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Research Article

Design of Three Level Neutral Point Clamped Inverter with Fuzzy Logic based MPPT for PV Applications

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Abstract: In this paper a solar photovoltaic (PV) system with maximum power point tracking (MPPT) for domestic low power applications. The proposed system contains a PV array which provides electrical power, while a DC/DC converter is incorporated to regulate the power derived from PV panels. Fuzzy logic control (FLC) based MPPT has been proposed. To convert the DC voltages and currents obtained from Solar panels to AC voltages and currents, a Neutral point clamped multilevel inverter is included. Furthermore, harmonics are removed by using the LCL filter. The PV system working, design of the DC/DC Boost converter, Novel MPPT techniques, Multilevel inverter topologies and LCL filter design are explained. Results reveal that the FLC based MPPT has much lesser total harmonic distortion (THD) in the PV system. With this property, FLC possesses faster convergence than the perturb & observe (P&O) and other MPPT techniques.

Keywords: Photovoltaic (PV), Fuzzy logic control (FLC), Maximum power point tracking (MPPT), Multilevel Inverters, Neutral point clamped inverter, Perturb & Observe (P&O), Renewable energy (RE), PV Cell.

1. INTRODUCTION

Solar panels have become more efficient and inexpensive in recent years, making them an increasingly appealing alternative for people and companies looking to decrease their carbon footprint and minimize their energy expenses. Solar panels, as a renewable and sustainable energy source, have the potential to play a critical role in lowering greenhouse gas emissions and combatting climate change. PV panels have efficiency on the lower side however research and advances have led to technologies like MPPT (maximum power point tracking), which attains maximum available power at the output of a PV panel at any instant of time. Maximum power point tracking is available for PV panels, and wind power plants. There are several techniques to track maximum power points (MPP) [1, 2]. Such as perturbation and observation (P & O), incremental conductance, fractional open circuit, fractional short circuit, Fuzzy logic based MPPT etc. P & O is the simplest, inexpensive, easy to implement, and hence the most commonly used method in MPPT, however, it introduces fluctuations in the power, has a slower convergence rate and fails to track MPP under rapid changes in the environmental conditions. FLC based MPPT is fast, more efficient and performs better under various harsh conditions. Getting power from the panel effectively is not the solution, but it is also important to regulate this power and deliver it for useful work. To do this, an inverter (DC to AC converter) is used [3]. The output voltage of a multilevel inverter is greater than two levels. As a result, the inverter output voltage has reduced harmonic distortion and produces high-quality waveforms at the inverter output. These features make MLI available for applications that require higher power and high voltage levels [4]. Although there are various multilevel inverters, diode clamped or NPC inverters are widely used in industry because of their low electromagnetic interference and high efficiency. Over the years, the multi-level inverter is being used popularly in high-power applications because of its lesser interference than the typical two-level inverter and its ability to operate at lower switching frequencies. Transformers are the most efficient electrical machines and they are the most

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important member of any electrical system. In this research, a step-up transformer was used to obtain galvanic isolation and the desired output voltage. The implementation of MPPT was discussed by Chim *et al.* [5], and Du *et al.* [6] compared different methods of MPPT with different solar irradiance profiles. Edouard *et al.* [7], and Busquets-Monge *et al.* [8] presented Perturb & Observe and Fuzzy logic MPPT.

2. PROPOSED SYSTEM

Figure 1 represents the block diagram of the modelled solar photovoltaic system with MPPT for domestic low-power applications. The proposed system essentially consists of a PV panel, DC-DC converter, inverter, transformer and filter, and FLC-based MPPT. Details of the system design are explained in the following sections.

3. PV PANEL

Photovoltaic solar panels are used to convert the solar energy into electrical energy. This section discusses the output of solar panels & factors affecting the performance of Solar panels [1, 20].

3.1.1 Introduction

PV panels are the arrangement of semiconductor components which are used to convert the solar light into electric current. A PV module is a collection of PV cells that uses sunlight as energy and generates a direct current. The collection of PV modules is called a PV array. These arrays are used in PV systems and their job is to supply electrical energy to the electrical loads.

3.1.2 Working of Solar Panel

Solar panel includes many smaller units called PV cells. Light energy from the sun hits the PV cell, it transfers the light energy to the cell and causes the electrons to get loosen from the atom. To conclude, solar panels work by detaching electrons from atoms by photons or particles of light, generating electrical currents [7, 9, 10].

3.1.3 Factors Affecting Output of Solar Panel

The following are some crucial factors that influence the output of solar panels.

3.1.4 Temperature

With the increase in temperature, the output of the PV cell decreases, and the performance of PV is better in cold weather as compared to hot. A 25 ˚C rated PV panel can be very different from the actual external environment. For each degree increase in temperature above 25 ˚C then 0.25 % decays the output of the PV panels. The effect of temperature is explained in Figure 2, with an increase in temperature, the output power decreases.

3.1.5 Irradiance

The power per square meter area from sun is solar irradiance. As the power from sun changes, so do the I-V and P-V properties. As solar radiation rises, open voltage and short current rise as well, shifting the maximum power point. From Figure 3, it is clear that more the irradiance, greater amount of power is produced.

4. MAXIMUM POWER POINT TRACKING (MPPT)

MPPT stands for Maximum Power Point Tracking and refers to an electronic system used to optimize the efficiency of solar panels. Solar panels generate electricity when exposed to sunlight, but the

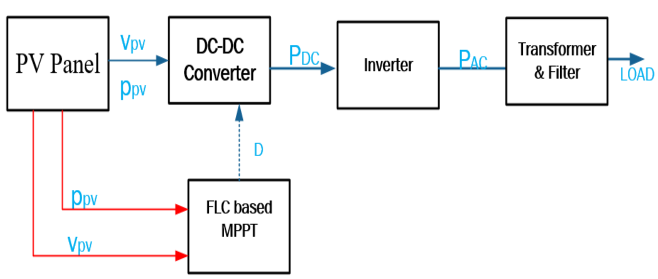

Fig. 1. Block diagram of proposed system

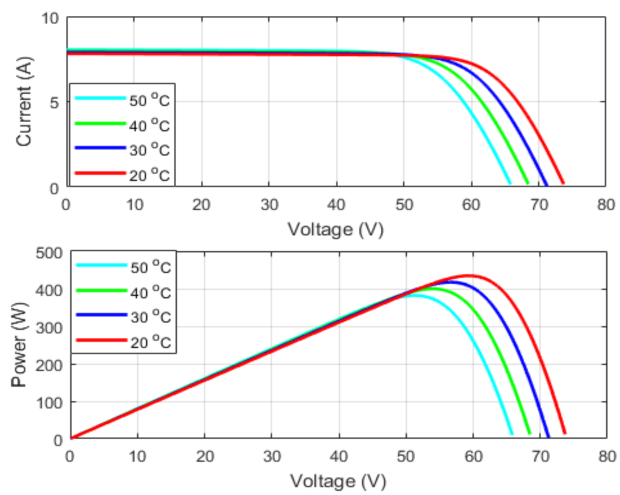

Fig. 2. Temperature effects on solar panels

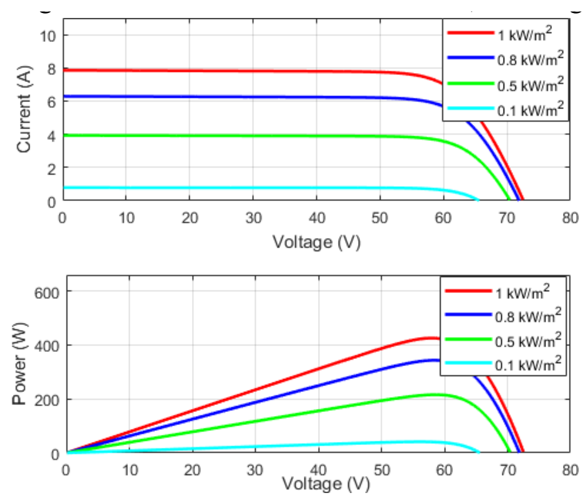

Fig. 3. Irradiance effects on solar panels

amount of electricity produced can vary depending on factors such as the angle and intensity of the sunlight and the temperature of the panels. MPPT systems work by constantly adjusting the voltage and current of the solar panel to ensure it is operating at its maximum power point i.e. Mpp the point where the module produces the most power under certain conditions. By optimizing the performance of the solar panel, MPPT systems can increase the efficiency of the entire solar power system and ensure that the maximum amount of energy is harvested from available sunlight. MPPT systems are widely used in on-grid solar power systems, off-grid solar power systems and in other applications where maximum efficiency is important [11].

4.1 Different MPPT Techniques

Many MPPT methods are implemented to reach the MPP. These MPP techniques vary from each other in many aspects such as the number of sensing devices, complexity, convergence speed, cost, range of effectiveness, accurate tracking etc. A few popular techniques are: [2, 12]

- Perturb and Observe
- Neural networks
- Fuzzy logic

In this research work FLC based maximum power point tracking technique is used, due to its fast and exploratory nature.

4.2 Fuzzy Logic based MPPT

FLC Maximum Power Point Tracking (FLC-MPPT), is a type of MPPT system that optimizes the efficiency of a solar panel using fuzzy logic. Fuzzy logic is a sort of mathematical logic that accepts imprecise or uncertain inputs, making it

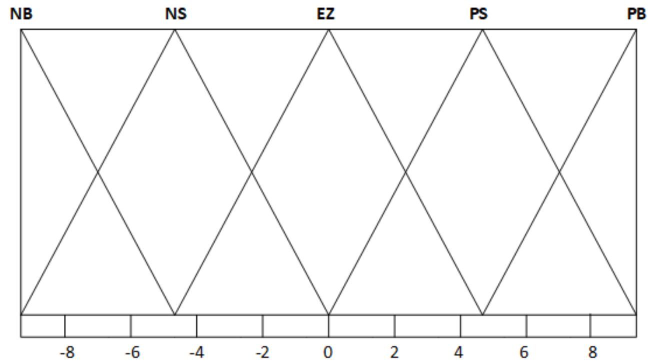

Fig. 4. Input membership function Vpv

especially effective in systems with complicated and changeable situations, such as solar power plants.

The input variables in an FL-MPPT system, such as sun irradiance and temperature, are translated into linguistic variables using fuzzy sets. The controller then applies rules based on expert knowledge or data to identify the solar panel's optimal operating position. The controller's output is a crisp value that is utilized to modify the duty cycle of DC/DC converters & regulate the solar panel's voltage and current to operate at its mpp. The FL-MPPT system offers several advantages over traditional MPPT systems. They can handle the non-linear and non-stationary behavior common in solar energy systems and can adapt to changing environmental conditions. Additionally, FL-MPPT systems are relatively simple and inexpensive to implement, making them a viable option for small-scale solar power systems. However, they may require more expertise to design and configure than traditional MPPT systems [13, 14].

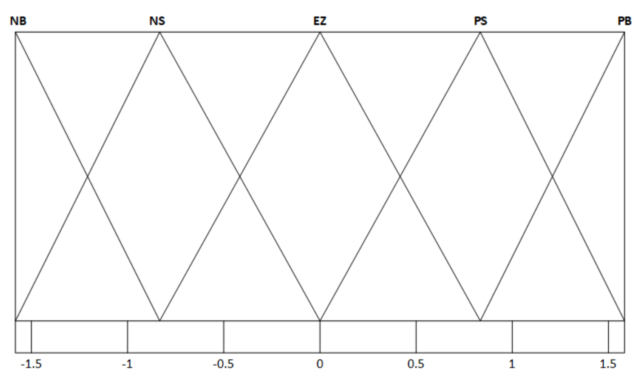

Fig. 5. Input membership function Ipv

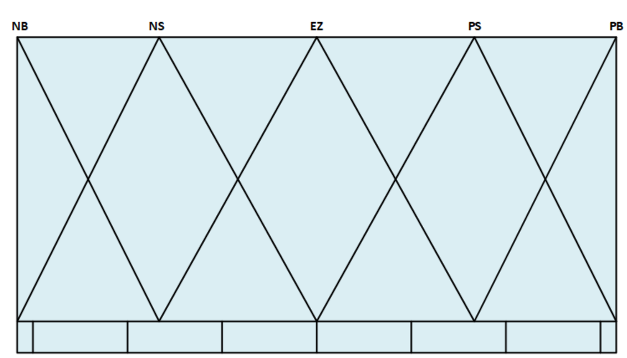

Fig. 6. Output membership function PWM

4.2.1 Design of FLC

FLC is designed by following steps:

- Variables are identified
- Fuzzy subsets are configured
- Fuzzy rule base is configured
- Fuzzification
- Combining the fuzzy outputs
- Defuzzification

The nature of FLC is robust as compared to conventional methods. FLC is based on three fundamental elements named 1st Fuzzification, 2nd Inference engine and 3rd defuzzification [3].

4.2.2 FLC based MPPT Design

During this research work, the following linguistic variables were used to define the membership functions [15].
NB: Neg Big
NS: Neg Small
EZ: Zero
PS: Pos Small
PB: Pos Big

The above-mentioned rules can be represented as the following Fuzzy rule base.

The fuzzy rules based on the if-then approach were:
1. (Vpv==NB) & (Ipv==BN) => (PWM=PB)(1)
2. (Vpv==NB) & (Ipv==NS) => (PWM=PS) (1)
3. (Vpv==NB) & (Ipv==ZE) => (PWM=NB) (1)
.
.
25. (Vpv==ZE) & (Ipv==PS) => (PWM=PB) (1)

The above-mentioned rules can be represented as the following Fuzzy rule base.

Figure 4 & Figure 5 are input membership functions, extracted for FLC. The variations in these functions lead to the generation of the output based on the membership functions provided in Figure 6. The pictorial representation of the PWM generated at the output of the FLC controller is shown in Figure 7.

5. DC/DC CONVERTER

A DC/DC converter is an electronic device used to convert direct current (DC) voltage levels from one level to another. It works by taking a DC type voltage at the input, changing its level to another DC output voltage, and using electronic circuitry to control current flow through the device. DC/DC converters can be used in a variety of applications including power supplies, battery charging systems, and solar power systems. This is especially useful in situations where the input voltage fluctuates, such as in solar power systems where the solar panel voltage can fluctuate with sunlight intensity.
There are several different types of DC-to-DC converters, including:

- **Buck converters:** These converters step down the voltage at input to a lower output voltage.
- **Boost converters:** These converters step up the input voltage to a higher output voltage.

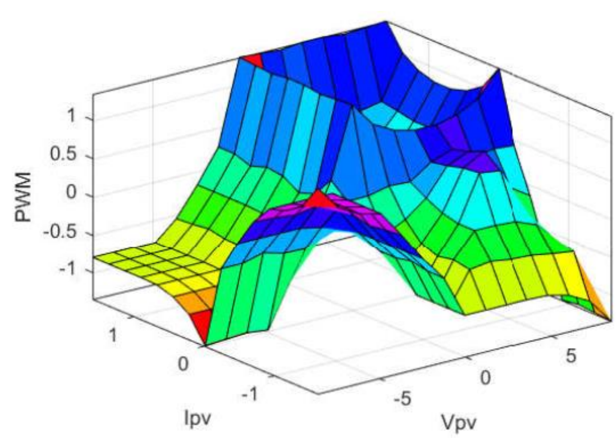

Fig. 7. Fuzzy rule surface

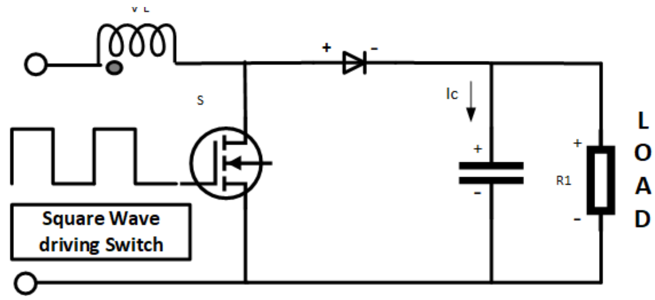

Fig. 8. Boost converter

- **Buck-boost converters:** These converters can both step up and step down the input voltage, depending on the needs of the system.
- **Flyback converters:** These converters store energy in a magnetic field and release it to the output in a series of pulses.

Depending on the requirements of the application, DC/DC converters can be implemented using different topologies and control methods. They are essential components of many electronic systems and play a key role in efficient power conversion and power management.

Among all DC/DC converter topologies, boost is an important topology used to step up the input voltage level given at the output. In this research work, a boost converter is used.

5.1 Boost Converter

A converter which shifts the level of input Dc voltage to the higher value at output is known as Boost converter. In the Figure 8, Switch S is controlled by the PWM scheme, generated by the MPPT algorithm.

5.1.1 Operation of Boost Converter

Firstly, when the switch is ON during time $0 \leq t \leq T_0$ which is the ON period for the switch, the output voltage is zero $V_0 = 0$ at that time, and the switch act as a short circuit. Current from the supply flows through the inductor and it starts charging. Therefore, the inductor current linearly rises; during ON time, the polarity of the Induce Emf is taken Positive, i.e, the left-hand side of the inductor is positive. When the switch is turned OFF during this cycle, this is the OFF period of switch $T_{off} = T\text{-}T_{on}$. In this period, the magnitude of the inductor current starts decreasing precisely in the same direction as in the ON period through an inductor, and the diode becomes forward-biased. The polarity of induced emf on the left-hand side is negative but added with supply voltage, making the current in the same direction. The current linearly decreases, keeping the voltage at a higher and constant level [16].

5.1.2 Design of Boost Regulator

The inductor and capacitor for the boost converter can be designed using the following equations: [17, 18]

$$Cmin = Vmpp \times Dmpp/2\Delta Vout \times RL \times fs \quad (1)$$

$$RL = Rmpp/(1 - Dmpp)^{\wedge}2 \quad (2)$$

$$Lmin = Vmpp \times Dmpp/2 \times \Delta Iout \times fs \quad (3)$$

6. INVERTERS

An inverter is an electronic device for converting direct current (DC) to alternating current (AC). Alternating current is the standard form of electricity used in most home and business appliances, while direct current is commonly used in batteries and other types of energy storage systems. A multilevel inverter is an electronic device used to convert direct current to alternating current by synthesizing a nearly sinusoidal step signal. It is designed to overcome the limitations of traditional 2-level inverters, which have limitations in output waveform quality, power loss and over-voltage of switching elements. The multilevel inverter uses a series of power solid state switches to produce a series of stepped voltage levels that approximate a sine wave. The number of voltage levels produced by the inverter determines the quality of the output waveform, with more levels providing a better approximation of a sine wave. Multi-level inverters offer many advantages over traditional two-level inverters, such as: B. Reduced harmonic distortion, reduced EMI and improved power efficiency. They are typically used in high power applications such as grid-connected solar power systems, motor drives and industrial applications [19].

6.1 Multilevel Inverter Classification

Multi-level Inverters can be classified into the following categories:

- Neutral point clamped Inverters
- Cascade Multilevel Inverters
- Capacitor clamped Inverters

This paper focuses on a neutral point clamped inverter.

6.2 Neutral Point Clamped Inverter

Diode clamped multilevel inverter (DCMLI), also known as neutral point clamp multi-level inverter. To produce L-levels of phase voltages, the DC bus of the inverter contains (L-1) capacitors. For three level inverter, DC bus consists of two capacitors, C1, C2. The DC voltage on each capacitor is Vdc/2 [4, 8].

No of capacitors	L-1
No of switching devices	2(L-1)
No of clamping devices	(L-1)(L-2)

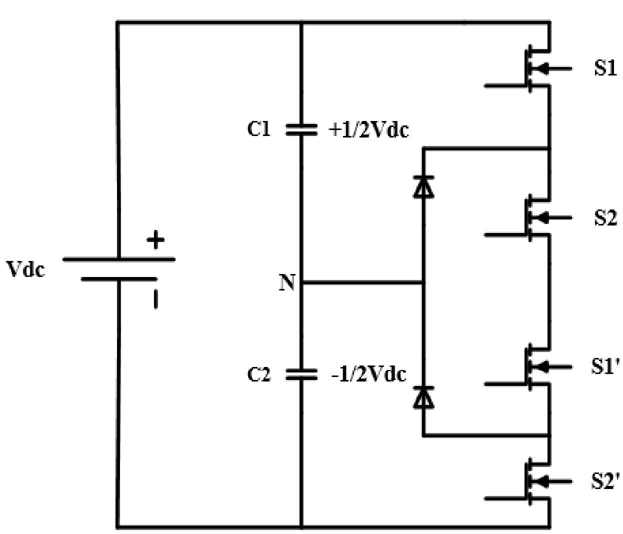

Fig. 9. One leg of typical NPC inverter

6.2.1 Principle of Operation

To achieve a waveform resembling a staircase output voltage, let us consider only one leg of the three-level inverter, as shown in Figure 9.

Table 1. Switching sequence for the one leg of NPC inverter

S1	S2	S1'	S2'	VRO
H	H	L	L	0.5Vdc
L	H	H	L	0
L	L	H	H	-0.5Vdc

To get the waveform shown in Figure 10, the switching sequence given in Table 1 is used. Figure 11 provides the circuit diagram for the full- bridge 3L NPC inverter.

Figure 12 shows the line voltage waveform of the NPC inverter. The Line voltage of the 3L NPC-MLI is obtained by taking, positive (+) voltage of one leg and negative (-) voltage other leg**.** For the above three-level inverter, the acquired line voltage is a 5-level step waveform. An L-level inverter gives k-levels of phase voltage and (2L-1) line voltage levels. The circuit diagrams shown in Figures 11 & 12 provides the base for simulation of the system.

7. TRANSFORMER & FILTER DESIGN

7.1 Transformer Design

A transformer where the output voltage is shifted to a higher level than its input voltage is called a step-

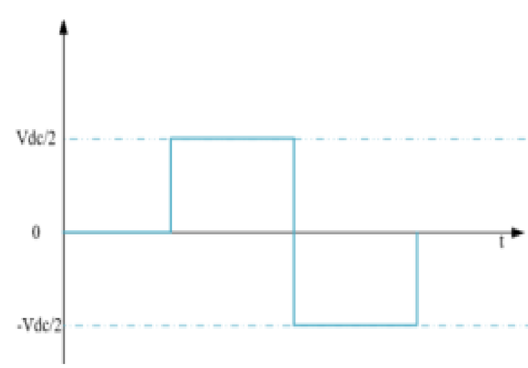

Fig. 10. Output of single phase of NPC inverter

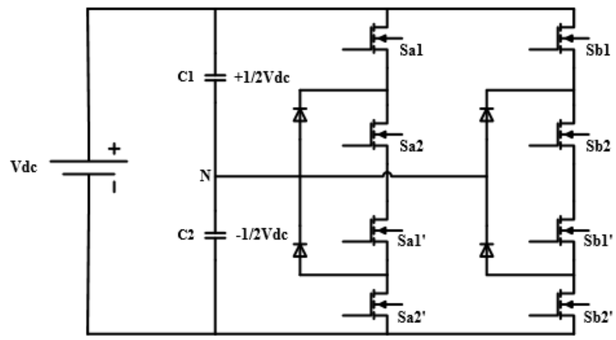

Fig. 11. Full bridge 3L NPC inverter

up transformer. In the step-up transformer amount of current reduces to maintain the input and output power of the same system.

The "step up" or "step down" transformer is decided by the voltage ratios of primary to secondary wire turns or called the turn ratio.

Voltage Transformation=Nsec/Npri
Current transformation =Npri/Nsec

Here N represents the No. of turn in the transformer winding.

The square root of a transformer's main to secondary inductance (L) ratio is called the transformer's transformation ratio. The working of the step-up transformer is given in Figure 13.
Voltage transformation=√((Lsec/Lpri))

7.2 Filter Design

During the course of this work, LC filter was used & was designed using following equations:

$$fc < \left(\frac{1}{10}\right) fswitchng \tag{4}$$

$$C = (\frac{1}{2} * S)/(2\pi V^2)f \tag{5}$$

$$L < \frac{0.2 \times Vac}{2\pi f I} \tag{6}$$

8. RESULTS & DISCUSSION

8.1 Simulation of Complete System

Figure 14 shows the simulation overview of the designed Photovoltaic system. As such, it reflects the simulation model of the designed system.

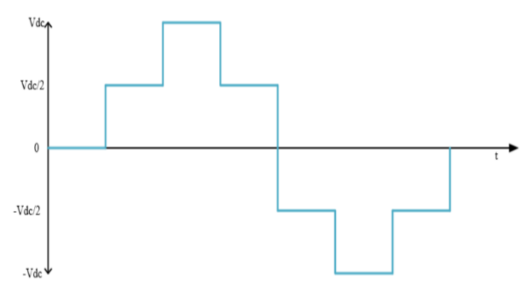

Fig. 12. Line voltage of 3L NPC inverter

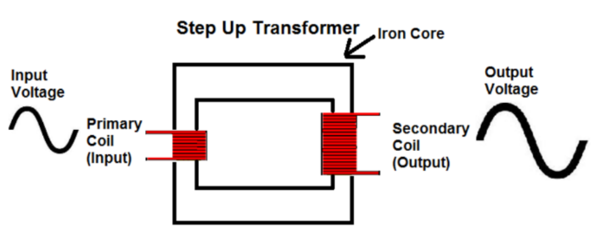

Fig. 13. Working of step-up transformer

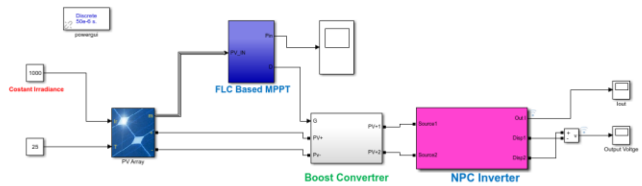

Fig. 14. MATLAB representation of complete system

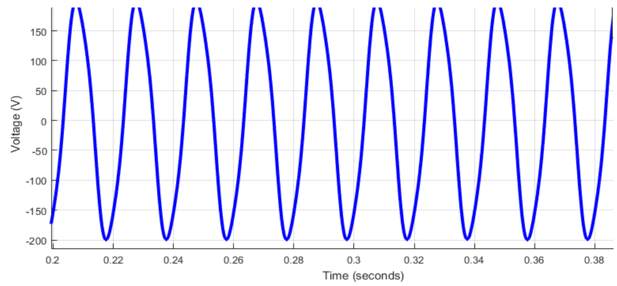

Fig. 15. Output voltage of the system

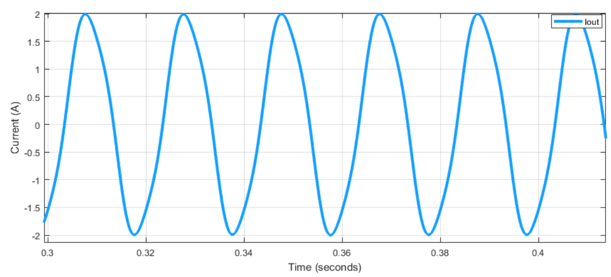

Fig. 16. Output current of the system

The output voltage and the output current of the system are shown in Figures 15 & 16 respectively, while Figure 17 shows the THD analysis of the designed system. The results shown in these three figures indicate that the system represented in this research work performs better than the conventional MPPT techniques mentioned by Nedumgatt *et al.* [12].

8.2 Simulated Results of Fuzzy Logic based MPPT and Full Bridge NPC Inverter

Figures 18 through 21 present the output of the simulated systems. Figure 18 shows the simulation of the designed Fuzzy logic controller, while Figure 19 shows the Simulink model of the inverter. Figure 20 & Figure 21 reflect the phase voltage & line voltage waveforms respectively. The aforementioned figures are simulated justifications for the Figure 11 & Figure 12.

9. CONCLUSION

A novel FLC based MPPT for Solar PV systems with NPC-MLI has been investigated. From the THD analysis of the system, it is concluded that the FLC based MPPT has much lesser THD in the system. With this property, FLC possesses faster convergence than the Perturb & Observe (P&O) and other MPPT techniques. Due to all of the above-explained reasons, the FLC based MPPT stands out as a very competitive alternative for P&O. Nevertheless, further research work is needed under various circumstances, which were not taken into consideration during this work.

10. CONFLICT OF INTEREST

The authors declare no conflict of interest.

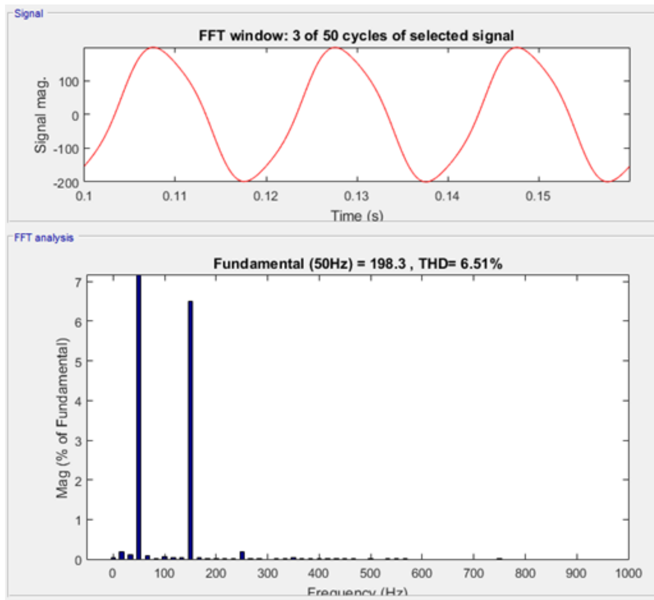

Fig. 17. THD analysis of the system

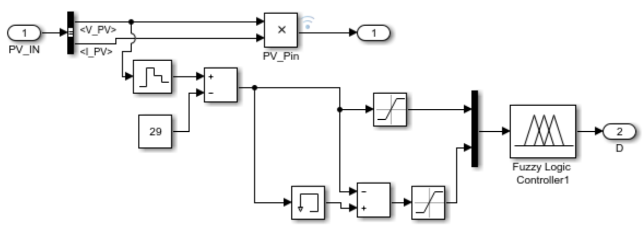

Fig. 18. FLC simulation in MATLAB Simulink

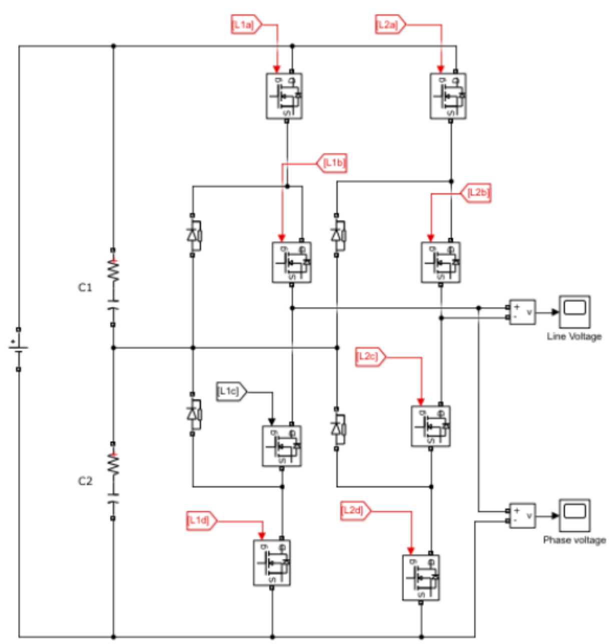

Fig. 19. Simulation of full bridge NPC inverter

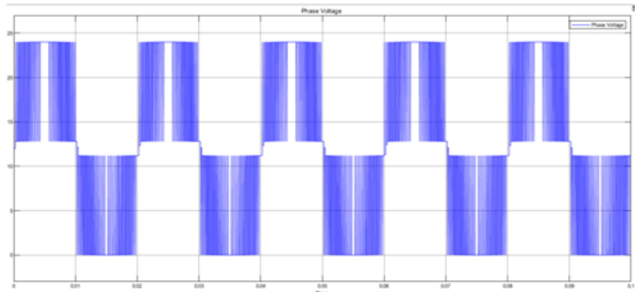

Fig. 20. Phase voltage of 3L NPC inverter

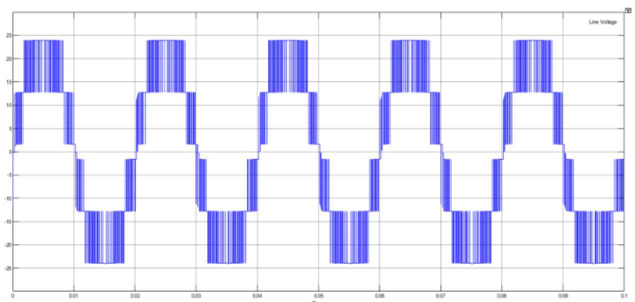

Fig. 21. Line voltage of 3L NPC inverter

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