,

$$\Delta P = ((P(t) - P(t-1))/(V(t) - V(t-1) \quad (1)$$

$$\Delta V = V(t) - V\,(t-1) \quad (2)$$

After ΔP and ΔV are calculated, this input result is observed in the Fuzzification. In this stage, the crisp input variables are transformed into linguistic variables based on the membership function. The ΔP and ΔV is the input variable and the output variable is change in duty cycle (ΔD). The simulation model is shown in Figure 8. The details operation of FLC component to generate modulation index are divided into three which are; Fuzzification, Inference Unit and Rule Based and Defuzzification.

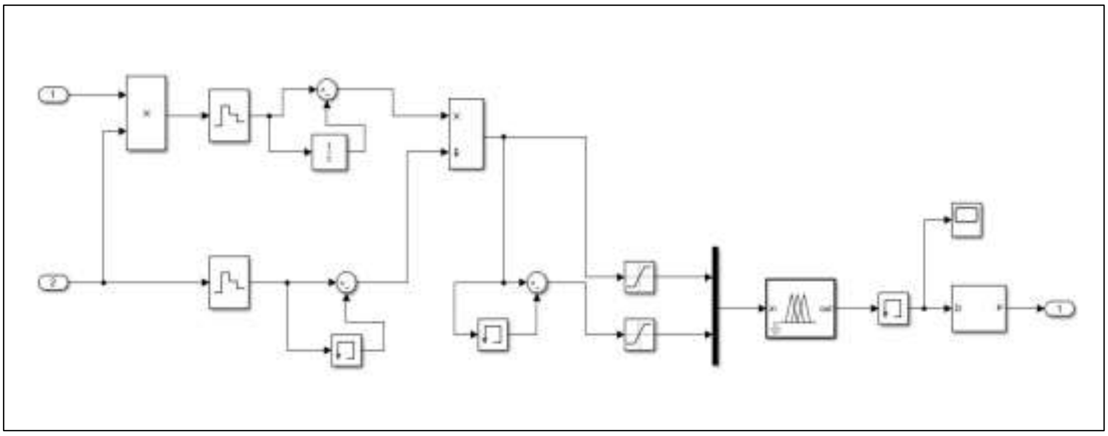

Figure 8. Fuzzy Logic Control (FLC)

Fuzzification

Membership function values are given to the linguistic variables, using five fuzzy sets which are negative small (NS), negative big (NB), positive small (PS), positive big (PB) and zero (ZE). The division of fuzzy subsets and the form of membership functions, which can adapt shape up to opportune system, are shown in Figure 9, 10 and 11. It shows the membership function for the inputs of the current power and the previous power ΔP, the current voltage and the previous voltage ΔV, and the output of the current duty cycle and the previous duty cycle ΔD.

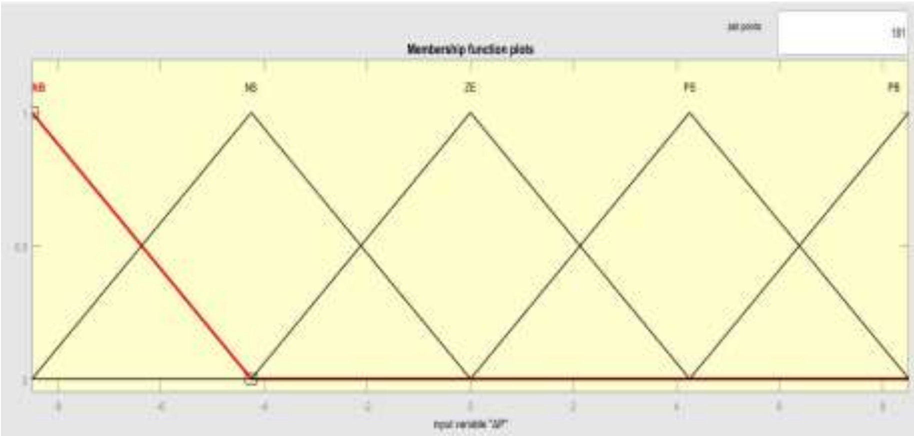

Figure 9. Membership functions plot for ΔP

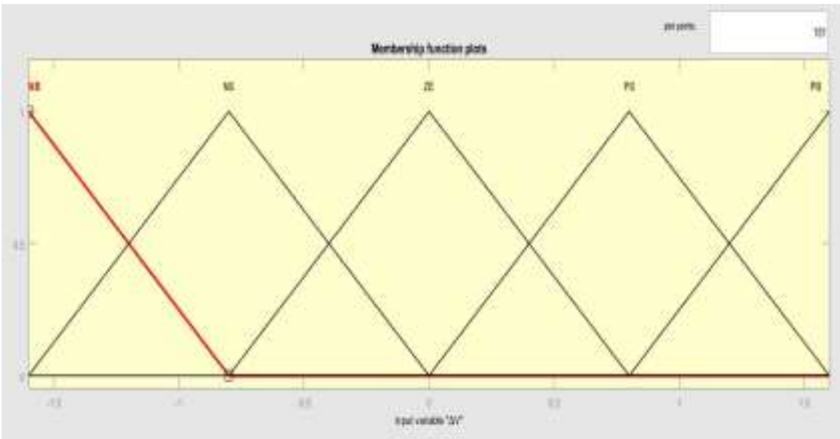

Figure 10. Membership functions plot for ΔV

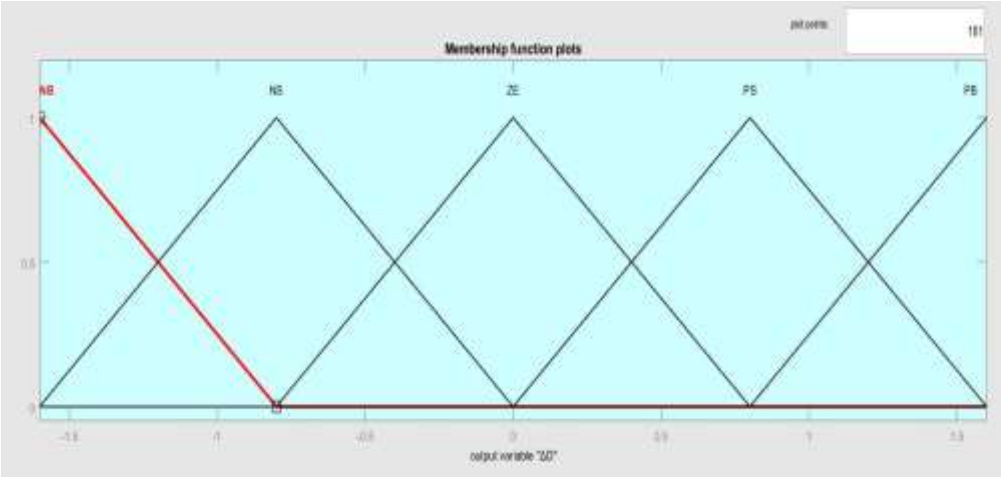

Figure 11. Membership functions plot for ΔD

Inference Unit and Rule based

The fuzzy implication sub-blocks and the Fuzzy Rule-Based are the main components of the inference method. The inputs are immediately fuzzified and sustained to the inference motor, after which the rule-based model is applied. The output fuzzy set is the identifier using the fuzzy implication method.

Table 2
Fuzzy rule-table

ΔD[o/p]	ΔV[i/p]					
ΔP[i/p]		NB	NS	ZE	PS	PB
	NB	PS	PB	NB	NB	NS
	NS	PS	PS	NS	NS	NS
	ZE	ZE	ZE	ZE	ZE	ZE
	PS	NS	NS	PS	PS	PS
	PB	NS	NB	PB	PB	PS

There are fuzzy sets that are implemented in the Fuzzification and Defuzzification processes to control the input and output variables. The FLC determines the next operational point based on the input result, using membership functions and a rule table. Once ΔP and the ΔE are evaluated, in the inference engine step, the value is turned into linguistic variables via the membership functions, and a decision is determined based on the fuzzy rule-table in Table 2.

Defuzzification

Defuzzification is required to convert the linguistic fuzzy sets back into their mathematical equivalents. The crisp output (ΔD) of the FLC is added to the initial value of duty cycle. Therefore, the result of duty cycle (D) is transferred to the DC-DC boost converter. Duty cycle, the output of FLC uses to control through PWM which made the pulse to control IGBT switch in DC-DC boost converter.

Results and Discussion

The result and discussion for Three-phase Inverter with FLC based MPPT technique for Grid Connected Photovoltaic System is presented. Steady-state test and Dynamic test have been tested and observed. Figure 3 shows the overall simulation model for this work.

Steady-state Test

Steady-state or static condition means the MPPT algorithm is operated under constant solar irradiance and temperature. Figures 12 shows the voltage and current generated from photovoltaic module at 1000W/m2 solar irradiance and 70̊C temperature. The voltage and current generated from PV module is 32.30V and 24.17A respectively. Figure 13 and 14 shows the voltage and current boosted from DC-DC boost converter. The boost converter successfully boosted the voltage of the PV module to the 34.42V but the current is decreased to the 3.442A from the actual output PV module due to the resistor. Therefore, there is a constant waveform of boost voltage and current.

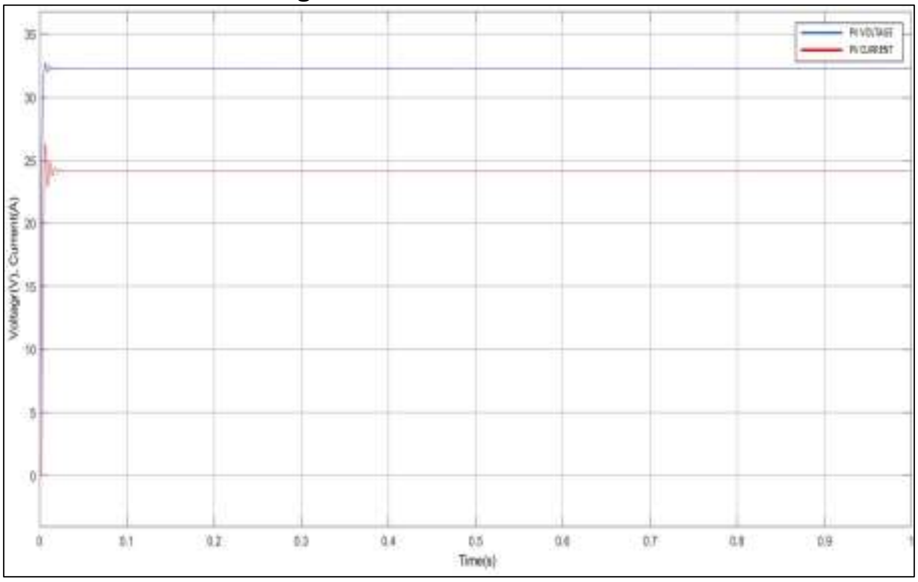

Figure 12. Voltage and current of PV module

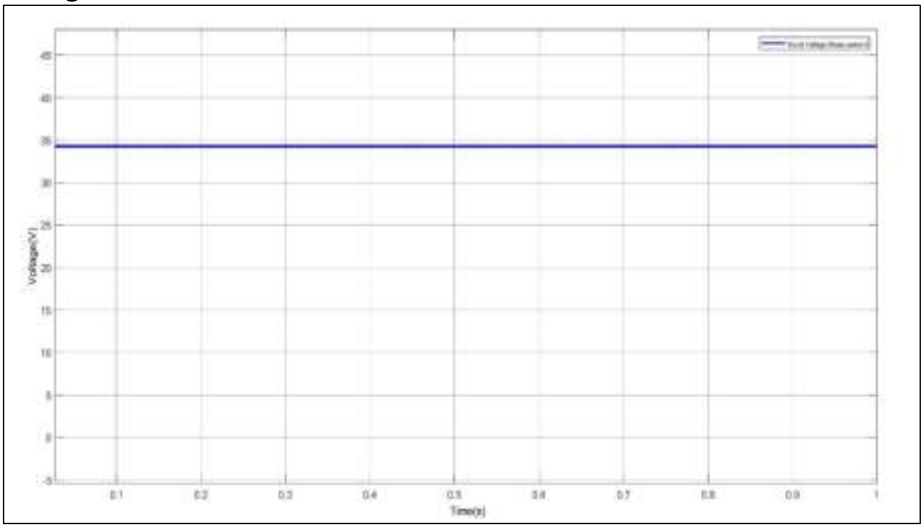

Figure 13. Voltage of DC-DC boost converter

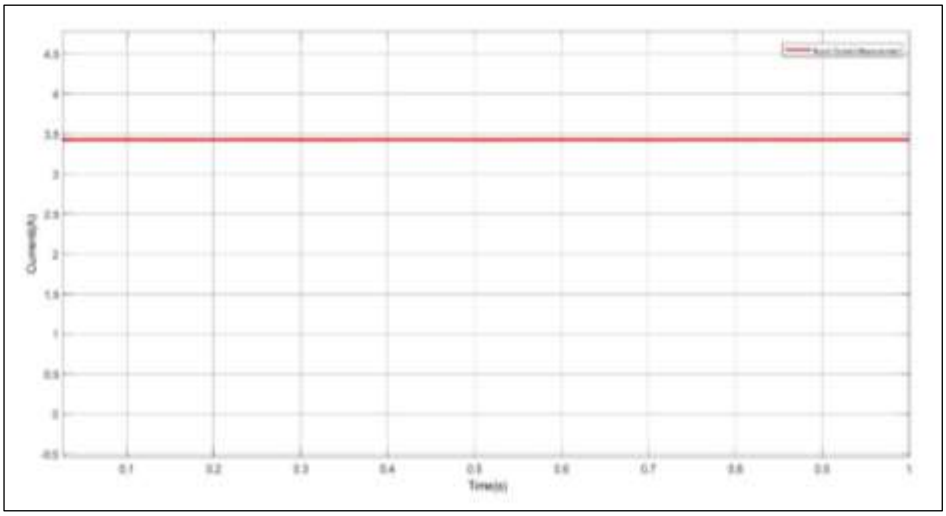

Figure 14. Current of DC-DC boost converter

Dynamic Test

Dynamic test where the MPPT dynamic response is tested by varies the solar irradiance and module temperature. The variations of the solar irradiance and temperature to observe the dynamic response test is set between 600 W/m2-1000W/m2 and 45̊ C-65̊ C respectively. This variation aims to apply real environmental conditions into the simulation model. This solar irradiance and temperature variations is set by using 'Signal Builder' in MATLAB/Simulink as shown in Figure 15.

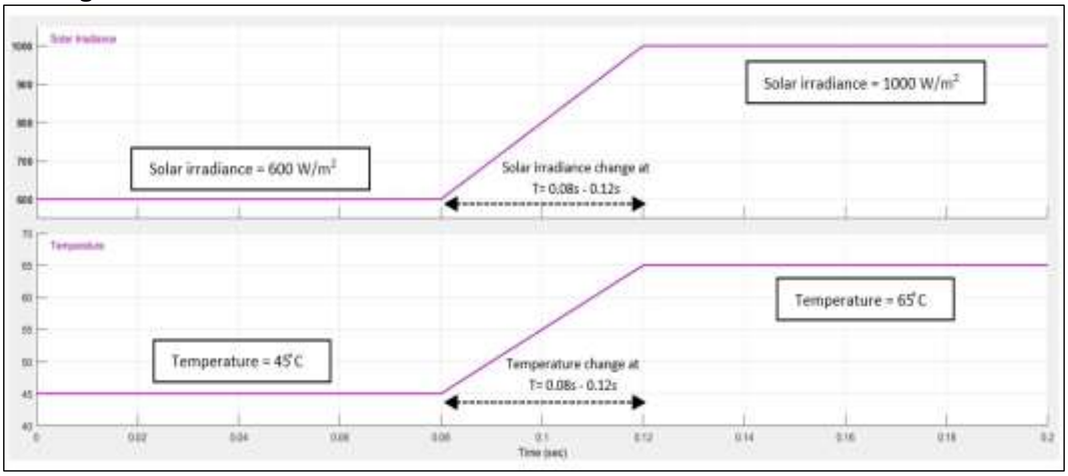

Figure 15. Variation of solar irradiance and temperature

In the actual condition, solar irradiance may change within 300ms or less, therefore MPP tracker need to response fast and accurate to get the optimum output from the PV module. Figure 17 and 18 shows that the voltage and current is drop around 1.5V, this happened because of the solar irradiance and temperature changed. The voltage is boosted but the current is decrease due to the resistor.

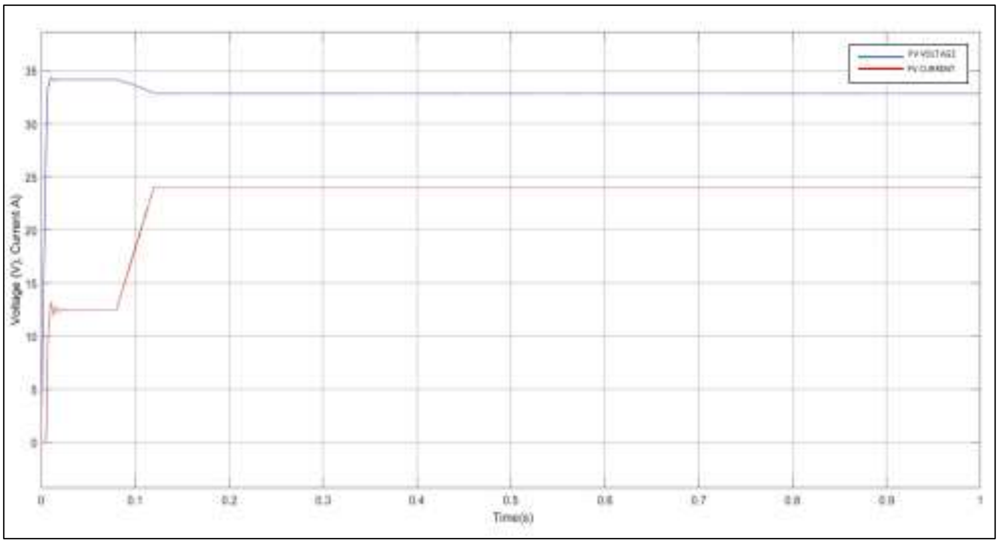

Figure 16. Voltage and current from PV module

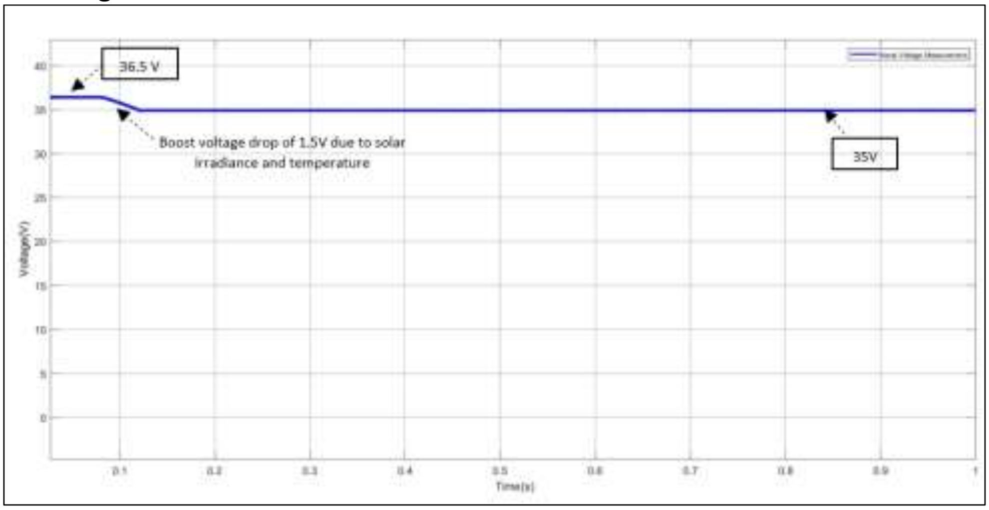

Figure 17. Voltage of DC-DC boost converter

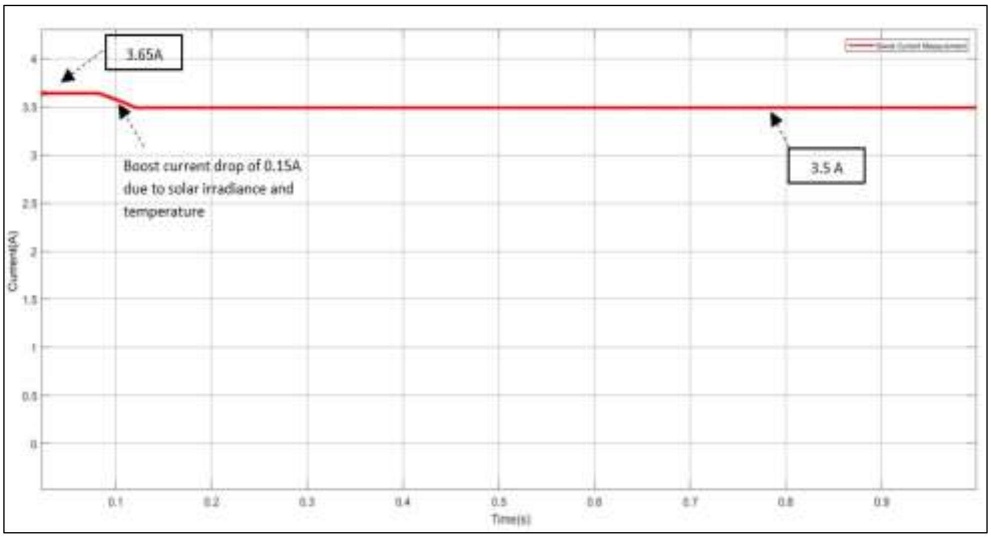

Figure 18. Current of DC-DC boost converter

AC Voltage and Current Waveform for Three-phase Grid Connected Photovoltaic System

The output AC voltage and current which are injected in the grid are represent in Figure 19 and 20, respectively.

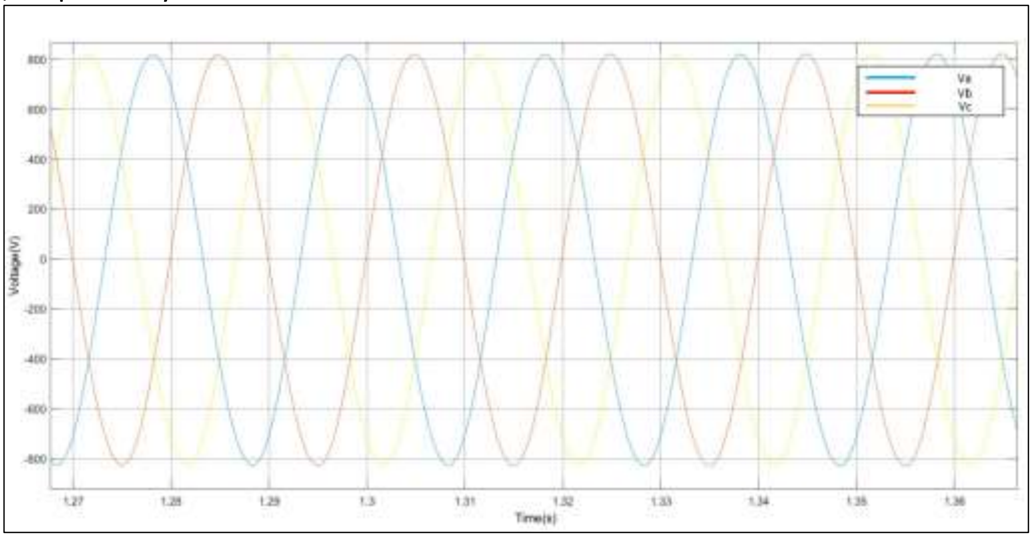

Figure 19. Voltage of Grid Connected PV system

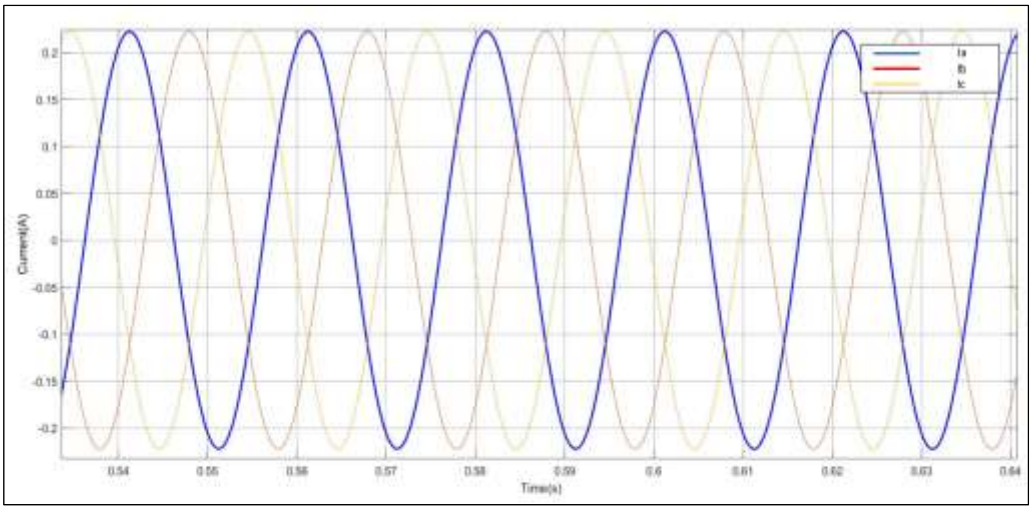

Figure 20. Current of Grid Connected PV system

Harmonic Distortion (THD)

The THD is a measurement of the harmonic distortion present in a signal and is defined as the ratio of the sum of the powers of all harmonic components to the power of the fundamental frequency. Three-phase Inverter with FLC based MPPT technique for Grid connected Photovoltaic System must supply the three-phase voltage source with a low THD value as to avoid noise or distortion on the equipment at the grid side. Figure 21 shows the THD value obtained for the three-phase voltage. THD obtained is 1.04% where it's acceptable value as to have a good system the voltage THD should not exceed 5%. There are LC filters that are connected at the three-phase inverter where these LC filters reduce the harmonic currents flowing in the power system from the source and thereby reduce the harmonic voltage distortion in the system, resulting in a low value of THD voltage.

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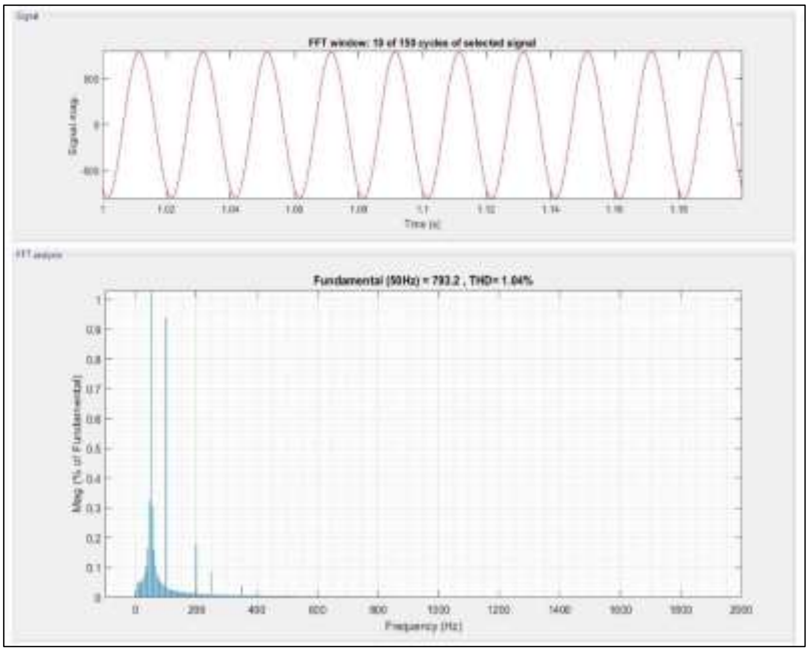

Figure 21. THD of Grid Connected PV system

Conclusion

As the performance of the photovoltaic module is dependent upon the environmental conditions due to the variation of solar irradiance and cell temperature, this leads to the quality of the output voltage that is generated by the photovoltaic module. From this work's objectives it achieved to overcome these challenges. The grid-connected photovoltaic system incorporates a power converter that tracks the Maximum Power Point (MPP) of photovoltaic modules by using artificial intelligence, which is Fuzzy Logic Control (FLC). It managed to track MPP fast and accurately while also being high in efficiency. The DC-DC boost converter developed to increase the photovoltaic output voltage can also help to extract the MPP from the PV modules under different solar irradiance and cell temperature conditions. The three-phase inverters that have been used convert the DC to AC output and make the THD obtained for three-phase voltage the lowest. It's successfully feeding into the grid by using a step-up transformer. In addition, future recommendations that can be implemented in this work are to include battery storage as a form of backup energy storage for the system. Besides, the impact of partial shading on the PV module could be another observation that could be observed and analysed. Furthermore, the system developed shows excellent performance in steady-state and dynamic tests.

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