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Design Control Systems for Buck-Boost and Cuk Converters for Solar Power Applications

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Abstract— Interests in solar power as a cheap and clean source of electrical power is increasing these days. A lot of research is released in the field of extracting electrical power efficiently from solar power using photovoltaic (PV) solar cells. In this paper, two different power converters are proposed to produce output voltage (24 V) for various loads (electronic circuits, charging, etc.). These power converters are Buck-Boost and Cuk converters that are designed based on their mathematic models. MATLAB/SIMULINK is used to model the power converters as open loop and closed loop control systems, whereas two control approaches are developed to provide the required output voltage under different conditions. These two control techniques are based on linearity and nonlinearity systems, which are Proportional Integral Derivative (PID) and Fuzzy Logic Control (FLC). The simulation results of the proposed PV systems show that these converters can provide the required output voltage (24 V), and the efficiency of Buck-Boost and Cuk converters found to be 91% and 92%, respectively. The system performance using FLC yields better and more robustness response than PID system under various conditions (load values and different sun radiation levels).

Index Terms— Photovoltaic Applications; Solar Systems; Buck-Boost Converter; Cuk Converter; Fuzzy Logic Controller, PID Logic Control.

1. INTRODUCTION

With the growing energy demand today, we need more reliable energy sources. Solar energy is one of the cleanest sources of energy because Solar panels do not use any water to generate electricity, they do not release harmful gases into the environment, and the source of their energy is boundless and best of all solar energy is free. Using solar energy instead of fossil fuels means reducing the need for carbon dioxide emitting. Along with its impressively low environmental costs, the solar power industry can also be economically beneficial. The sun delivers energy to the Earth much more than all people use, photovoltaic (PV) rapidly becoming inexpensive due to the technological development and significant investment in this field, its maintenance is very low as solar panels last over 30 years, on a smaller scale, using solar panels at home can help reduce your electric bill significantly. Solar power mainly depends on the sun and the weather, so the output of solar panels is not constant, here lies the benefit of the power electronics and power converters to ensure that we get steady, discontinuous and ripple-free output [1].

This work focuses on designing and modeling Buck-Boost and Cuk converters for solar panels. Linear and nonlinear control systems are designed to control the output voltage of these converters for the load requirements. These control techniques are Proportional Integral Derivative (PID) and Fuzzy Logic Control (FLC) systems. The performance and characterization of these converters are investigated concerning various conditions of the system. MATLAB/SIMULINK is used in this work to simulate these design power converters. The paper also emphasizes the review of the Buck-Boost and Cuk converters for solar power applications and brings out a few research results about the performance of different existing converters based on the literature analysis by the authors. As seen in Fig. 1, the output of the power converters (from the harvested power by solar panels) can be used to power different applications, such as various loads, charging batteries, etc. This paper focuses on designing and developing Buck-Boost and Cuk converters for a solar panel, to provide the required power to loads.

This paper is organized as follows. Section 1 shows the importance of solar power in generating electric energy. Section 2 describes the literature survey of using Buck-Boost and Cuk converters for PV applications. The operation of the two power converters and PID & FLC control systems are described in section 3. Simulation results are reported and illustrated in section 4. The discussion and analysis about this PV system are illustrated in section 5. Finally, the conclusion is drawn in section 6.

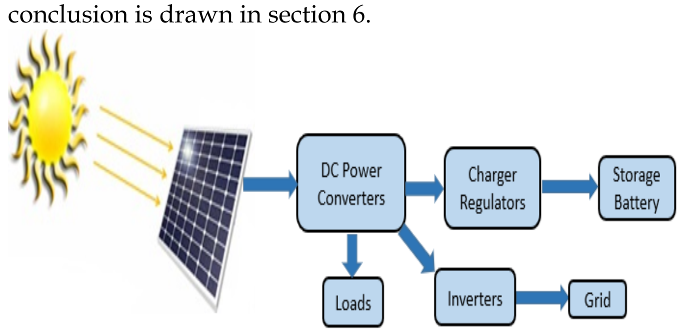

Fig. 1. Solar power system block diagram.

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2. Literature Survey

There are many researchers develop DC power converters for solar power applications. In this section, a survey for Buck-Boost and Cuk converters for solar power applications is described. F. S. Dinniyah *et al*. designed and simulated a closed loop Buck-Boost converter for solar panels using PID controller. Proteus 8.4 was used to simulate the converter that achieves the desired output voltage with a range of efficiency from 90 to 99%. An Arduino microcontroller is used to control the output voltage, the experiments showed that the converter outputs a constant value of 12 V, with a range of voltage input of 10 to 50 V [2]. M. Z. Zulkifli *et al*. simulated a Buck-Boost converter using SIMULINK to harvest power from solar panels. A simple control scheme was presented to decide the mode suitable for the buck and boost mode. Their proposed system was based on two modes, where the converter was the centerpiece between the solar panel, the battery, and the load. Buck mode was active when the power flow happened from the PV panel to the load and the battery. Boost mode was functioning when the power flow occurred from the battery to the load [3]. W. A. Jabbar *et al*. proposed a Buck-Boost converter based on Arduino microcontroller to maintain the output voltage of the PV system at the desired value by controlling the duty cycle of the converter using a pulse width modulator (PWM). The experimental results showed that the developed converter performed well and attained 12 V constant output voltage in buck and boost modes [4]. P. Singh *et al*. analyzed a Buck-Boost converter on the solar PV module in MATLAB SIMULINK. This Buck-Boost converter was employed after a solar module consisted of 36 solar cells [5]. S. Mageshwari *et al*. designed and implemented a Buck-Boost converter for residential PV applications. They developed Maximum Power Point Tracking (MPPT) system for the converter to maximize the power output from PV module and to reduce the cost of the PV array system by decreasing the number of solar panels required to generate the power. The proposed design system was carried out in simulation studies, where the efficiency was increased to be used for PV residential applications where the constant voltage was required and it enhanced the advantage of the series compensation approach [6]. J. K. Shiau *et al*. focused on the development of a circuit simulation model for MPPT evaluation of solar power that involves using different buck-boost power converter topologies; including SEPIC, Zeta, and four-switch type buck-boost DC/DC converters. They conducted a comparative study for MPPT evaluation by using the different converter topologies through circuit simulation, where MATLAB/SIMULINK was used to verify the complete circuit simulation model [7]. G. Ang *et al*. designed and implemented a DC-DC Buck-Boost converter with a FLC for harnessing solar energy. They used a microcontroller which measured the input and the output voltages of the system. The specific objectives of this research were to design and construct a Buck-Boost converter for PV cell, create FLC for the charging circuit and integrate a microcontroller to observe the state of charge of the battery. They verified that the converter was not able to boost the voltage higher due to a very small input current. When the output voltage of the solar panel was 20 V the buck mode was active and boost mode operated for less than 20 V since the used batteries were less than 20 V [8]. S. Kiruthiga *et al*. designed a Buck-Boost converter for solar panels using a PID controller. They discussed designing this converter for solar panels, with a voltage input range of 10 to 30 V. Their design was simulated using MATLAB and yielded a voltage output with an efficiency of 90 to 99%. The design of the Buck-Boost converter using a two switch configuration was carried out and the converter operation was studied under various operating modes, the control of the converter was done through a PID controller which settled the voltage with an error around 2% [9]. O. Elbaksawi used a Buck-Boost converter to design a PV system based on Buck-Boost converter, MPPT, and PID controller using MATLAB Simulink. The proposed model depended on the slope of the derivative of the current to the voltage to reach MPPT from measurements of the voltage and current, and the algorithm determined the PV output power and its derivative as in terms of the voltage [10].

A. Karaarslan designed closed loop control systems for a Cuk converter, which are PI and One-Cycle controllers. One-Cycle control is a nonlinear algorithm that controls the duty ratio of the switch by averaging the switching variable every cycle. MATLAB/SIMULINK was used to simulate both controllers, the simulation results showed that the One-Cycle control had a faster response than PI, less settling time, and less maximum deviation than the PI controller [11]. S. Ramasamy *et al*. designed a modified Cuk converter using MPPT technique within the FLC to improve the performance of the PV system. The modified Cuk converter had reduced the conduction losses and switching losses by replacing the passive elements with switched capacitors to provide a smooth transition of voltage and current. The simulation and experimental results showed that the efficiency of the PV system was increased by 3% [12]. B. Mohana *et al*. designed FLC for a Cuk converter to achieve MPPT of a PV system under variable operating conditions. MATLAB/SIMULINK was used to simulate the system, where the simulation results showed a smooth change of current and a constant voltage in variable load, represented in little steady-state error and overshoot. The simulation results of asymmetrically distributed memberships illustrated faster response than the symmetrically distributed membership functions [13]. B. Jeba *et al*. designed FLC based on the Particle Swarm Optimization technique for MPPT of PV systems. They used MATLAB to simulate a Cuk converter to keep the power track with various irradiations [14]. A.

Geetha et al., designed and developed FLC based on MPPT system to generate the maximum power of the solar power system. They designed a Cuk converter and bidirectional converter to charge a battery in normal conditions, and this battery was used to drive load under abnormal conditions. The system was simulated using MATLAB/SIMULINK, which converted 231 V to 12 V [15].

3. Power Converter and Control Systems Designs

In this paper, Buck-Boost and Cuk converters are designed for PV systems. Control systems are designed and developed to achieve the required output voltage (24 V) that can be used to power electronic systems and charge battery, as shown in Fig. 2. The output of the control systems is compared with a sawtooth signal to generate PWM (1Vpeak-to-peak, 100 kHz) and (1Vpeak-to-peak, 50 kHz) for Buck-Boost and Cuk converters, respectively. MATLAB/SIMULINK is used to model and simulate the proposed systems as open-loop and closed-loop systems. The following subsections describe the basic operation of the power converters and PID&FLC control systems.

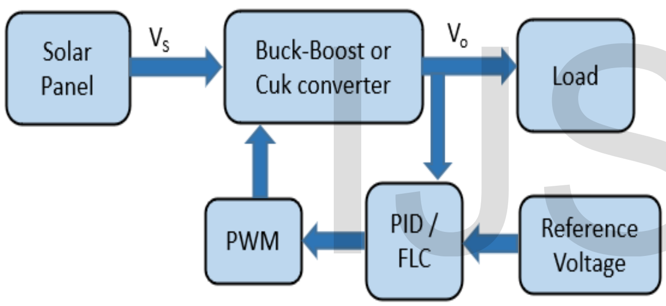

Fig. 2. Block diagram of closed-loop control system for DC power converter.

3.1 Design of Buck-Boost Converter

The buck-boost converter is a type of DC-to-DC converter, which can function as a buck converter and a boost converter depending on the duty ratio value. The buck-boost is a switching regulator that works using a high-frequency switch (above 20 kHz). The output of the Buck-Boost converter is phase-shifted by 180o from the input voltage. Fig. 3 illustrates the circuit diagram of the Buck-Boost converter that consists of an inductor (L), a switch (S), a diode (D), and a capacitor (C). The inductor (L) is used to store energy when the switch is closed and then transfer it to the load when the switch is opened. The shunt capacitor element (C) is used on the load terminal to reduce the output voltage ripples [16].

When the switch (S) is active on the input voltage source (V_s) is directly connected to the inductor. This causes accumulating energy in the inductor, the capacitor supplies energy to the output load. When the switch is off, the inductor is connected to the output load and capacitor, so energy is transferred from L to C and R (load). There are three mode operations that depend on the duty cycle (D_C). If D_C is bigger than 0.5 then the converter acts like a Boost converter and the V_o will be bigger than Vs. If the D_C is lesser than 0.5 then the converter acts like a Buck converter and V_o will be lesser than the V_s. If D_C equals 0.5 in this situation the V_o is equal to the V_s with a negative sign. We can get the required D_C through this equation [16]:

$$D_C = \frac{|V_o|}{V_s+|V_o|} \tag{1}$$

To determine the minimum value of the inductor [16]:

$$L_{min} = \frac{(1-D_C)^2\, R}{2\, f} \tag{2}$$

where, f is the switching frequency and R is the load (as an example). The capacitance of the shunt capacitor [16]:

$$C = \frac{V_o\, D_C}{\Delta V_o\, R\, f} \tag{3}$$

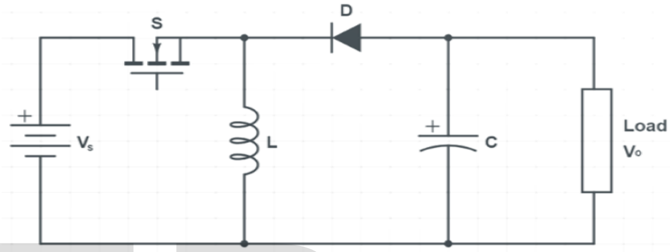

Fig. 3. Circuit diagram of Buck-Boost converter.

3.2 Design of Cuk Converter

The Cuk converter is a type of DC-to-DC converter, which consists of input inductor L_1, output inductor L_2, energy transfer capacitor C_1, filter capacitor C_2, load, diode, and a switch S, as illustrated in Fig 4. The L_1 acts as a filter for the dc power supply to prevent large harmonic content. Unlike some converters which use topologies where energy transfer is associated with the inductor, energy transfer for the Cuk converter depends on the capacitor C_1. The C_2 reduces the ripple of the output voltage [17].

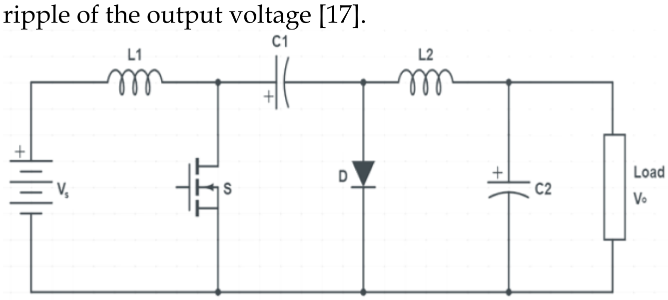

Fig. 4. Circuit diagram of Cuk converter.

When the switch is on the diode will be opened. While the C_1 is discharged by L_2 current, current from L_2 is fed to C_2 and the load. The D will be connected and the C_1 is charged via the input voltage (via the current of L_1) when the switch is off, the current through L_2 equals C_2/R. It is recommended using the principle that the average current through a capacitor is zero for steady-state operation. Let us assume that inductors L_1 and L_2 are large enough that their ripple current can be neglected, we can get the values of L_1, L_2, C_1, and C_2 through these equations [11].

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$$L_1 = \frac{V_S\,D}{(\Delta I, L1\,)\,f_S} \qquad L_2 = \frac{V_S\,(1-D)}{(\Delta I, L2\,)\,f_S} \tag{4}$$

$$C_1 = \frac{D}{(R.f_S)\,(\frac{\Delta V\,C_1}{V_O})} \qquad C_2 = \frac{(1-D)}{(8L_1.f_S^2)\,(\frac{\Delta V\,C_2}{V_O})} \tag{5}$$

3.3 Design of PID Controller

The PID controller is considered a linear control system. It consists of proportional (*P*), integral (*I*), and derivative (*D*) values that determine the reaction to the current error, the reaction based on the sum of recent errors, and the reaction to the rate at which the error has been changing, respectively. The weighted sum of these three actions is used to adjust the process via a control element. The main purpose of using the PID controller is to obtain a constant output voltage for input disturbance and this can be achieved by directly tuning the PID gains to achieve the desired output requirements, as shown in Table 1. The rise time (t_r), settling time (t_s), steady-state error, and overshoot increase/decrease while tuning the PID gains [18-19].

TABLE 1
EFFECTS OF PID GAINS

Gain	t_r	Overshoot	t_s	Steady-state error
K_p	Decrease	Increase	Small change	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	Small change	Decrease	Decrease	None

3.4 Design of FLC Controller

FLC is considered as nonlinear control, which is designed and simulated for the proposed power converters FLC has been applied to the regulation of load voltage in different operation conditions. FLC has two inputs (error (e) and change in error (Δe) signals, these signals are inputs to fuzzifier that convert crisp values (real values) to fuzzy sets (each element has a degree of membership to some function) then to the inference engine which determines the degree of matching between the input with rules in rule base then the result fed to defuzzifier to convert fuzzy set to a crisp value as shown in Fig 5. Rules in Rule Base are shown in Table 2, where NB: Negative Big, NS: Negative Small, ZE: Zero Error, PS: Positive Small, and PB: Positive Big [20]. Membership functions are triangular functions distributed equally between -1 and 1 for inputs and output. It is widely used in machine control applications.

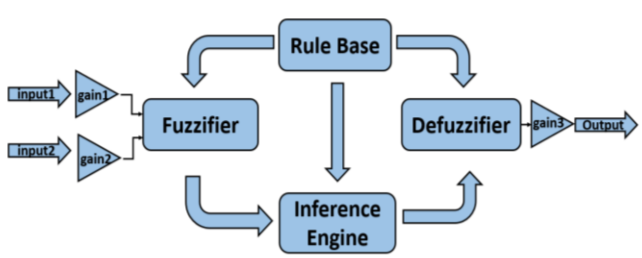


Fig. 5. Fuzzy Logic Architecture.

TABLE 2
FLC RULES

Δe \ e	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	NS	ZE	PS	PB	PB
PB	ZE	PS	PB	PB	PB

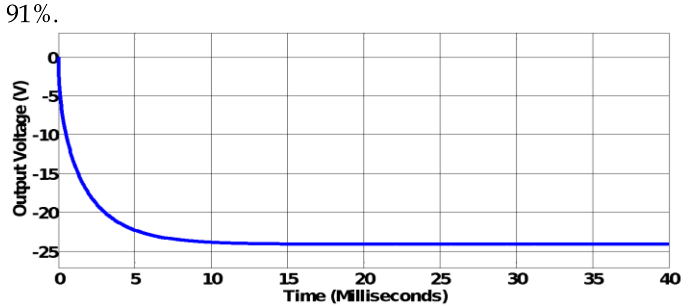
4. SIMULATION RESULTS

This section describes the simulation results of MATLAB/SIMULINK. As seen in Fig. 1, the output voltage (harvested from sun radiation) is input to the power converters. The input voltage source (V_s) is set to 17 V that is the output voltage from a solar panel, and these power converters are designed to provide 24 V (V_o). The reference voltage is set to 24 V for the closed loop control systems, as described in Fig. 2. The following subsections illustrate simulation results of the open loop system (no feedback system) and closed loop control systems using PID and FLC for the Buck-Boost and Cuk converters.

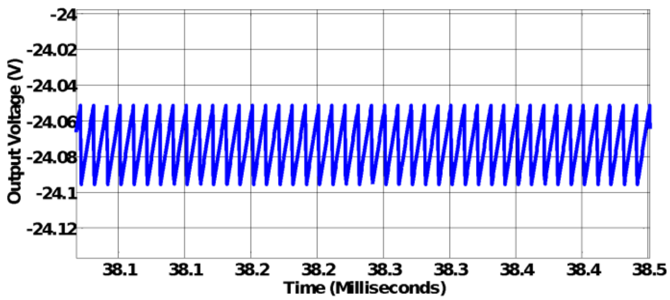
4.1 Open Loop Mode

We used the derived equations in Section 3.1&3.2 to calculate the component values to achieve 24 V output voltage from a solar panel 17 V (VS). The component values of the Buck-Boost are *L* (0.75 µH), *C* (250 µF), and switching frequency (f_s) 100 kHz. The component values for the Cuk converter are L_1 (430 µH), L_2 (650 µH), C_1 (18 µF), C_2 (3 µF) at switch frequency (f_s) 50 kHz.

The output voltage of the Buck-Boost converter is reversed in polarity according to its operation [2], while the input voltage is positive, as shown in Fig 6 (a). As illustrated in Fig 6 (b), the peak-to-peak output ripple voltage is about 50 mV and the t_s is 10 milliseconds, the input current has a peak of 28 A. output current was 1.2 A with ripple 2 mA. By measuring input and output power, the input power is 32.1 W and the output power is 29.3 W resulting in efficiency of 91%.



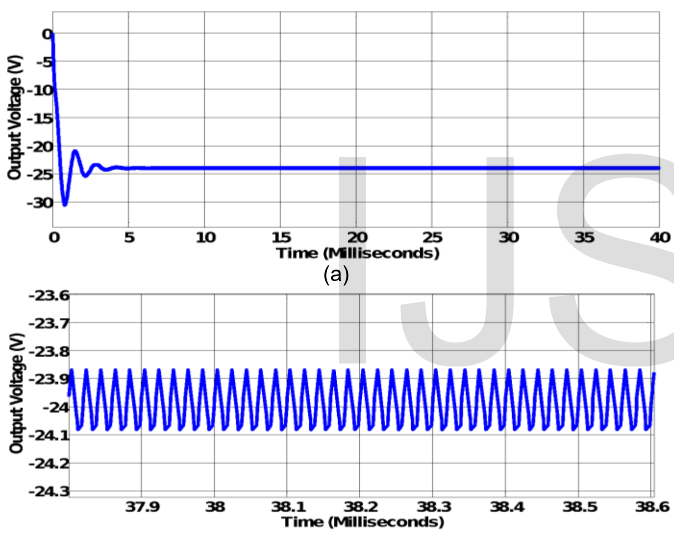
(a)



(b)

Fig 6. Output response of Buck-Boost converter as open-loop (a) output voltage (b) peak to peak ripples.

The output voltage for the Cuk converter is also in reverse polarity according to its operation [2]. The output voltage of the Cuk converter is shown in Fig. 7, where there is overvoltage to 30 V. The ripple of 200 mV and the t_s is 4 milliseconds. The input current is 3.7 A with a ripple of 450 mA. The input and output powers were 62.5 and 57.5 W, respectively which results to efficiency of 92%.



(b)

Fig 7. Output response of Cuk converter as open-loop (a) output voltage (b) peak to peak ripples.

4.2 Closed Loop PID Control System

The gains of the PID controller are tuned for the power converters to achieve the desired output. Table 3 lists the tuned gains for the current conditions (resistive load and input voltage (17 V)). With respect to the model of the Buck-Boost and Cuk converters, the PI controller is preferred to use, as it achieves better and faster performance than adding the derivative gain.

TABLE 3

PARAMETERS OF THE BUCK-BOOST & CUK PID CONTROLLER

Parameter	Buck-Boost	Cuk
Kp	5	0.9
Ki	2.5	94

The PV system of Buck-Boost converter is simulated when the input voltage (V_S) from a solar panel is constant at 17 V and variant, as the sun radiation is varying over time. The output voltage for constant V_S stabilizes after 0.1 milliseconds, as illustrated in Fig. 8. For the variant output voltage from a solar panel (V_S), the input voltage is set to 10, 20 and 30 V at 0.2, 0.4 and 0.6 seconds, respectively to test under different sun radiation levels. The output voltage is stable at 24 V (as the desired value) without any overvoltage, where the voltage ripple 0.1 V and the t_s is 0.32 milliseconds while the VS is changing, as shown in Fig 9.

For the Cuk converter design, the V_O reaches 24 V over 75 milliseconds when the input is 17 V, as shown in Fig. 10. The output voltage (23.97 V) settles after 0.09 seconds while the V_S is changing, with ripples 20 mV. Maximum overshoot occurs at 0.21 seconds when the Vs changed to 20 V from 10 V, as illustrated in Fig 11.

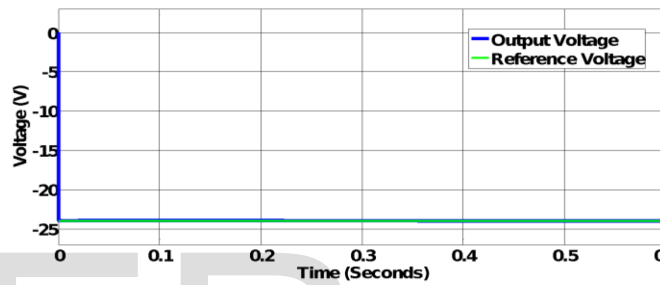


Fig 8. Output voltage of Buck-Boost converter using PID with 17 V input voltage.

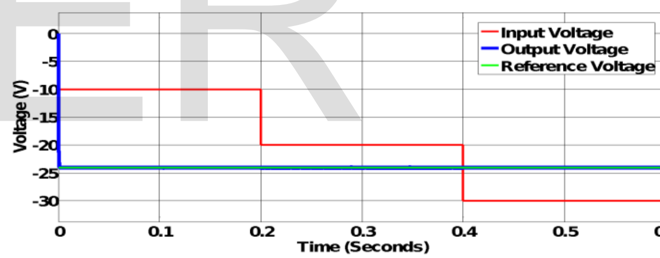


Fig 9. Output voltage of Buck-Boost converter using PID with variant source.

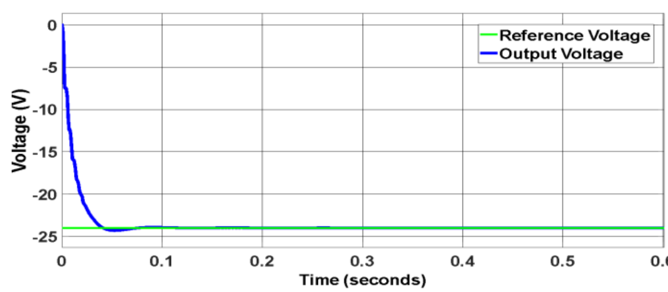


Fig 10. Output voltage of Cuk converter using PID with 17 V input voltage.

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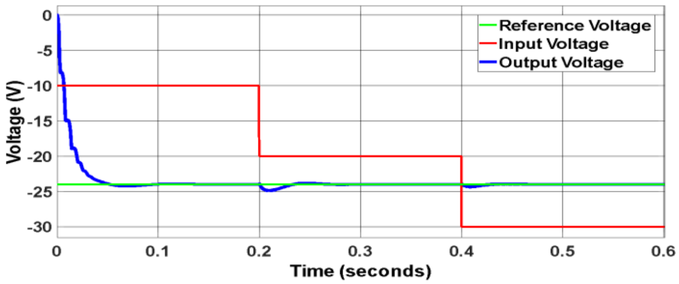

Fig 11. Output voltage of Cuk converter using PID with variant V_S.

4.3 Closed Loop FLC System

FLC surface rule base for the power converters is shown in Fig 12, which is a relationship between inputs and output. Both surface rule bases have high nonlinearity behavior, where the output of the fuzzy rule varies with respect to the input values, which has different profiles for the Buck-Boost and Cuk converters. The gains of input and output signals error signal gain are tuned to achieve the required output voltage (24 V) at different conditions of simulations, as shown in Fig. 5. The output of FLC is compared with the sawtooth signal 1 $V_{peak\text{-}to\text{-}peak}$ at 100 and 50 kHz for Buck-Boost and Cuk Converters, respectively, to generate a square wave to drive the switch. The proposed power converters using FLC are simulated under the same conditions of simulating the PV system using PID to compare the system performance.

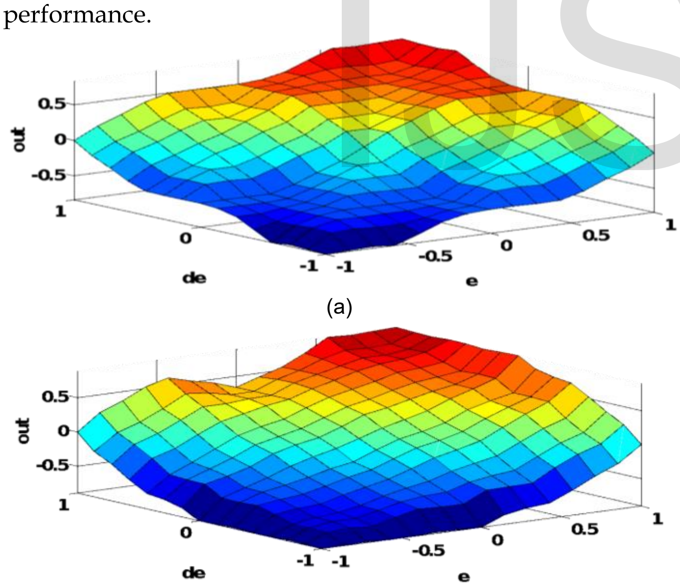

Fig 12. Surface rule base for; (a) Buck-Boost and (b) Cuk converters.

The error, change of error, and output gains for the Buck-Boost converter are set to 20, 5, and 75, respectively, as illustrated in Fig. 5. Fig 13 shows the output voltage when the input voltage (output from a solar panel) is constant at 17 V. Under the same conditions for PID with Buck-Boost input is variant and reference voltage 24 V, the output voltage is almost constant at 24 V (without any overshoot) while the input voltage changes at different times, as shown in Fig 14. The ripple voltage is 300 mV and maximum settling time happened is 0.3 milliseconds.

For the Cuk converter, the gains of the error, change of error, and output signals are configured as 0.25, 0.2, and 0.1, respectively. The output voltage is 24 V with overshoot about 10 V and settling time 4 milliseconds as shown in Fig. 15 when the Vs is 17 V. Fig. 16 shows the output voltage at different input voltage levels, where maximum overshoot occurred by extra 3 V at 0.02 seconds and the maximum t_s is 20 milliseconds when input changes from 20 V to 30 V. It is noticed that with every change in input voltage the output voltage needs about 15 milliseconds to settle to the desired output voltage (24 V).

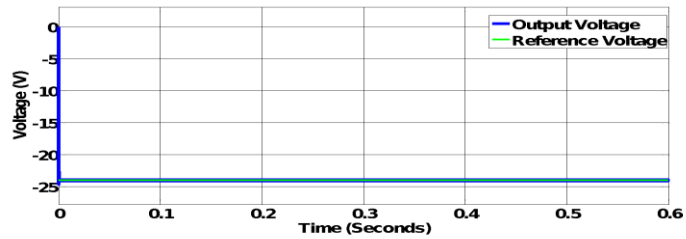

Fig 13. Buck-Boost closed-loop using FLC with 17 V input voltage.

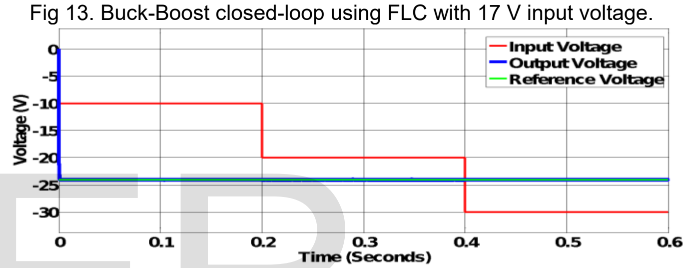

Fig 14. Buck-Boost closed-loop using FLC with variant input voltage.

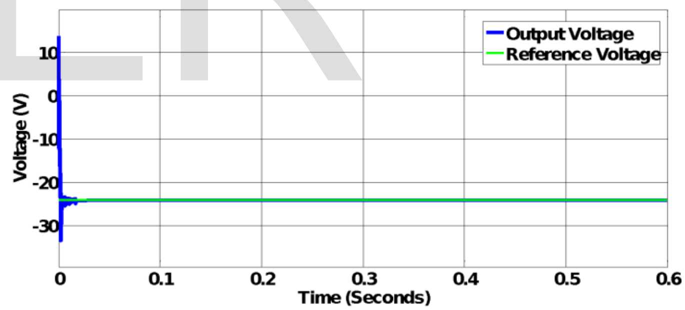

Fig 15. Cuk closed-loop using FLC with 17 V input voltage.

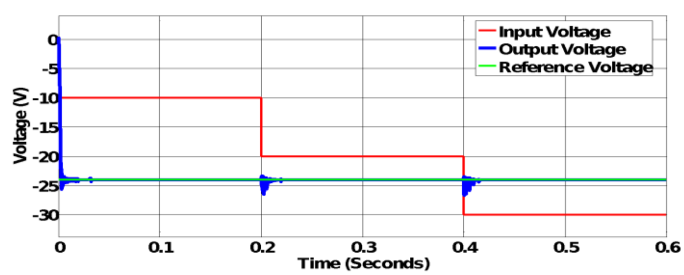

Fig 16. Cuk closed-loop using FLC control with variant input voltage.

5. Discussion

There are common advantages and disadvantages of Buck-Boost and Cuk converters, as described as follows. The advantages of the Buck-Boost converter are: 1- short circuit protection can be easily implemented, 2- both buck and boost operations are achieved simultaneously, it performs step-up or step-down of voltage using minimum components, 3- it offers high efficiency across wide input and output voltage ranges, and 4- it offers a lower operating duty cycle. While the disadvantages of the Buck-Boost converter are: 1- it is difficult to control, 2- its transfer function contains a right half plane zero which introduces the control complexity, 3- input current and charging current of the output capacitor are discontinuous resulting in larger filter size and more electromagnetic interference (EMI) issues, 4- high gain cannot be achieved because efficiency is poor for high gain (i.e. very small duty cycle or large duty cycle), and 5- there is no isolation from the input side to the output side which is very critical for many applications (transformer-less) [2-10, 21].

The pros of the Cuk converter are: 1- the inductor on the input acts as a filter for the dc supply to prevent large harmonic content, 2- unlike some converters which use topologies where energy transfer is associated with the inductor, 3- it eliminates the burden of needing two inductors by winding them both on the same core, with an exact 1:1 turns ratio, and 4- with slight adjustments to L1 or L2, either input ripple current or output ripple current can be forced to zero. While the cons of the Cuk converter are: 1- the requirement of the C_1 with large ripple current capability, 2- it is difficulty of stability achieved, 3- complex compensation circuitry tends to make the converter operate properly [11-15, 22].

Table 4 summarizes comparison open loop and closed loop controller systems in a function of time response for the proposed converters. The main parameters are used for comparison are overshoot (OS) in % of 24 V, ripple voltage in mV, delay time (t_d), peak time (t_p), settling time (t_s), and rise time (t_r) that are reported in milliseconds. These Buck-Boost and Cuk converters are modeled and simulated using resistive or complex loads, although the linear control system (PID) showed different output response profile when the load value changes. This is due to high nonlinearity behavior of these power converters. The performance response of the PV systems using FLC are faster and more robust than PID system when the sun radiation levels and load are varying over time, as illustrated in the simulation results and Table 4.

The output voltage (V_O) profiles of Buck-Boost and Cuk converters are reversal polarity than the input voltage (V_S). Buck-Boost converters are less costly compared to most of the other converters if compromised performance is desired for a low cost [21]. The complex compensation for the Cuk converters needs to slow down the response of the converter, which prevents the PWM dimming capability of the converter [22], as shown in simulation results of Figs. 7, 10-11, and 15-16, and Table 4. According to the high gain and low EMI of Cuk converter, Cuk converter is considered a good solution than Buck-Boost for specific applications that require low EMI, while Buck-Boost converter is a suitable candidate for applications need fast response.

TABLE 4
COMPARISON BETWEEN MODES

Mode	OS	Ripples	t_d	t_p	t_s	t_r
Open-loop Buck-Boost	0	50	2	N/A	15	10
PID Buck-Boost	0	100	0.055	N/A	0.75	0.6
FLC Buck-Boost	0	300	0.06	N/A	0.8	0.55
Open-loop Cuk	1.2	200	0.25	0.8	4	0.5
PID Cuk	1.1	20	7.5	65	90	24
FLC Cuk	1	100	1.7	3.25	15.5	2.65

6. CONCLUSION

This paper has presented and discussed design control systems for Buck-Boost and Cuk converters for solar power applications. The proposed converters are designed to output (V_O) 24 V that can be used to power electronic systems, charge batteries, and feed loads/grid via inverters, as shown in Fig. 1. We focused on designing and analyzing Buck-Boost and Cuk converters for a solar panel (its output voltage is around 17 V). MATLAB/SIMULINK was used to model and simulate the design of Buck-Boost and Cuk converters, where open-loop and closed-loop (PID/FLC) control systems are simulated according to operation and mathematical equations of each converter for various conditions. The responses of the Buck-Boost and Cuk using PID and FLC are compared for voltage regulations under different conditions, such as different sun radiation levels (results to different V_S) and load values. Simulation results illustrate that the PV systems based on FLC yield better transient and dynamic response than the PID control system, as shown in Figs. 8-12 and 13-16. Table 4 list the comparison response of the Buck-Boost and Cuk converters concerning the operation modes and output performance. The simulation results showed that the maximum efficiency was 91% for the Buck-Boost converter and 92% for the Cuk converter. With respect to the results and the conducted analysis, the output of Buck-Boost and Cuk converters are 1800 shifted (reversal polarity) from the input. Both converters achieved high efficiency around 91%, the PV system performance of the Buck-Boost converter is faster than Cuk converter systems, and the PV system based on Cuk converter is suitable for low EMI applications.

Conflict of Interest Statement

The technology, products, views, and opinions expressed by the author are solely theirs, and are in no manner associated with, endorsed by, or attributable to Genesis Robotics and Motion Technologies, LP, or its affiliates.

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