Analysis between Perturb and Observe Controller and Fuzzy Logic Controller for a Photovoltaic System with CUK and SEPIC Converter

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***Abstract*—The power generation is using Photovoltaic (PV) cell is the best alternative developing for fossil fuel since it renewable green power, energy conservation and demand-side management. Solar energy most useful for sustainable development but due to it has a nonlinear current-voltage characteristic. It is difficult to track the maximum power produce by the PV module. This paper presents a comparison between the Single-Ended Primary-Inductor Converter (SEPIC) and CUK converter by using both Fuzzy Logic Controller (FLC) and Perturb & Observe (P&O) methods in maximum power point tracking (MPPT). In this paper, the performance, advantage and disadvantage for both converters and MPPT algorithm are described. A general model of a Photovoltaic system with proposed MPPT controller and converters is implemented in MATLAB/Simulink software. The input parameter of temperature and irradiation level will be under constant and variable level as to prove the system efficiency towards changing conditions. The simulation result will be analyzed in different case studies in order to prove the effectiveness timely response performances, efficiencies of our power of converting over input power of the PV module and the comparison of transient response of voltage ripple of the systems.**

***Index Terms*—Fuzzy Logic; MPPT; P&O; PV.**

I. Introduction

Nowadays, the global demand for energy consumption increasing rapidly due to modern technologies and machines fully depends on electrical energy. The increasing of energy demand leads to an interest for researchers explore more on renewable energy sources that are more environmentally friendly. As opposed to other renewable energy resources, the Photovoltaic (PV) system seems more practical due to ease of installation and isolated operation of power generation [1]. Moreover, PV systems are classified as static type power generation that requires less maintenance. Hence, PV systems are contemplated as the best solution for supplying electrical energy in rural areas or industrial applications.

Modern technologies and further investigations are essential for an effectiveness of the utilization of PV systems. The SEPIC is one of the buck-boost converters that used to provide a constant DC voltage. Thus, the application of SEPIC design will be implemented in this research work. Besides that, the switching for the SEPIC requires a PWM signal generator which is crucial in extracting the maximum power of the PV system. Other than SEPIC, there are also a common type buck-boost converter family that have implemented such CUK converter. This converter is also used to extract the maximum power of the PV system same as the SEPIC.

In this approach, the FLC is recommended to be applied in this system due to the straightforward implementation, fast response and does not require complex calculation [2]. According to Hegazy Rezk and Ali M. Eltamaly in year 2015 [3], it is likewise the best solution to obtain the highest power value through the Maximum Power Point Tracking (MPPT) techniques followed by P&O, INC, and, HC MPPT techniques in both dynamic response and steady-state in most of the normal operating range. In order to compare the effectiveness of the FLC algorithm, the P&O algorithm is going to be applied in this system too. In 2014, according to Ahmed M. Atallah, Almoataz Y. Abdelaziz, and Raihan S. Jumaah [4], this algorithm implements a simple feedback arrangement and little measured parameters. Thus, it is relevant and still can be applied to the system, although it is conventional compared to the other algorithm.

For the comparison and analysis purpose of PV system, the designs and topology need to be tested and simulate using MATLAB/Simulink to provide a practical value and suitable output value that meet the power demand. Moreover, by performing simulation in the software, improvement of the output result can be achieved to ensure the efficiency of the system at the highest level. In this research work, the optimized PV system must be able to generate stable power output and high efficiency.

II. Overview of Photovoltaic System Model

A. Photovoltaic Module Equivalent Circuit

In real time, it is impractical for the PV module system to be implemented directly to the load or electrical appliances. This is because the efficiency of PV systems depends on many factors such insolation, temperature, spectral characteristic of shadow, and sunlight [5]. Modelling of PV system requires a basic understanding of the equivalent circuit of an ideal PV cell as provided in Figure 1.

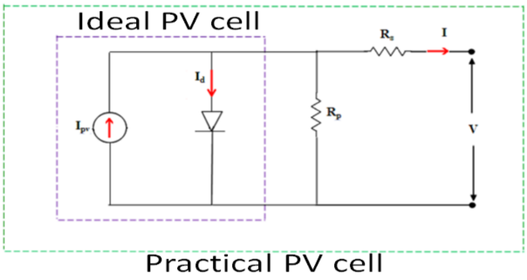

Figure 1: Equivalent Electrical Circuit of Solar Cell [5]

B. *Equations for Photovoltaic Cell*

A solar PV cell basically is a p-n semiconductor junction. Whenever certain amount of light is being exposed on the solar panel, then a DC current varies linearly with the solar PV irradiance. The equivalent electrical circuit of an ideal PV cell can be considered as a current source parallel with a diode. Thus, the basic equations can be formed to describe the I-V characteristic of the PV cell as provided in Equation (1) to (3).

$$I = I_{pv,cell} - I_d \tag{1}$$

$$I = I_{pv,cell} - I_{o,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right] \tag{2}$$

Therefore,

$$I = I_{pv} - I_0\left[\exp\left(\frac{V + R_s I}{Vta}\right) - 1\right] - \left(\frac{V + R_s I}{R_p}\right) \tag{3}$$

Where,

$I_{pv,cell}$	= Current generated by the incident light
I_d	= Shockley diode equation
$I_{o,cell}$	= Reverse saturation current of the diode
q	= Electron charge (1.60217646×10^{-19}C)
k	= Boltzmann constant (1.3806503×10^{-23} C)
T	= Cell Temperature in Kelvin (k)
V	= Solar cell output voltage (V)
R_s	= Solar cell series resistance (Ω)
R_p	= Solar cell parallel resistance (Ω)

C. *Characteristic of Voltage, Current and Power of PV*

By referring to the mathematical equation stated before, the PV cell can be modelled using mathematical models in MATLAB/Simulink. Thus, the characteristics of the photovoltaic output can be produced and the performance curve of the I-V and P-V curves that show the relation of current, voltage and power as showed in Figure 2 and Figure 3 [6].

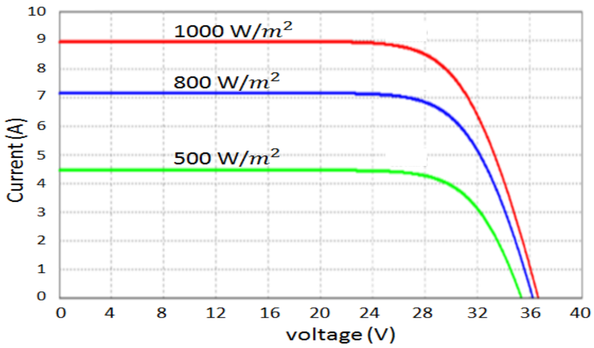

Figure 2: The Relation of Current And Voltage at Photovoltaic Curve [6]

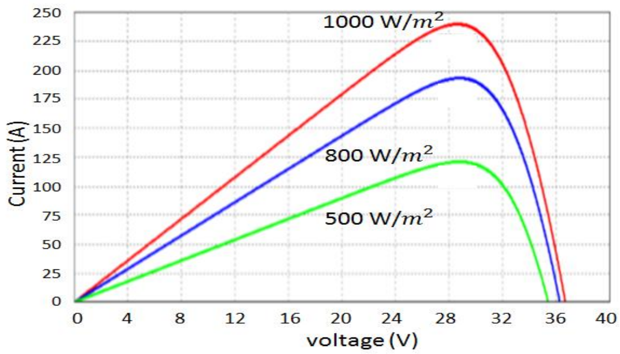

Figure 3: The Relation of Power and Voltage Photovoltaic Curve [6]

III. MAXIMUM POWER POINT TRACKING

The MPPT is a technique in order to gain the highest power from the PV. The location for MPPT is not constant under different condition of temperature and irradiance. In that case, to get the highest power many algorithms have been developed and utilizes in some solid-state devices. There are more than 19 distinct MPPT techniques available and being researched in the past few years, however the two most favorable algorithms will be discussed in this section which are P&O and FLC.

A. *Fuzzy Logic Controller (FLC)*

In FLC design, the main control variables should be identified and determine the sets that describe the values of each linguistic variable. The input variables of the FLC are the input variables of the fuzzy logic controller are the slope of the power variation, $E(k)$ and the change of the slope, $CE(k)$ of the PV module [7]. The output of the FLC is the duty cycle, D of the PWM signal controls the converter switching gate. The triangular membership functions are used for the FLC for easier computation. A five-term fuzzy sets, such Negative Big (NB), Negative Small (NS), Zero (Z), Positive Small (PS), and Positive Big (PB), are defined to describe each linguistic variable [2]. The fuzzy logic control system can be generalized in a block diagram as in Figure 4.

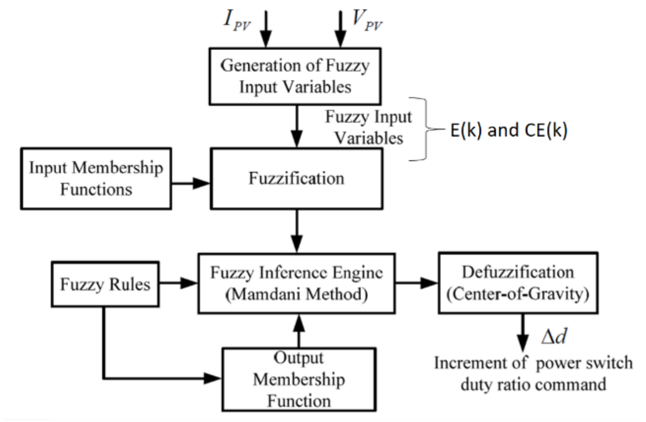

Figure 4: Fuzzy Logic Controller for The MPPT Design [7]

The input variables of the fuzzy logic controller are the slope of the power variation and the change of the slope defined as in Equations (4) and (5).

$$E(k)=\left(\frac{P_{pv}(k)-\mathrm{P}_{pv}(k-1)}{V_{pv}(k)-V_{pv}(k-1)}\right) \tag{4}$$

$$CE(k)=E(k)-\mathrm{E}(k-1) \tag{5}$$

The fuzzy rules of the proposed SEPIC and CUK DC-DC converter can be represented in a symmetric form as in Figure 5 that been classified in three regions. The operation of the fuzzy logic technique based on regions of the P-V graph can be explained by referring to Figure 6.

Fuzzy Rule		E(k) NB	E(k) NS	E(k) ZE	E(k) PS	E(k) PB
CE(k)	NB	ZE	PB	PS	ZE	NB
	NS	PB	PS	ZE	ZE	NB
	ZE	PB	PS	ZE	NS	NB
	PS	PB	ZE	ZE	NS	NB
	PB	PB	ZE	NS	NB	ZE

Region 1 Region 2 Region 3

Figure 5: Region of Fuzzy Rules for P-V Slope and Change of Slope As Inputs [7]

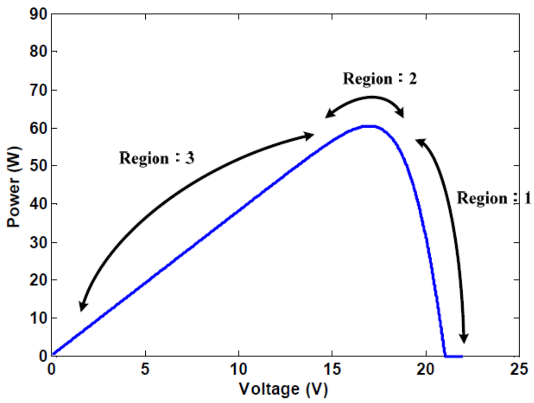

Figure 6: Region on Power Against Voltage Graph [7]

In region 1, the slope is negative and it show the operational point of the PV cell is positioned on the right side of the MPP. In order to track and achieve the MPP, duty ratio should be raised at this period. The second set of input variables, which are the change of slope, $CE(k)$ would be used to determine the magnitude of the duty ratio to be increased. Though, when $E(k)$ and $CE(k)$ are both NB, the calculations may conduct the wrong outputs. When both ΔP_{pv} and ΔV_{pv} being very small values which are close to the MPP operating point, the output would be set as ZE to avoid $E(k)$ from becoming NB and produce error output after division.

The rule database was set to increase the duty ratio when $E(k)$ is NS and $CE(k)$ is either negative or zero. This is because the operating point would be situated in the right side of the MPP and is tending to move to the right side further. Difference when $CE(k)$ is positive, the operating point is approaching the MPP from the right side and the output would be set to ZE. This will prevent from the MPPT over-increasing the duty ratio and causing the system to oscillate.

Furthermore, in region 2, the operating point is close to the MPP curve. Thus, the $E(k)$ will be ZE so that it can maintain the same duty ratio under that condition. As for preventing the operating point move to the right side of the peak, the controller will be used in PS to suppress the change of magnitude of the duty ratio in the opposite direction. The controller will be using NS to prevent over-increase of the duty ratio. In region 3, the slope, $E(k)$ is positive and operating point will be at the left side. Thus, the operational rule database will be inversely to the operating on the region 1 to prevent over-decreasing the duty ratio and system oscillation.

B. Perturb and Observe (P&O)

The most popular MPPT algorithm being applied in PV system monitoring is the P&O technique. This technique will track the operating point of the PV system and generate the duty cycle of the PV system according to the voltage and power relationship as show in Equation (6).

$$\frac{dP}{dV_{pv}}(n)=\frac{P(n)-P(n-1)}{\mathrm{V}_{pv}(n)-V_{pv}(n-1)} \tag{6}$$

The advantage of this method, only voltage is sense which easy to implement the system. The power output of the system is checked by varying the supply voltage. If on increasing the voltage, power is also increased then more δ is increased otherwise start decreasing the δ. Likewise, while decreasing voltage if power increases the duty cycle is decreased. These steps continue till the maximum power point is reached [8]. The flowchart as illustrated in Figure 7 explains the process of the P&O method.

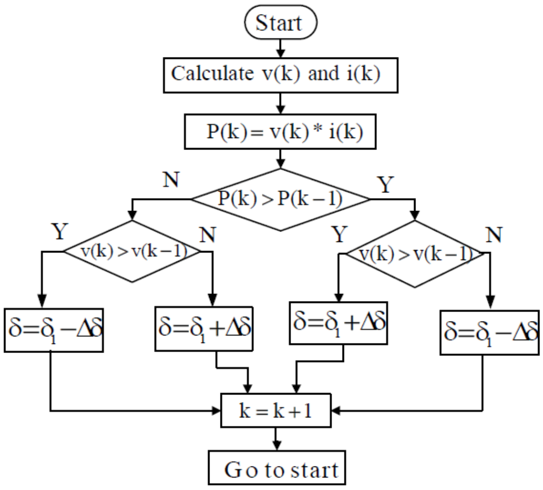

Figure 7: Flow Chart Of P&O Method [8]

The P&O scheme can be explained by the following mathematical equations as shown in Equations (7) to (9).
On the condition of the voltage source:

$$\frac{\delta P}{\delta V} > 0 \ , V_{ref} + \Delta V_{ref} \qquad (7)$$

On the condition of the current source:

$$\frac{\delta P}{\delta V} < 0 \ , V_{ref} + \Delta V_{ref} \qquad (8)$$

On the condition of the power point:

$$\frac{\delta P}{\delta V} < 0 \ , V_{ref} - \Delta V_{ref} \qquad (9)$$

IV. DC-DC CONVERTER

DC-DC converters regulated the input voltage and functioned automatically to give a constant and regulated voltage output. Besides, it is a power electronics application that switch a DC voltage to another DC voltage level. To obtain the maximum power to be transferred or consume by the load, the resistance load needs to be adjusted equal to panel internal resistance. The CUK and SEPIC converter topology are proposed in this paper to compare the performance of the PV system. Both are in the Buck-boost converter family which the output voltage can be step-up or step-down.

A. CUK Converter

The CUK converter, can alter input voltage into greater than, equal or less than the input voltage magnitude. The CUK converter is calculated by using the duality principle on the circuit of a buck – boost converter. The most important feature of this topology is instead of an inductor, the capacitor is used as the primary means of storing and transferring energy from input to the output. This causes energy transfer to occur during both ON and OFF gated switch intervals [9].

The circuit structure of the CUK converter using MOSFET switch is shown in Figure 8 for the case of the CUK converter the output voltage is reversed in input voltage. When the input voltage turned on and MOSFET (SW) is switched off, while the diode D is forward biased. The capacitor C1 is charged through L1–D. Thus, the operation of the converter divided into two modes [10].

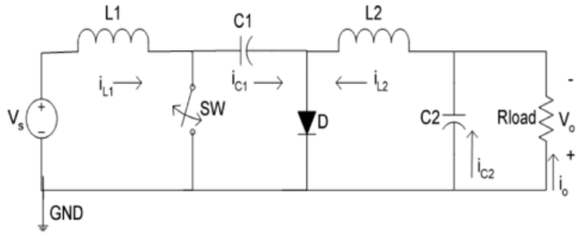

Figure 8: Circuit Diagram of CUK Converter [10]

- Mode 1: When the MOSFET switch is turned on at t=0. The current through L1 rises. And at the same time the voltage of C1 reverse biases diode D and turn it off. The capacitor C1discharges its energy to the circuit C1-C2-load-L2 as showed in Figure 9.
- Mode 2: When the MOSFET switch is turned off at t = t1. The capacitor will start to charge from input supply vs and the energy stored in the inductor transferred to the load. The capacitor C1 is the medium for transferring energy from source to load as showed in Figure 10 [10].

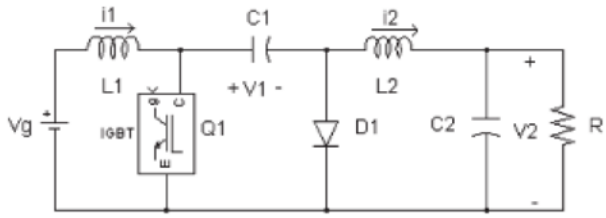

Figure 9: CUK Converter with Switch ON (Mode 1)

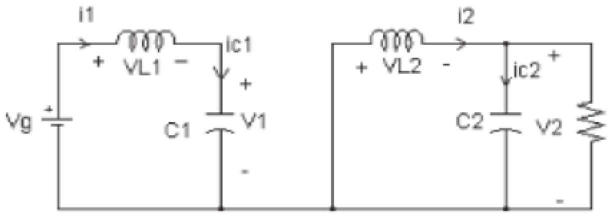

Figure 10: CUK Converter with Switch OFF (Mode 2)

B. SEPIC Converter

SEPIC converter is one of the buck-boost converter that can control the output voltage higher or lower than the input voltage. In addition, the SEPIC is actually overcome the drawback of a buck-boost converter which operates in isolated mode [2]. The SEPIC converter is similar to the CUK converter, but the CUK converter produces an invert polarity of the output. The switching topology for the SEPIC converter is shown in Figure 11.

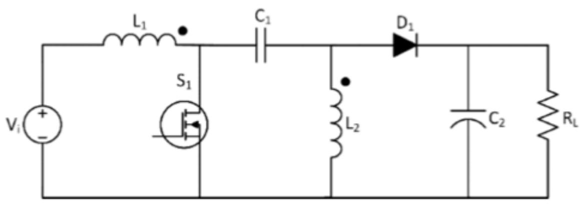

Figure 11: The Equivalent Circuit of SEPIC Converter [2]

The SEPIC converter consists of an active power switch (MOSFET), a diode, two inductors (L1, L2) and two capacitors (C1, C2). C1 capacitor, which is between the inductors L1 and L2, ensures DC isolation which blocks any DC current path between the input and the output. If the SEPIC converter is operating in the CCM, two switching modes are considered and the equivalent circuits belong to each mode are given in Figure12. The L1 and L2 are charged by V_i and V_{C1} in Mode 1 (S1 is turned on), respectively as depicted in Figure 12(a). While, the C1 and C1 in Mode 2, (S1 is turned off) are discharged by i_{L2} and the output current as depicted in Figure 12(b). The inductors L1 and L2 can be used for uncoupled, which are separated or coupled which are wound on the same core [11].

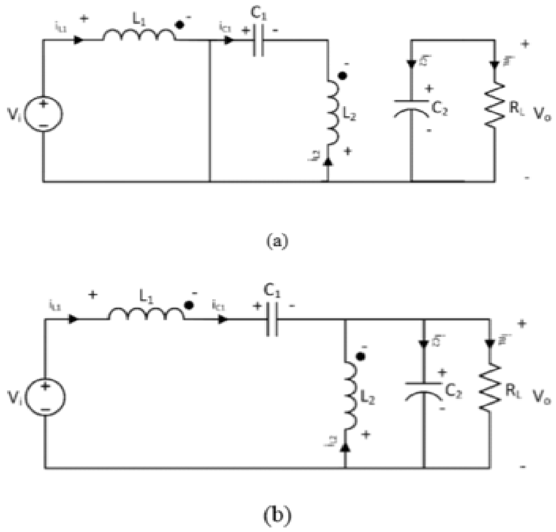

Figure 12: The Equivalent Circuit of The SEPIC Converter In (a) Mode 1 (S1 is ON) (b) Mode 2 (S1 is OFF) [11]

V. SYSTEM DESIGN

Block diagrams of simulation for the system design are illustrated in Figure 13 to 16.

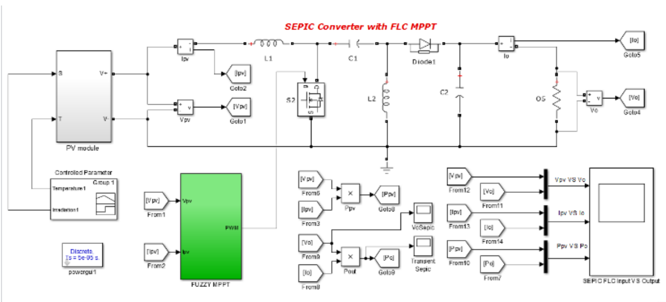

Figure 13: Model of Fuzzy Logic Controller with SEPIC Converter

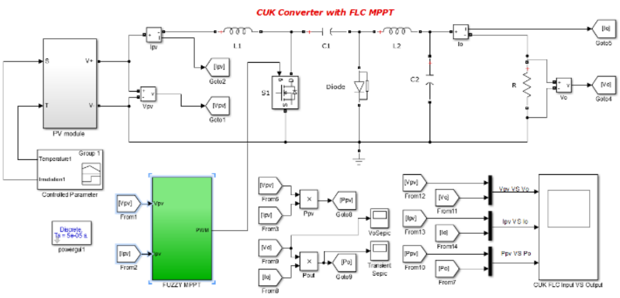

Figure 14: Model of Fuzzy Logic Controller with CUK Converter

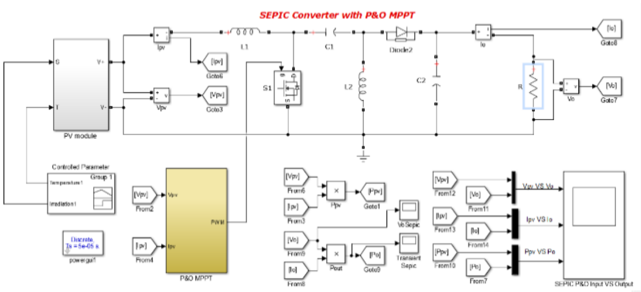

Figure 15: Model of Perturb & Observe Controller with SEPIC Converter

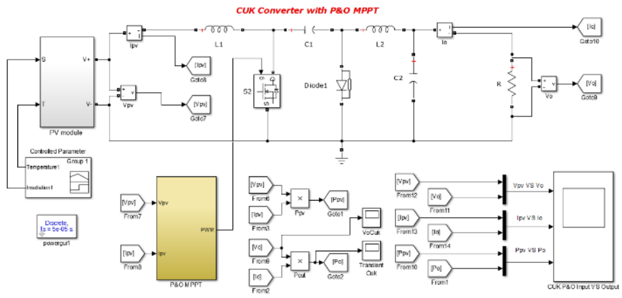

Figure 16: Model of Perturb & Observe Controller with CUK Converter

Simulation is using MATLAB Simulink program with PV module characteristic data shown in Table 1. The component parameter for the both converter can be calculated by having 20V as output voltage of the converter. Below are the tables of parameter used in designing the converter shown in Table 2 and the component parameter on each DC-DC converter shown in Table 3.

Table 1
Properties Characteristic of SOLAREX MSX60 PV Panel Operate At 25℃

Electrical Characteristic	Specification
Maximum power, P_{max}	60 W
Voltage at max, V_{mpp}	17.1 V
Current at max, I_{mpp}	3.5 A
Open-circuit voltage, V_{oc}	21.6 V
Short-circuit current, I_{sc}	3.8 A
Temperature, T	25°C

Table 2
Parameter of Converter Design

Design Parameter	Computation
Resistive Load, R	10 Ω
Switching Frequency, F_{sw}	50khz
Output Voltage, V_{out}	20 V
Output Current, I_{out}	2 A
Primary Capacitor Ripple Voltage, $\Delta V c_1$	0.3333 V
Output Capacitor Ripple Voltage, ΔV_{out}	0.1 V

Table 3
Components Parameter on Both DC-DC Converter

Component	CUK	SEPIC
D	0.50617	0.50617
L1	1.5185×10^{-5}H	1.5185×10^{-5}H
L2	1.5185×10^{-5}H	1.5185×10^{-5}H
C1	6.074×10^{-5}F	6.074×10^{-5}F
C2	3.252×10^{-5}F	2.025×10^{-4}F

VI. RESULTS AND ANALYSIS

In general, both MPPT can perform in locating the maximum power point as has been reviewed previously. In that case, performance of FLC and P&O techniques can be determined by the output power produce on the load side of the system. Besides that, the efficiency of power delivered can be obtained by referring to the output power to produce the input power generates in the PV. In Figure 17 and Figure 18 are the illustrated simulation result of the output power on the SEPIC converter using FLC and P&O techniques respectively. While in Figure 19 and Figure 20 is the output power produced by the CUK converter using FLC and P&O respectively

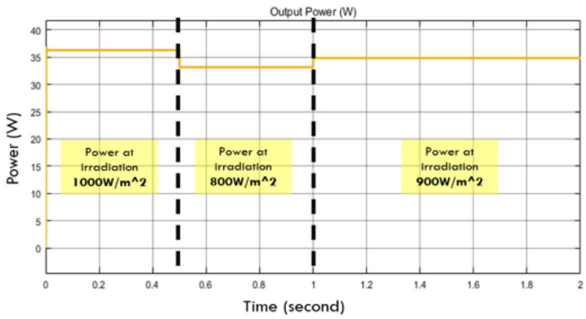

Figure 17: Simulation Result of Output Power By SEPIC Converter using FLC

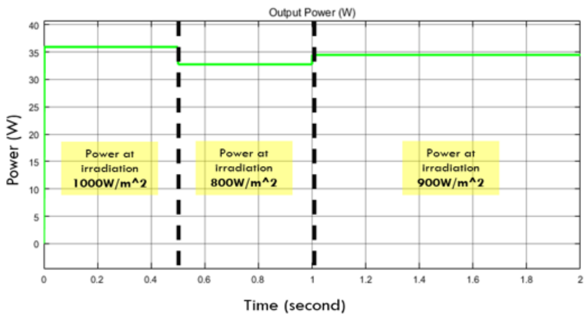

Figure 18: Simulation Result of Output Power By SEPIC Converter using P&O

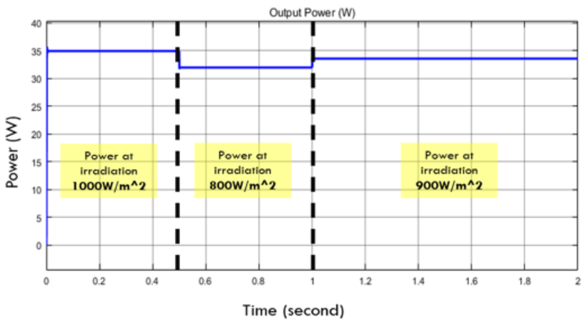

Figure 19: Simulation Result of Output Power By CUK Converter using FLC

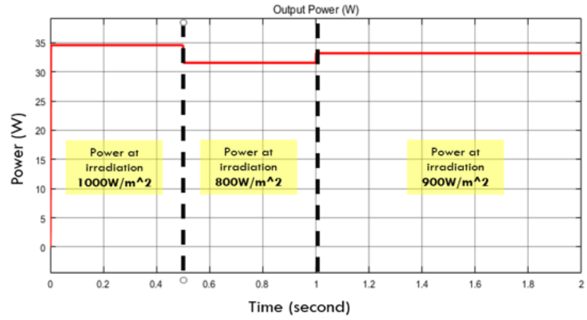

Figure 20: Simulation Result Of Output Power By CUK Converter using P&O

Simulation result show that the output power produced by both SEPIC and CUK by using fuzzy logic controller is slightly higher compared with converters with P&O techniques. Although the different level can be considered small, in practical application such in the power grid system, the optimum power cannot be achieved.

The simulation shows that, the CUK converter has reverse polarity compared to the SEPIC converter, but with slightly different magnitude of voltage levels. Hence, efficiency of both converters corresponding to the output voltage can be obtained. The data collected is presented in Table 4.

In this section, the performance of both converters can be analysed into the efficiency of the output voltage level, ripple voltage and current, and duration of the system to be in a steady state or stable. In order to determine the voltage, efficiency, the output voltage is expected to obtain 20V due to the converter been designed to have 20V of output voltage. Although the power level changes according to irradiation level, the current value will follow the changes of PV module, but the voltage will remain fixed [10]. Figure 21 and Figure 22 are the voltage level between SEPIC and CUK converter respectively.

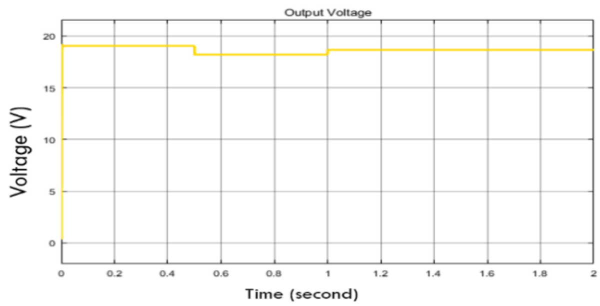

Figure 21: Simulation of SEPIC Converter Output Voltage

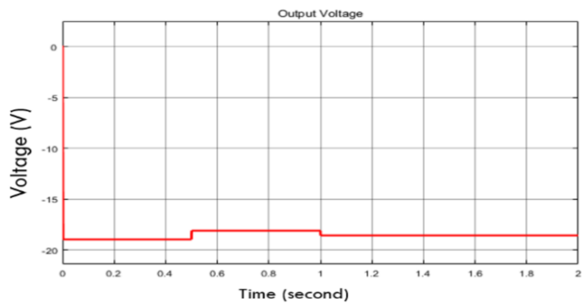

Figure 22: Simulation of CUK Converter Output Voltage

Through observation on the simulation, the output power produced by both SEPIC and CUK by using fuzzy logic controller is slightly higher compared with converters with P&O techniques. Although the different level can be considered small, in practical application such in the power grid system, the optimum power cannot be achieved.

The simulation shows that, the CUK converter has reverse polarity compared to the SEPIC converter, but with slightly different magnitude of voltage levels. Throughout this result, the efficiency of both converters corresponding to the output voltage can be obtained. The data collected is presented in Table 4.

Table 4
Data Result of Output Power for the System at 1000 W/m^2 Irradiation and 25°C Temperature

Type of Converter	SEPIC		CUK	
Control Technique	FLC	P&O	FLC	P&O
Input Power, P_{pv} (W)	39.35	37.88	39.00	36.40
Output Power, P_{out} (W)	36.27	34.89	35.94	33.19
Efficiency (%)	92.17	92.11	92.15	91.18

Besides that, from the Table 5, the SEPIC converter performs well in maintaining the voltage level compared to the CUK converter in different level of irradiation. Apart from that, the converters also can be analyzed according to the duration of the system to become a steady state after having changed on irradiation. This can be analyzed through the output power for both converters that been simulated in a certain period of time. In Figure 23 is the resulted simulation of output power produce in SEPIC and CUK converter using P&O method respectively.

Table 5
Output Voltage of Converters at Different Irradiance

Irradiation level (W/m^2)	Output Voltage (V)			
	SEPIC		CUK	
	FLC	P&O	FLC	P&O
1000	19.05	18.68	-18.96	-18.59
900	18.21	17.87	-18.10	-17.76
800	18.67	18.31	-18.57	-18.22

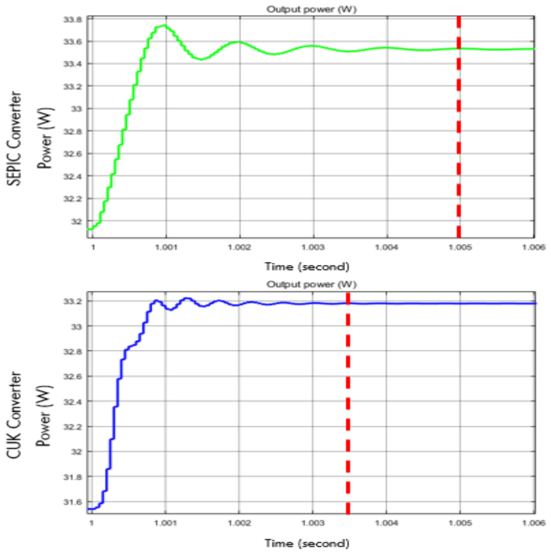

Figure 23: Simulation of Output Power Of SEPIC And CUK Converter at Period Of 1 Second

From the simulation, the ripple level produce by the SEPIC converter was high compared to the CUK converter. The steady state period for SEPIC converter takes a longer duration which occurs at 1.005 seconds compared to the CUK converter which is at 1.0035 seconds. This oscillation is an effect caused by a transient response of a circuit system. It is a momentary event preceding the steady state (stable). In this case, both SEPIC and CUK converter with same MPPT being analyzed the effect of sudden changes in the ordinance. The result show that power of the converter also increases. This event happens due to a sudden change of voltage or current in the circuit. In his case, during a period of time of 1 second, ordinance change from level 800 W/m^2 to 900 W/m^2. Besides being the DC transient graph being scaled from 31.8W to 38.8W for SEPIC and 31.4W to 33.2W for CUK converter.

VII. Conclusion

Throughout this project, the objective of analyzing the performances of MPPT techniques and converters is verified as the result is achieved as expected. In this paper, the use of conventional MPPT technique such P&O is still significant due to the results obtain are quite precise and valid compared to fuzzy logic controller. The fuzzy logic controller performs well to track and extract the maximum power of a PV system although it is quite complex. In addition, it also possible to be implemented to a higher level system such in power grid compared to P&O which needs hybrid technique in order to implement in the grid system.

Other than that, the SEPIC converter which is a family of the Buck-Boost converter performs better with the FLC method. Both CUK and SEPIC converter get desired voltage level output. Throughout analysis, we can see the drawback of SEPIC which is producing higher ripple level and longer duration to stable, but the SEPIC converter has better results in obtaining higher power output and positive voltage terminal output.

As conclusion, the objectives of this project are achieved throughout simulation and analysis using MATLAB Simulink and both SEPIC converter and Fuzzy Logic Controller worked best as MPPT technique.

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