An Efficient Modified CUK Converter with Fuzzy based Maximum Power Point Tracking Controller for PV System

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Abstract - **To improve the performance of photovoltaic system a modified cuk converter with Maximum Power Point Tracker (MPPT) that uses a fuzzy logic control algorithm is presented in this research work. In the proposed cuk converter, the conduction losses and switching losses are reduced by means of replacing the passive elements with switched capacitors. These switched capacitors are used to provide smooth transition of voltage and current. So, the conversion efficiency of the converter is improved and the efficiency of the PV system is increased. The PV systems use a MPPT to continuously extract the highest possible power and deliver it to the load. MPPT consists of a dc-dc converter used to find and maintain operation at the maximum power point using a tracking algorithm. The simulated results indicate that a considerable amount of additional power can be extracted from photovoltaic module using a proposed converter with fuzzy logic controller based MPPT**

Keywords - Modified Cuk Converter, Photovoltaic System, Maximum Power Point Tracker, Fuzzy Logic Controller.

I. INTRODUCTION

In recent years, renewable energy sources have been given more attention in the research area as they provide excellent opportunity to generate electricity to meet the growing CONCERN over the scarcity and undesirable environmental impacts on thermal and nuclear power plants [1, 2]. In general, solar energy conversion systems can be classified into two categories: photovoltaic systems which convert solar energy to electricity and thermal systems which convert solar energy into heat [3]. Photovoltaic system offers the potential to generate electricity in a clean and consistent method. However, there are still certain limitations like low conversion efficiency of PV system and converters [4]. In order to handle this problem, it is essential to employ an approach to extract maximum power from the PV cells. Maximum Power Point Tracking (MPPT) technique is an approach which effectively makes use of the photovoltaic cells. It extracts the maximum power from the photovoltaic cells. The most widely used low cost approach is a Perturb and Observe (P&O) technique. The main drawback of this method is that, it oscillates the operating point of the converter around its Maximum Power Point (MPP) at steady state. Hence it increases the power loss.

This research focuses on investigating the functionalities of a different type of converters and its influence on the output power of the module [5]. A MPPT is applied for extracting the maximum power from the solar PV module and send out that power to the load [6, 7]. A DC/DC converter (step up/ step down) helps in transferring maximum power from the solar PV module to the load. A DC/DC converter acts as an interface between the load and the module as shown in Fig. 1. Load impedance as seen by the source is altered by altering the duty cycle, and matched at the point of the peak power with the source so as to transfer the maximum power. Once the MPP is attained, a triggering signal with a particular duty cycle is produced and utilized to trigger the boost converter switches to guarantee that the converter operates as close as possible to the PV Maximum Power Point [8].

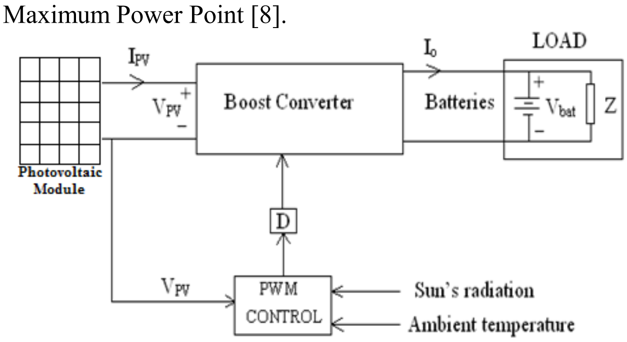


Figure 1: Typical MPPT Controller

For an efficient MPPT controller, two considerations can be made, initially by establishing an improved algorithm for tracking MPP of PV systems and then by establishing an efficient boost converter circuit which is an essential component in the controller [9]. Many ongoing researches are mainly based on the converter circuit in order to extract maximum power from the PV panel. Some of the converter circuits used to obtain maximum power are buck converter, boost converter and cuk converter. The operation and drawbacks of these conventional converters are discussed in the next sections.

In this paper, a modified cuk converter with fuzzy logic controller based MPPT technique has been proposed to extract the maximum power from the PV panel. The proposed converter is compared with modified cuk converter with P&O MPPT controller and also compared with the boost converter with P&O controller in the MATLAB/Simulink environment. The MATLAB simulation results under changing atmospheric conditions are presented

II. Conventional Converters

This section, discussion about the three different converters such as buck, boost and cuk converters can be utilized in the MPPT. The operation and drawbacks of these converters are discussed clearly in this section.

A. Buck Converter

The typical presented simulation of open loop and closed loop controlled buck converter system for solar installation system. The MATLAB models for open loop and closed loop systems are developed using the simulink and the same are used for simulation studies. The closed loop system is able to maintain constant voltage. This converter has advantages like reduced hardware and good output voltage regulation. The simulation results are in line with the theoretical predictions [10]. It converts one DC voltage level to another, by storing the input power temporarily and then releasing that power to the output at a different voltage. The circuit diagram of the buck converter is shown in Fig. 2. In the time of switching process, the MOSFET switching frequency is increased so switching power loss is occurred.

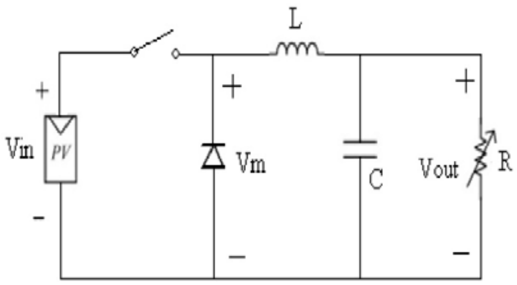


Figure 2: PV Array with buck converter circuit diagram

B. Boost Converter

A boost converter is the front-end constituent of a PV system associated between a PV array and a load. DC output voltage of the Boost converter is higher than its input voltage. It comprises of at least two semiconductor switches, a diode and a transistor and at least one energy storage element. Filters formed of capacitors in association with inductors are generally added to the output of the converter to minimize the output voltage ripple [11]. Boost converter is a DC-DC converter that steps up its input voltage based on the formula given in (1)

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

Where, V_{out} represents the output voltage of the boost converter, V_{in} represents the input voltage and D represents the duty cycle which is the ratio between the time within which the IGBT. The circuit diagram of the boost converter to validate the effectiveness of the proposed converter. To ensure this, an experimental setup has been made to test the proposed converter.
is shown in Fig. 3. It consists of an inductor, an IGBT switch, a fast switching diode and a capacitor.

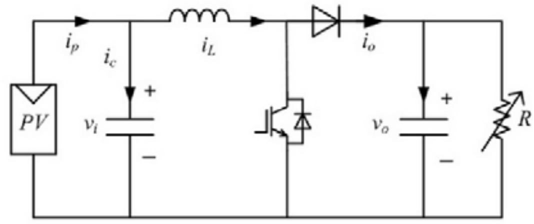


Figure 3: Circuit of a boost converter

The main drawback of the boost converter is the reverse-recovery issue and raises the rating of all components. Thus, the performances of conversion are ruined and thus end up in severe electromagnetic interference issue under this scenario [12]. In order to handle this reverse-recovery issue of high voltage diodes, voltage-clamped approach is implemented in the converter design. But, this approach causes voltage stress on the switches and voltage gain is minimized by the turn-on time of the auxiliary switch [13]. The other issue in boost converter function is the leakage energy of the storage inductor which is produced by the turning off action of the converter switches which would lead to a high-voltage ripple across the switch because of the resonant phenomenon induced by the leakage current. Hence, in order to protect the converter switching devices, two mitigating actions can be carried out, which means, through a high voltage rating device with a snubber circuit and by reducing the inductor leakage energy. In order to enhance the conversion efficiency of a boost converter, a new boost converter circuit has been developed through integrating diodes and capacitors to the traditional converter circuit to transmit and sink the leakage energy of the inductor during transient switching.

C. Cuk Converter

Cuk converter has many benefits over the buck converter. Cuk converter offers capacitive isolation which defends against switch failure (unlike the buck topology) [14]. The input current of cuk is continuous, and ripple free current can be extracted from a PV array that is essential for efficient MPPT.

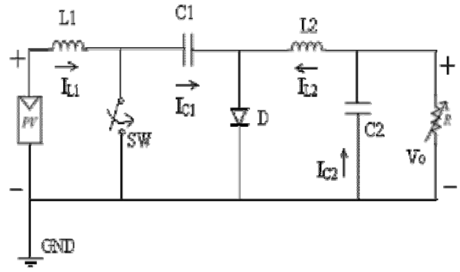


Figure 4: Circuit diagram of conventional cuk converter

As shown in Figure 4, Cuk converter utilizes a capacitor as the main energy storage. Thus, the input current is continuous. The circuits have low switching losses and high efficiency [15]. Because of the inductor on the output stage, the Cuk converter can offer a better output current characteristic. The circuit arrangement of the Cuk converter through MOSFET switch is shown in Fig. 4. In case of Cuk converter, the output voltage is opposite to input voltage. When the input voltage turned on and MOSFET (SW) is switched off, diode D is forward biased and capacitor C_1 is charged through L_1 and D.

III. Modified Cuk Converter

Among all the existing topologies, cuk, sepic and buckboost converters offer the chance to have either higher or lower output voltage, compared with input voltage. Though buck- boost configuration is cheaper than cuk, some limitations such as discontinuous input current, pulsated output current, high peak currents in power components and poor transient response make it less efficient. Like buck boost converters, sepic converter is also having a pulsating output current. It requires higher current handling capability capacitor at the output side. Alternatively, cuk converter does not have this disadvantage. But it has low switching losses and maximum competence among non-isolated DC-DC converters. It can also offer a better output current trait because of the inductor on the output stage. Hence, cuk configuration [16] is an appropriate converter to be employed in designing the MPPT.

Cuk converter is actually the cascade combination of a boost and a buck converter. Cuk converter has the following advantages such as continuous input current, continuous output current and output voltage can be either higher or lower than the input voltage But, Cuk cannot offer a steep step-up and step-down of the line voltage, as needed by several sophisticated applications. To offer a high voltage-conversion ratio, the fundamental converters would have to operate with a higher value of the duty cycle that is higher than 0.9 in voltage-step-up converters, smaller than 0.1 in voltage-step-down converters. An extreme duty cycle impairs the competence and enforces obstacles for the transient response [17]. Moreover, in order to create such an extreme duty cycle, the control circuit must include a fast and expensive comparator. The extreme duty cycle may even result in failures at high switching frequency because of the very short conduction time of the diode (self-driven transistor) in step-up converters, or of the active transistor in step-down converters.

In order to overcome this, simple switching dual structure to step-up the voltage is proposed in this paper. The step-up structure is formed by two capacitors and two diodes. The step up structure is inserted in classical cuk converter to offer a new power supply named Modified Cuk Converter (Boost Mode) with a steep voltage conversion ratio. The circuit diagram of the Modified Cuk converter (Boost Mode) [18] is shown in Fig. 5(a).

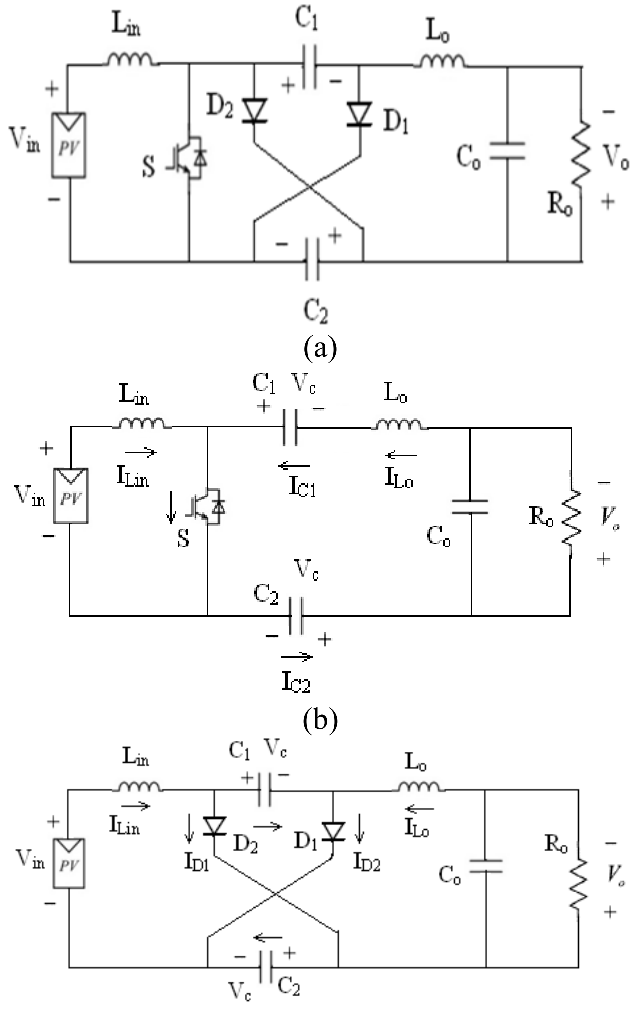


Figure 5 (a) Converter diagram (b), (c) Converter switching topologies (t_{on} & t_{off} mode)

During turn on (T_{on}) of the switch S, the input inductor (L_{in}) is charged by the input voltage V_{in} and the capacitors C_1, C_2 are discharged in series as in Fig. 5(b).

$$i_{switch} = i_{in} + \qquad (2)$$

$$i_{C1} = i_{C2} = \qquad (3)$$

Similarly, when the switch S is turned off (T_{off}), the input inductor is discharged and the capacitors C_1, C_2 are charged in parallel as in Fig. 5(c)

$$i_{D1} = i \qquad (4)$$

$$i_{D1} = \frac{1}{2}(i_{in} + i_o) \qquad (5)$$

$$i_{D2} = \frac{1}{2}(i_{in} - i_o) \qquad (6)$$

The voltage balances on L_{in} and L_o in Figure 5 (a),

$$V_{in}D + (V_{in} - V_c)(1 - D) = 0 \qquad (7)$$

$$(V_o - 2V_c)D + (V_o - V_c)(1 - D) = \qquad (8)$$

Therefore, the output voltage is given as,

$$V_o = \frac{1+D}{D_1} V_{in} \qquad (9)$$

where, $D_1 = 1 - D$ and D = Duty Cycle

IV. Fuzzy Logic Controller

The main drawback of P&O MPPT approach is that the PV module operating voltage is disturbed every cycle [19, 20]. This algorithm will always carry out an increment or decrement of ΔV to the PV operating voltage. The process of maximum power tracking will be carried on even the MPP has been effectively tracked. This is because of the output power of PV module for the next perturbed cycle is unpredictable.

The method of fuzzy logic controller (FLC) has found to increase in PV applications with different converters. In this FLC, member function specifies the degree to which a given input belongs to a set. To find out the operating point, corresponding to the maximum power for various irradiation levels. The panel voltage is generally used to compute the partial derivative of power with respect to cell voltage. As an alternative of finding the optimum point via derivative, we use a fuzzy logic controller. Usually, a DC/DC converter is utilized between the panel and the load for the purpose of maximum power point tracking.

In the PV system, the solar irradiation is one of the sensitive parameter by triangle shape membership function even a small change in input magnitude can be identified and the corresponding output will be applied to the gate of the converter to bring the system to stabilize quickly [21]. Hence the triangular membership functions have been chosen for the input of error dP/dV, change in error ΔdP/dV and output U Duty cycle. A functional block diagram of fuzzy logic controller for the MPP tracker is shown in Fig. 6. Input of the FLC include dP/dV and its variations to get better accuracy as well as the variations of converter duty cycle to improve the dynamic character.

Input and output variables of fuzzy logic controller are related by the following equations:

$$\frac{dP}{dV}(K) = \frac{P(K)-P(K-1)}{V(K)-V(K-1)} \qquad (10)$$

$$\Delta\left(\frac{dP}{dV}(K)\right) = \frac{dP}{dV}(K) - \frac{dP}{dV}(K-1) \qquad (11)$$

$$U(K) = U(K-1) + \Delta U(K) \qquad (12)$$

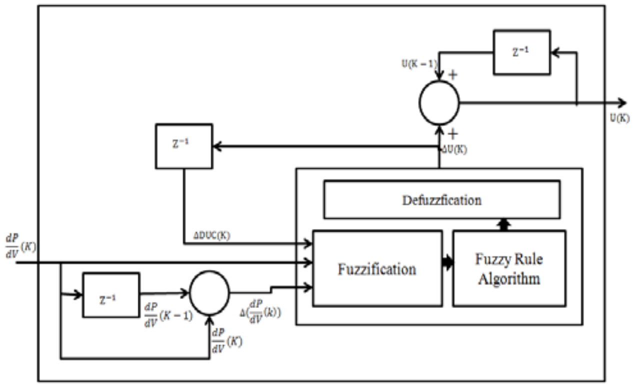


Figure 6: Functional block diagram of fuzzy logic controller (FLC)

The input range for the dP/dV, ΔdP/dV and the control output U are normalized based on the power and voltage from the PV panel. The linguistic descriptions of the input membership function are Negative Big (NB), Negative Small (NS), Zero (ZE), Positive Small (PS) and Positive Big (PB). The output membership function are Negative Big (NB), Negative Small (NS), Zero (ZE),Positive Small (PS) and Positive Big (PB). The union maximum operation has been for the fuzzy implication. For the two input fuzzy system , it is generally expressed as

$$\mu_{A1(x1)\cap A1(x2)} = \min\{\mu_{A1(x1)}, \mu_{A1(x2)}\} \qquad (13)$$

Where $A_{1(x1)}$ and $A_{1(x2)}$ are input fuzzy sets.

The rule base of the fuzzy controller relates the premise $\frac{dP}{dV}(K)$ *and* $\Delta(\frac{dP}{dV}(K))$ to consequent $U(K)$. Practically the solar irradiation level on the PV module is time variant. If the solar irradiation level is increased or decreased, it will influence the output of converter. By utilizing control techniques, the power and voltage output is satisfied and the system output is maintained without any oscillation at every irradiation level. Based on the system frame work 25 linguistic fuzzy control rules are developed. Table 1 lists 25 linguistic fuzzy rules for the fuzzy controller. The structure of the control rules of the fuzzy controller with two inputs and one output is expressed as,

If ($\frac{dP}{dV}(K)$ is NS and $\Delta(\frac{dP}{dV}(K))$ *is PB*) then the control signal $U(K)$ is PS (14)

The centroid defuzzification has been made to find the crisp value of output. The centroid defuzzfication is defined as,

$$\Delta U(K)^{crisp} = \frac{\sum_{i=1}^{n} D_i \mu(D_i)}{\sum_{i=1}^{n} \mu(D_i)} \qquad (15)$$

Where

$\Delta U(K)^{crisp}$ is the output of the fuzzy controller,

D_i denotes the center of the membership function of the consequent of i-th rule,

µ denotes the membership value for the rule's premise and n represents the total number of fuzzy rules.

Table 1 Fuzzy controls rules

U(K)		$\Delta(\frac{dP}{dV}(k))$				
		NB	**NS**	**ZO**	**PS**	**PB**
$\frac{dP}{dV}(K)$	**NB**	NB	NB	NB	NS	ZO
	NS	NB	NB	NS	ZO	PS
	ZO	NB	NS	ZO	PS	PB
	PS	NS	ZO	PS	PB	PB
	PB	ZO	PS	PB	PB	PB

The output of the fuzzy logic controller is a fuzzy subset. As the actual system is requires a nonfuzzy value of control, defuzzification is required. The centroid technique is the mostly used defuzzification technique as it has better averaging properties and it yields better outcome. Where, D_i is the centroid output membership is is function and $\Delta U(K)$ is the output of FLC processor. While performing defuzzification, fuzzy logic controller output is converted back to a numerical variable. Therefore, this offers an analog signal to control the switch in the modified cuk converter.

V. SIMULATION RESULTS

The performance of the controller is investigated at various solar irradiance but only at constant temperature of 25°C. The simulation diagram for the fuzzy logic controller based MPPT with modified cuk converter is shown in Fig. 7.

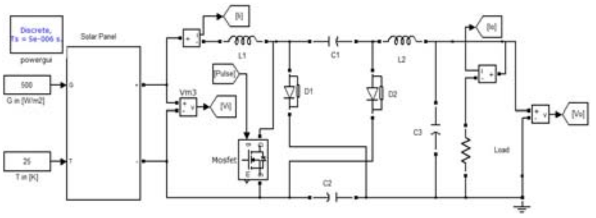


Figure 7: Simulation diagram for the proposed converter

Table 2 is the solar array specification for the proposed converter.

Table 2 Solar Array Specification (25° C)

Parameters	Typical Value
Maximum Power (Pmax)	224 W
Open Circuit Voltage (Voc)	36.6V
Short Circuit Current (Isc)	8.33A
Maximum Power Voltage (Vmp)	29.3V
Maximum Power Current (Ipm)	7.66A
System Fuse Rating	15A
Dimensions	994 X 1640 x 46 mm

The simulation parameters used to test the proposed fuzzy based modified cuk converter are as follows: L_{in} = 4mH; L_o = 4 mH; C_1 = 100 µF; C_2 = 100 µF; C_o = 270 µF; R_o = 30 Ω; and D = 0.5

The proposed system is tested by evaluating the output power, voltage and current at two values of solar irradiations namely, 500 watts / m^2 and 1000 watts / m^2. The results obtained at the solar irradiations of 500 watts / m^2 are presented in Fig. 8(a) - 8(c).

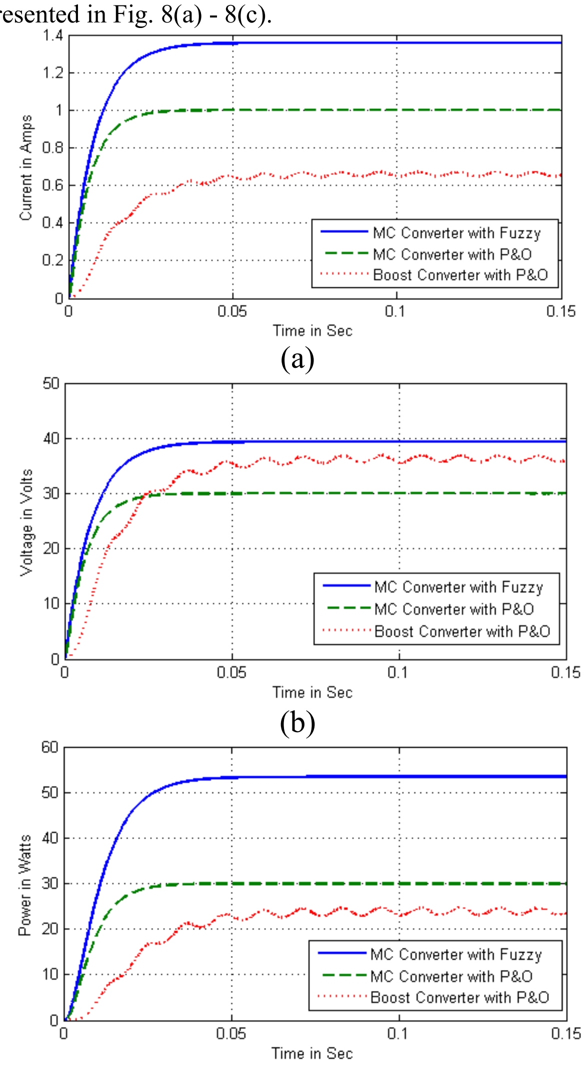
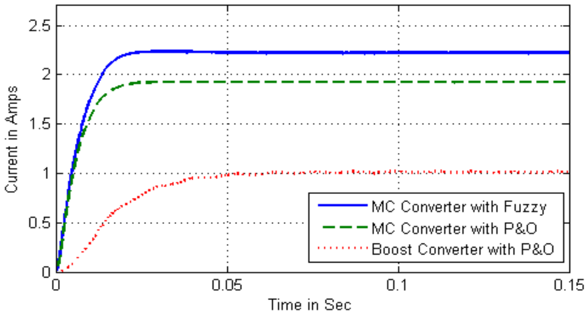
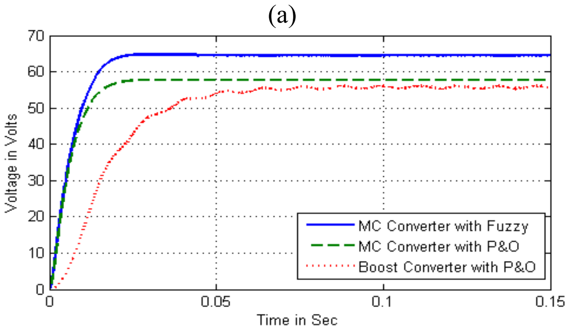


Figure 8: Output of Solar Irradiation at 500 watts / m^2 (a) Current, (b) Voltage, (c) Power

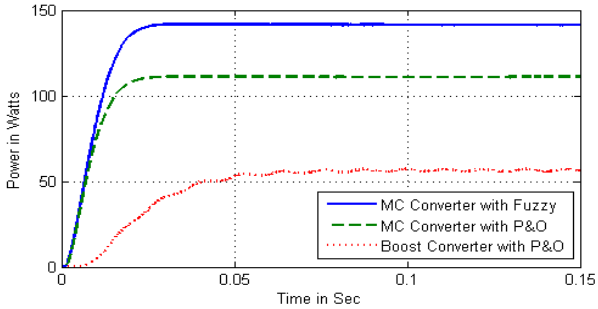
Similarly, the results obtained at the solar irradiations of 1000 watts / m^2 are presented in Fig. 9(a) - 9(c). Simulation results revealed that the fuzzy logic controller based MPPT modified cuk converter performance was better for stabilizing the output under different solar irradiation levels and also reduce the output oscillation than the conventional P&O based MPPT in modified cuk converter and P&O based MPPT in boost converter. From the comparison, one can observe that the proposed system efficiency is higher than that as compared with conventional P&O based MPPT in modified cuk converter and P&O based MPPT in boost converter.



(a)



(b)



(c)

Figure 9: Output of Solar Irradiation at 1000 watts / m^2 (a) Current, (b) Voltage, (c) Power

The performance by numerical comparison of different solar irradiation level, the proposed converter efficiency is 96.53% for solar irradiations of 1000 watts / m^2 and 96.42% for solar irradiations of 500 watts / m^2 as compared with conventional P&O based MPPT in modified cuk converter and P&O based MPPT in boost converter its better efficiency. Table 3 is the numerical comparison of different solar irradiation level.

Table 3 Numerical comparison of Different Solar Irradiation Level

Solar Irradiation / Electrical Parameters	**1000 Watts / m^2**						**500 Watts / m^2**					
	Boost Converter with P&O		**MC Converter with P&O**		**MC Converter with Fuzzy based P&O**		**Boost Converter with P&O**		**MC Converter with P&O**		**MC Converter with Fuzzy based P&O**	
	Input	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**	**Input**	**Output**
Power in Watts	63	56.56	118	111.1	148.5	143.36	26.04	23	31.88	29.96	55.35	53.37
Voltage in Volts	9	56	20	58.5	22.5	64	6.2	35.17	10.6	30	13.6	39.34
Current in Amps	7	1.01	5.9	1.9	6.6	2.24	4.2	0.67	3	0.99	4.07	1.35
Efficiency	**89.77 %**		**94.15 %**		**96.53 %**		**88.32 %**		**93.97 %**		**96.42 %**	

VI. HARDWARE DESCRIPTION

A photovoltaic solar cell is developed to extract maximum power using a Modified boost mode Cuk converter. The solar panel used in this research work is shown in Fig. 10. The controller integrated with the solar PV panel is shown in Fig. 11.

Figure 10: Solar PV Panel Experimental Setup

Figure 11: Experimental setup showing controller integrated with the Solar PV Panel

The electrical characteristics of the proposed panel are as follows.

Table 4 shows the solar irradiation data's of Salem district. It shows the annual solar irradiation level variations of erode district, Tamilnadu state, India. These data are collected from the annual report of Myrada Krishi Vigyan Kendra [22].

The converter Inductance (L_{in}) and (L_{out}) of the system is 100μH. The Power MoSFET of the proposed system is IRF540. The switch mode power rectifiers used in the system are D_1 = MUR3060 and D_2 = MUR3060. The capacitors C_1 and C_2 used in the system have a capacitance of 47μF and the voltage rating of 160V where as Capacitor C_o has a capacitance of 100μF with the voltage rating of 160V. The switching frequency utilized in this proposed approach is 40 kHz. V_o and I_o of the proposed system is 66.4V and 2A respectively.

Table 4 Solar Irradiation Measured in Kwh/m^2/Day

Month	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sep	Oct	Nov	Dec	Avg
Kwh/m^2	4.84	5.76	6.41	6.06	5.87	5.1	4.7	4.87	5.15	4.47	4.05	4.25	5.13

The controller used for the proposed PV system hardware is DSPIC30F2010. DSPIC30F devices contain extensive Digital Signal Processor (DSP) functionality within high-performance 16-bit microcontroller (MCU) architecture. Opto coupler used in this research work is HCPL3120. HCPL-3120 contains a GaAsP LED which is optically coupled to an integrated circuit with a power output stage.

It is ideally suited for driving power MOSFETs used in the inverter system. The Lamp with voltage of 12 V and current of 2 A is used in this system with a power of 21 watts. Programming has been carried out in Embedded C (Mirco C Compiler). The programmer kit for this approach is MP LAB. The MPLAB C Compiler for dsPIC DSCs is a full-featured, ANSI compliant optimizing compiler.

It is observed from the figure that the proposed approach produces an output of 66.4 V for the input voltage of 24.4 V. The output and input of current is 2.03A and 5.86A respectively. The gate signal for this experimental setup is shown in Fig. 12. The efficiency of the proposed fuzzy based modified boost mode Cuk converter is 94%. The fuzzy logic controller based MPPT with modified cuk converter system has been designed and implemented in an easier way than a conventional converter system.

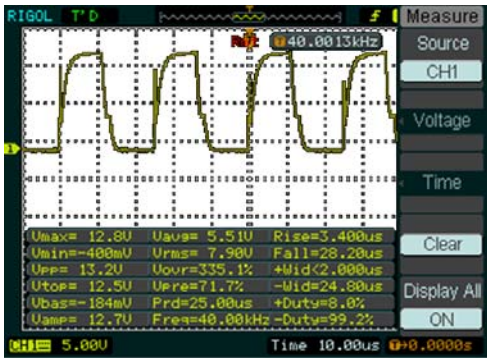


Figure 12: Gate Signal

VII. CONCLUSION

The proposed modified cuk converter was simulated in MATLAB simulation platform and the output performance was evaluated. Then, the mode of operation of proposed converter was analyzed by the different solar irradiation level. From that, output current, voltage and power were considered. For evaluating the output performance, the proposed modified cuk converter output was tested with PV system. From the testing results, the output power of the modified converter efficiency and the efficiency deviation were analyzed. The analyses showed that the proposed modified cuk converter was better when compared to conventional cuk converter and boost converter.

Experimental setup has been done to prove the effectiveness of the proposed system.

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