Voltage Control of Cuk Converter with PI and Fuzzy Logic Controller in Continuous Current Mode

M. YILMAZ, M. F. ÇORAPSIZ and M. R. ÇORAPSIZ

Abstract— In today's energy systems, many equipment operates with Direct Current (DC) voltage. However, it is not always possible to obtain the voltage level required for the operation of these equipment from standard power supplies. For this reason, DC-DC converters are used to achieve the desired voltage values for equipment with different DC voltage levels. These converters are divided into three general categories, named Buck, Boost and Buck-Boost. The most preferred converter is the Cuk converter with low output ripple voltage, which can operate in both buck and boost modes. In this study, a detailed analysis of the Cuk converter, which is frequently used in Photovoltaic (PV) Panels was performed and different control methods of the output voltage were proposed. While performing this analysis, the dynamic model of the Cuk converter was created in which, Proportional-Integral (PI) and Fuzzy Logic (FL) are used to control the output voltage of the Cuk converter. The performances of both controllers were compared with respect to performance parameters such as steady state error, settling time and rise time. When the results obtained were evaluated as a whole, it was observed that FLC achieved the desired reference with less rise and settling time. In this study, modeling and controller applications of Cuk converter are realized by using MATLAB / SIMULINK program.

Index Terms— **DC-DC Converter, Cuk Converter, Fuzzy Logic Controller, PI Controller, Voltage Control**

I. INTRODUCTION

DC-DC converters are circuit topologies that convert the direct current voltage into a DC voltage at the desired

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voltage level [1]. The inputs of these converters are generally non-adjustable DC voltages, obtained by rectifying the line voltage. DC-DC converters are used to convert this non-adjustable voltage to the desired voltage level using appropriate switching techniques [2]. The DC converter is similar to the DC equivalent of a transformer with adjustable AC conversion ratio can be changed. It is used to achieve the desired voltage levels by decreasing or increasing the DC source voltage at the input of the DC transformers as well as by adjusting the voltage to the desired values when the transformers AC are applied [3]. The most important characteristics of these converters are their high efficiency and fast dynamic response. They are usually controlled by the DC-Pulse Width Modulation (DC-PWM) method [1].

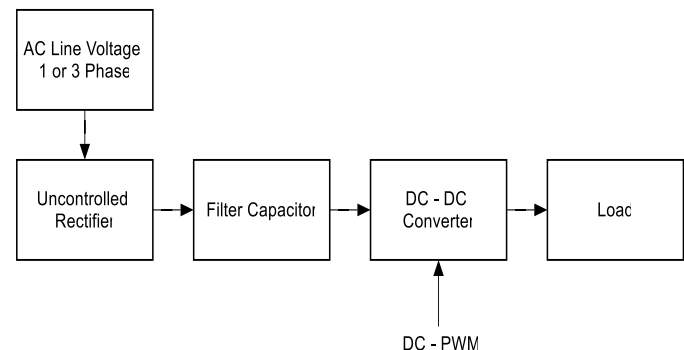The block diagram of the DC-DC converters is shown in Figure 1.

Fig. 1 DC-DC converter block diagram

Generally, DC-DC converters are used in DC motor drive applications, switched power supplies, marine cranes, electric cars, power factor correction applications and PWM based photovoltaic systems [1-3]. DC-DC converters are classified according to circuit topologies as buck converter, boost converter, buck-boost converter, SEPIC converter and Cuk converter etc. [3]. Buck and boost converter are the basic ones among those converters. The Cuk and buck-boost converter is obtained by the cascade connection of the buck and boost converter.

There are many studies on the Cuk converter in the literature. For example, Gupta and Lakshmi [4] designed a PI-controlled converter for photovoltaic panels. State-space modeling technique was used for continuous case modeling and Ziegler-Nichols method was used to determine PI parameters. The authors showed that, the output voltage reaches the desired

reference voltage after approximately 0.2 sec. Simulation studies were performed in MATLAB / SIMULINK program. Rakshit and Maity [5] designed a Cuk converter with closed loop fuzzy logic control. They applied PI and PID controller approaches to the same Cuk converter circuit structure and compared the obtained results. Settling time was 0.6 sec. for PID controller, 0.4 sec. for PI controller and 0.05 sec. for FLC. When the overshoot was compared, it was observed that the FLC controller performed better than the PI and PID controller. Boaretto et al. [6] modeled the Cuk converter for both continuous and discontinuous operating states with PWM switching methods and then compared both models. They suggested that the PWM switching method is suitable for continuous operation. Mohamed Assaf et al. [7] performed simulation studies of DC-DC converters. A dynamic analysis of the DC-DC converters was performed. Using the state equations obtained, the authors applied cascade controllers to the aforementioned converters. They observed that the settling time of the Cuk converter was 0.357 sec. and the output voltage percent was 1.96%. They used MATLAB / SIMULINK program in simulation studies. Fernão Pires et al. [8] designed a new non-isolated DC-DC converter topology for PV. This new topology was created by combining conventional DC-DC Cuk and boost converter circuits in which a single switch is used. The DC-DC converter they designed has higher static voltage gain than the conventional boost converter. This converter was designed using a fixed frequency PWM technique that can be associated with the MPPT algorithm. Besides Mohamed M. Algazar et al. [9] performed FLC for MPPT for PV, a new control method for Cuk converter was proposed. They studied this method under variable temperature and isolation conditions. As a result of the study, they suggested that the system with MPPT using FLC increases the efficiency of energy production from PV panels. Dileep and Singh [10] studied the selection of non-isolated DC-DC converters for PV systems. Consequently, comparative information about the characteristics of different isolated non-isolated DC-DC converters was presented. In addition, the authors investigated various research studies on MPPT PV-based DC-DC converters. They observed that the selection of the DC-DC converter had a significant effect on the overall performance of PV systems. Modeling and stability analysis of the closed loop current mode controlled Cuk converter was conducted by Kamran Mehran et al. [11]. Modeling and stability analysis were performed using Takagi-Sugeno (TS) fuzzy algorithm. Julio Cezar dos Santos de Morais et al. [12] conducted a Cuk converter PV AC module with switched inductor structure. In order to develop a PV AC module, a high static gain Cuk converter structure was proposed with switched inductors. There are also several topologies in the literature based on the traditional CUK converter [13-15].

II. CUK CONVERTER AND DYNAMIC ANALYSIS

Cuk converters are electronic circuits that transfer the DC input voltage to the output at desired voltage levels. It was discovered by Slobodan M. Cuk [16]. Cuk converters were obtained by sequentially connecting the boost and buck converters. The most distinctive aspect of Cuk converters is

the use of capacitors for energy transfer [17]. The basic circuit diagram of the Cuk converter is shown in Figure 2.
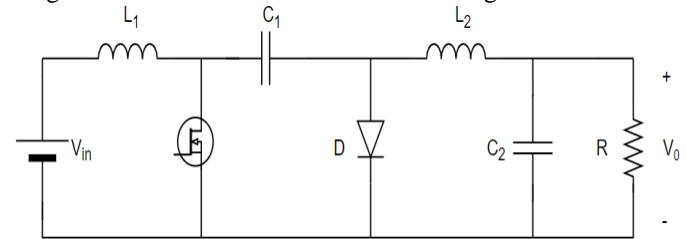

Fig. 2 Cuk converter basic circuit

The current and voltage waveforms for continuous current in a permanent state are shown respectively in Figure 3 and Figure 4 [3].
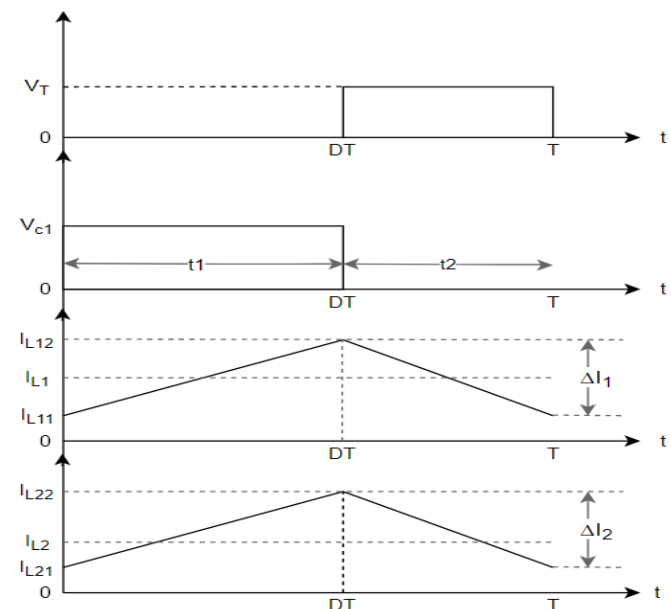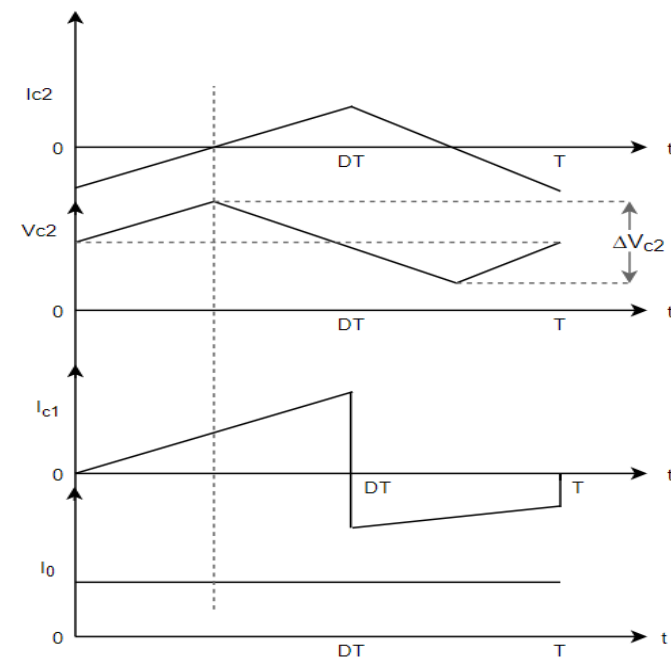

Fig. 3 Cuk converter waveforms

Fig. 4 Cuk converter waveforms

Before beginning, we give the nomenclature used in the study here:

V_0 Output Voltage, V

V_{in} Input Voltage, V

V_{c1} Average Capacitor Voltage, V

t_1 Time of switching element is closed, s

t_2 Time of switching element is open, s

T Switching Period, s

D Duty Cycle

ΔI Ripple Current, A

Assuming that the inductor current of inductance L_1 increases linearly from I_{L11} to I_{L12} during t_1,

$$V_{in} = L_1 \frac{I_{L12} - I_{L11}}{t_1} = L_1 \frac{\Delta I_1}{t_1} \tag{1}$$

Time expression from Equation (1),

$$t_1 = L_1 \frac{\Delta I_1}{V_{in}} \tag{2}$$

If V_{in} voltage is applied to input, capacitor C_1 starts to charge. If capacitor C_1 decreases the inductor current of inductance L_1 linearly from I_{L12} to I_{L11} during t_2,

$$V_{in} - V_{c1} = -L_1 \frac{I_{L12} - I_{L11}}{t_2} = -L_1 \frac{\Delta I_1}{t_2} \tag{3}$$

Time expression from Equation (3),

$$t_2 = -L_1 \frac{\Delta I_1}{V_{in} - V_{c1}} \tag{4}$$

Equation (2) and (4) in the ΔI_1 are equalized and if $t_1 = DT$, $t_2 = (1-D)$ T is the average capacitor voltage,

$$V_{c1} = \frac{V_{in}}{1 - D} \tag{5}$$

Assuming that the inductor current of inductance L_2 increases linearly from I_{L21} to I_{L22} during t_1,

$$V_{c1} + V_0 = L_2 \frac{I_{L22} - I_{L21}}{t_1} = L_2 \frac{\Delta I_2}{t_1} \tag{6}$$

Time expression from Equation (6),

$$t_1 = L_2 \frac{\Delta I_2}{V_{c1} + V_0} \tag{7}$$

If the inductor current of inductance L_2 decreases linearly from I_{L22} to I_{L21} during t_2,

$$V_0 = -L_2 \frac{\Delta I_2}{t_2} \tag{8}$$

Time expression from Equation (8),

$$t_2 = -L_2 \frac{\Delta I_2}{V_0} \tag{9}$$

Equation (7) and (9) in the ΔI_2 are equalized and if $t_1 = DT$, $t_2 = (1-D)$ T is the average capacitor voltage,

$$V_{c1} = -\frac{V_0}{D} \tag{10}$$

Since the equation (5) and (10) are equivalent to each other, the average output voltage,

$$V_0 = -D \frac{V_{in}}{1 - D} \tag{11}$$

As with other converters, the dynamic analysis of the Cuk converters is examined for two separate cases, namely the switching element is open and when it is closed. The equivalent circuit is shown in Figure 5 when the switching element is closed, and the equivalent circuit is shown in Figure 6 when the switching element is open.
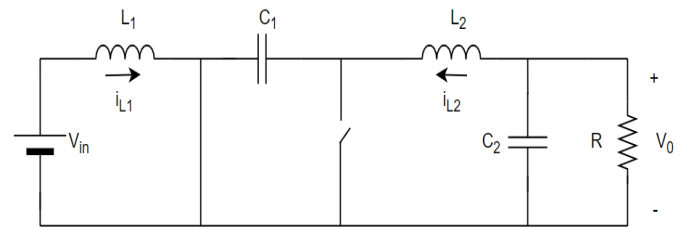
Fig. 5 Switching element is closed

When the switching element is closed, the circuit is examined in two parts. In the first case, the current from the source provides energy to the inductance. In the second case, the capacitor C_1 leads the diode to open and is discharged via capacitor C_2, resistor R and inductance L_2. The circuit model for the closed state of the switching element is obtained as shown in equations (12), (13), (14) and (15).

$$\frac{di_{L1}}{dt} = \frac{1}{L_1} V_{in} \tag{12}$$

$$\frac{dV_{C1}}{dt} = \frac{1}{C_1}(-i_{L2}) \tag{13}$$

$$\frac{di_{L2}}{dt} = \frac{1}{L_2}(-V_0 + V_{C1}) \tag{14}$$

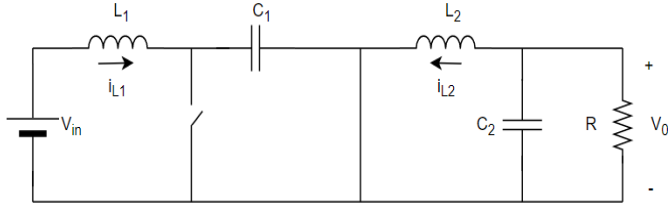$$\frac{dV_0}{dt} = \frac{1}{C_2}(i_{L2} - \frac{V_0}{R}) \tag{15}$$

Fig. 6 Switching element is open

The current will flow through the diode when the switching element is open. At this time, the capacitor C_1 is charged via the source and inductance. The capacitor C_1 provides energy to the L_2 inductance, the C_2 capacitor and the R resistance. The circuit model for the open state of the switching element is obtained as shown in equations (16), (17), (18) and (19).

$$\frac{di_{L1}}{dt} = \frac{1}{L_1}(V_{in} - V_{C1}) \tag{16}$$

$$\frac{dV_{C1}}{dt} = \frac{1}{C_1}i_{L1} \tag{17}$$

$$\frac{di_{L2}}{dt} = \frac{1}{L_2}(-V_0) \tag{18}$$

$$\frac{dV_0}{dt} = \frac{1}{C_2}(i_{L2} - \frac{V_0}{R}) \tag{19}$$

III. PI CONTROLLER

PI controller is obtained by integrating proportional (P) and integral controller (I). It is the most commonly used controller type in industrial control systems due to its simplistic structure. [18]. A new control signal is generated by the PI controller based on the error value between the output signal and the reference signal. Then, the generated control signal is sent to the system and the operations are repeated until the steady state error is minimized. The transfer function of the PI controller is given in equation (20). The block diagram of the system controlled with the PI controller is shown in Figure 7.
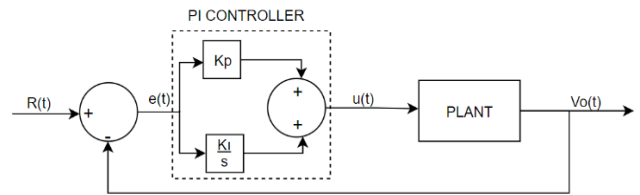

Fig. 7 PI Controller

$$u(t) = K_p e(t) + K_i \int e(t)dt \tag{20}$$

Where in K_i presents the integral gain and K_p is used for the proportional gain.
The controller is tuned optimally by using a trial and error method, and gains are found as $K_p = 0,04$ and $K_i = 4$.

IV. FUZZY LOGIC CONTROLLER

The most prominent feature of fuzzy control, which has become a major competitor to classical controllers in the field of control in recent years, is that it saves the designer from mathematical operations [19]. Fuzzy logic-based controllers can now be found in almost every area, ranged from automobile braking systems, washing machines, freezers to product quality control systems in factories [20]. In the classical types of controls (PI, PD, PID), a number of mathematical expressions need to be analyzed to design the controller. Although this process is simple for linear systems, it requires solution of difficult mathematical operations in nonlinear systems. However, when designing a FLC for any linear or non-linear system, there is no need to analyze the mathematical expressions. When using FLC, the components of the controller are prepared in systemically based on verbal expressions rather than a system of mathematical expressions [21].

A. Components of Fuzzy Logic Controller

The fuzzy logic controller, which was first used by Mamdani in 1974 [22], consists of basically three components: fuzzification, rule base and defuzzification. The FLC basic block diagram is shown in Figure 8.
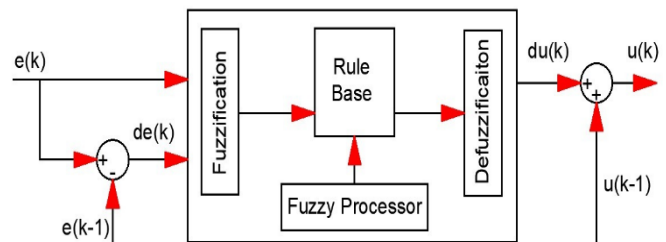

Fig. 8 Basic block of fuzzy logic controller

According to Fig. 8, the error (e) and change of error (de) refers to inputs of the system and, the control signal (u) refers to the output of the system. The relationship between error, change of error and output signal can be expressed as follows;

$$e(k) = V_{ref}(k) - V_{out}(k) \tag{21}$$

$$de(k) = e(k) - e(k-1) \qquad (22)$$

$$u(k) = du(k) + u(k-1) \qquad (23)$$

B. Fuzzification

The FLC has two definite inputs: error (e) and variation (d_e) are in the absolute number space. These precise entries are transferred to the rule base by converting them into fuzzy values with a degree of membership (μ) ranging from "0" to "1" in the blur unit. Triangle, trapezoid, bell, gaussian, cauchy, sinusoidal or sigmoid membership functions are used in the selection of the membership function. In this study, trapezoidal and triangular membership functions are used for five fuzzy levels.

C. Rule Base

In the rule base, the fuzzy rules, that are made by area experts in advance, are executed and fuzzy values are generated consequently.
If e is NS and de is PS then du is ZZ

In this rule base, "e" represents error, "de" represents error change and "d_u" represents degree of exit membership. In addition, the rules are defined as Negative Big (NB), Negative Small (NS), Zero (ZZ), Positive Small (PS) and Positive Big (PB). The operation of fuzzy control rules can be summarized as follows [23].

1. If the output of the system is lower and farther than the given reference point, that is, there is a large error in the positive direction, the controller must increase the output voltage rapidly.
2. If the output of the system is lower but close to the given reference point, that is, there is a small error in the positive direction, the controller should increase the output slowly.
3. If the output of the system is exactly at the given reference point, a meaning that there is no error, the controller should not interfere with the output.
4. If the output of the system is higher but close to the given reference point, that is, if the error is small in the negative direction, the controller should reduce the output slowly.
5. If the output of the system is higher and for away compered to the given reference point, that is, if the error is large in the negative direction, the controller should reduce the output rapidly.

D. Defuzzification

Finally, the fuzzy values are converted to exact values in a rinsing unit, just as in the input, and this exact value is sent to the output named the rinsing output (d_u). The control mark (u) is obtained by adding the previous value of the output to the defuzzification output. Membership functions and rule base used in this study are shown in Figure 9 and Table 1,

respectively. In the defuzzification process, there are different methods such as the center of the areas, the average of the maxima, Sugeno, Tsukamoto. When the central method of the areas is used in the defuzzification process;

$$u = \frac{\sum_{k=NB}^{PB} \mu_k(u_k) u_k}{\sum_{k=NB}^{PB} \mu_k(u_k)} \qquad (24)$$

In Equation (24), k represents the active fuzzy set at the output and u represents the controller output. In addition, $\mu_k(u_k)$ is the degree of membership obtained from the active rule for fuzzy output, and u_k is the absolute output value with the largest membership in the active output fuzzy set in the same rule. In this study, Mamdani fuzzy inference system model type was used. In addition to, a limiter was used to keep the error values in the range of -1 to 1 at the input of the fuzzy logic controller. The control signal (u) obtained from the fuzzy logic controller was compared with a carrier signal similar to the sawtooth and, then the duty ratio of the controlled switch was determined.
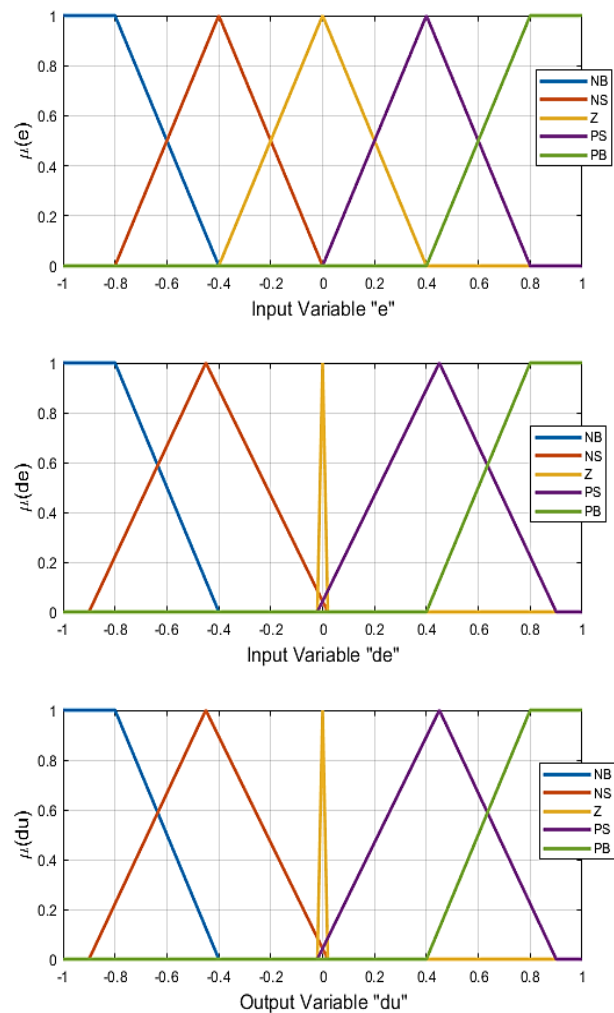

Fig. 9 Membership Functions

TABLE I
RULE BASE

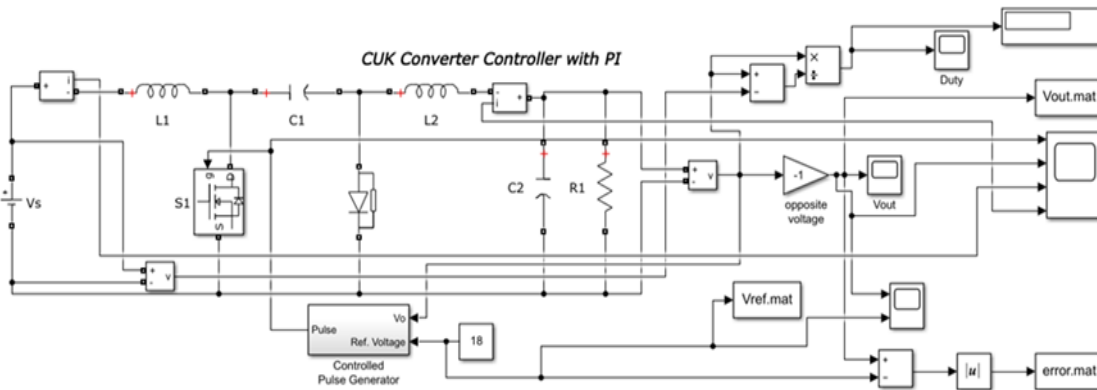|		error				
		NB	NS	ZZ	PS	PB
de	NB	NB	NB	NB	NS	ZZ
	NS	NB	NB	NS	ZZ	PS
	ZZ	NB	NS	ZZ	PS	PB
	PS	NS	ZZ	PS	PB	PB
	PB	ZZ	PS	PB	PB	PB

V. SIMULATION RESULTS

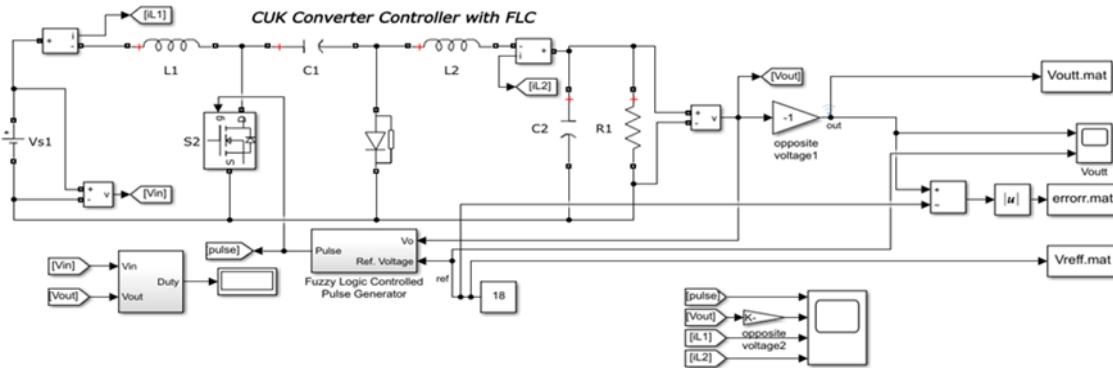Fig. 10 Cuk converter simulation model controlled by PI controller

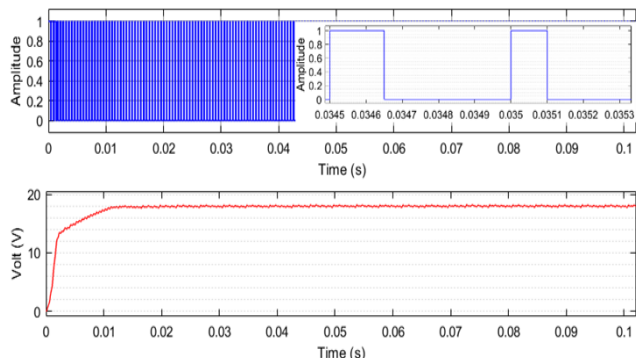Fig. 11 Cuk converter simulation model controlled by FL controller

Fig. 12 Change of output voltage and duty period with PI controller
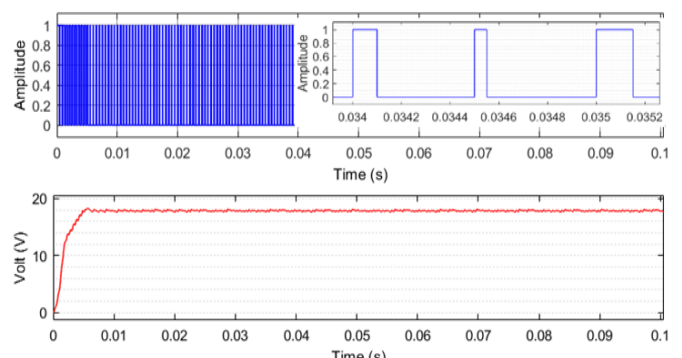

Fig. 13 Change of output voltage and duty period with FL controller

In this study, PI and FL controller is applied to Cuk converter circuit to obtain the desired output voltage. Table 2 shows the values of the parameters used in the Cuk converter simulation model. From the simulation results, the performance parameters such as steady state error, settling time and rise time of the controllers were obtained and a given in Table 3. Figure 10 shows the simulation model using the PI controller, and Figure 11 shows the simulation model using the FLC.

TABLE II
CUK CONVERTER CIRCUIT PARAMETERS

Input Voltage	12V
Output Voltage	-18V
Inductor Values L_1 & L_2	100µH & 100µH
Capacitor Values C_1 & C_2	150 µF & 3300µF
Switching Frequency	2 kHz
Load Resistance	20 Ω

The change of output voltage and duty period with PI controller is applied to Cuk converter and shown in Figure 12 and the change of output voltage and duty period with FL controller is presented in Figure 13. In addition, if the PI controller is applied, the output voltage error graph is shown in Figure 14. Similarly, the error plot of the voltage at the converter output in FL controller is shown in Figure 15.

A visual comparison of the output voltages obtained when both controllers are applied to the Cuk converter circuit is presented in Figure 16.

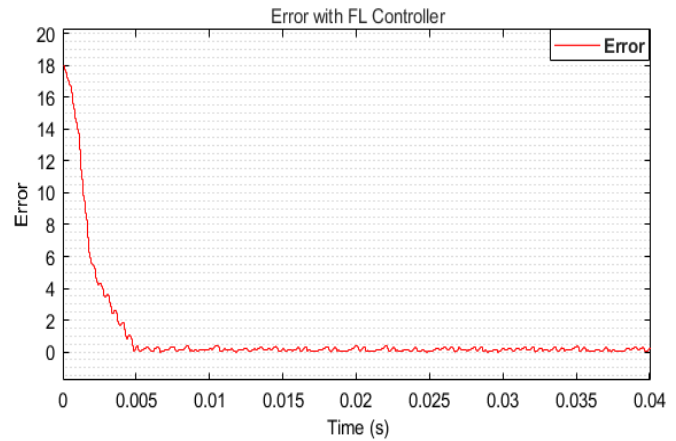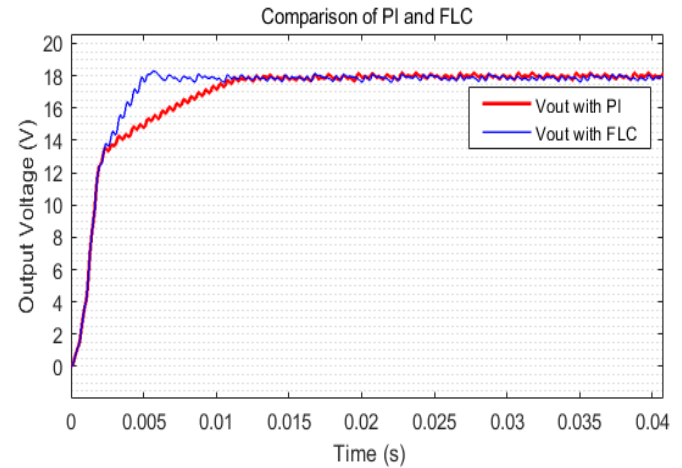Fig. 14 The output voltage error controlled with PI controller

Fig. 15 The output voltage error controlled with FLC

Fig. 16 Comparison of output voltages when both controllers are applied to the Cuk converter circuit
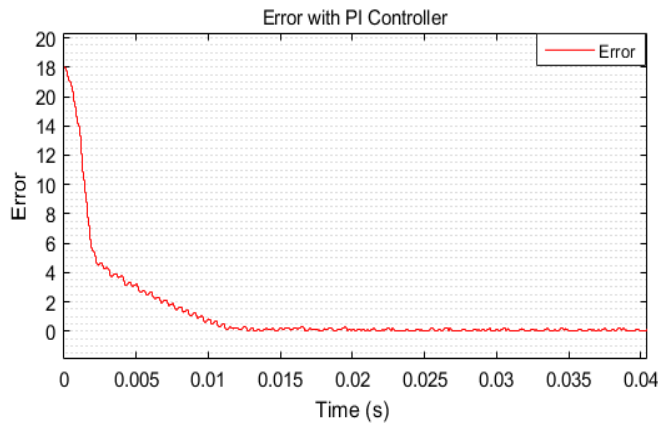
In Figure 12, it was observed that the Cuk converter output voltage reached a reference value of 18V after 10 ms without overshoot. In Figure 13, it is observed that the Cuk converter output voltage reaches a reference value of 18V after 5 ms. In Figure 14, it was observed that the error reached 0 after 10 ms when the PI control method was applied and when the FL control method was applied in Figure 15 the error reached 0 after 5 ms. In Figure 16, it is observed that FL control method gives better results than PI control method.

TABLE III
COMPARISON OF CONTROLLER

CONTROLLER	PI	FLC
Error_RMSE	0.7442	0.7235
Rise Time (ms)	6.55	3.6
Settling Time (ms)	10	5

VI. CONCLUSIONS

In this study, dynamic analysis and modeling of Cuk converter is done by using MATLAB / SIMULINK. PI and FL controller are used to follow the desired reference value. PI controller parameters $K_p = 0,04$ and $K_i = 4$ are found. The output voltage follows the reference after about 10 ms when the PI controller is used, and the reference follows after 5 ms when the FLC is used. While the PI controller is used, the ripple is %2,6 and the FLC is %2,5. As a future research, Cuk converter controlled in real time with PI, PID and FLC with PV panels can be analyzed.

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BIOGRAPHIES

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