

Improvement of PID parameters for Ćuk converter using fuzzy logic in PV system

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Abstract

Worldwide use of DC electrical system is continuously growing, increasing the need for converting DC voltage from one level to another following the requirements. One such DC-DC converter is the Ćuk converter. In its practical operation, the Ćuk converter frequently encounters deviations from its nominal operating conditions. This would consequently result in temporary or permanent change in output voltage from the desired value. To achieve fast transient response or prevent instability upon external disturbances, a good controller will be needed. This paper examines performance comparison between PID and fuzzy-PID methods in controlling the output of a Ćuk converter. The study was conducted through simulation by applying the disturbance in the form of changes in reference voltage, input voltage, and load. Results show that the deviation from the desired output voltage using the fuzzy-PID control is smaller than that of the PID. Results further demonstrate that the fuzzy-PID method offers a faster recovery time than the PID method does. It can be concluded that Ćuk converter with the fuzzy-PID controller performs better than one utilizing the PID controller.

Keywords: *PID control, Ćuk converter, fuzzy logic, nonlinear system*

1. Introduction

Renewable energy resource as photovoltaic (PV) has become an effective solution of sustainable resource and mitigating pollution [1, 2]. The use of PV both in the form of modules and arrays is mostly done in daily life depends on our necessity [3]. The PV system consists of several parts, which are PV, MPPT and controller as shown in Fig. 1 [4]. The need for DC supplies ranges from low voltage used in microprocessors and ICs, medium voltages used in electric motors and generators, and high voltage for power transmission. One critical component in DC electrical system is DC-DC converter. There are many DC-DC converter topologies, but one that is commonly known is the Ćuk converter. The converter can produce an output voltage that is higher or lower than the input voltage. The basic power stage of this converter consists of a switching component such as MOSFET, a diode, two capacitors and two inductors [5].

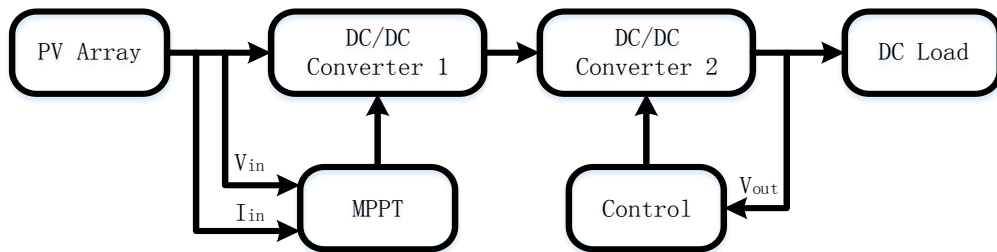


Fig. 1. Block diagram of PV system [4]

Ćuk converter offers very good characteristics, such as capacitive energy transfer, utilization for transformers, and good steady-state performance like wide conversion ratio, smooth input and output currents [6]. Ćuk converters are widely used in industrial applications, such as wind power plants, power systems using photovoltaic (PV), electric-powered vehicles, transmissions and receivers for radars, Light Emitting Diode (LED) drivers, telecommunications systems, and controllers for compressors and motors [7].

If the load changes in a Ćuk converter, a change in the output voltage will occur. In order for the output voltage to match the desired value, a controller is required. There are various types of controllers including P, P-I, P-D and P-I-D controllers. The P controller is used to reduce the steady-state error, but the P controller also produces oscillations and amplifies the noise. The P-I controller is used to eliminate the steady-state error produced by the P controller. The P-I controller has several disadvantages including inability to predict future errors, inability to decrease the rise-time, and inability to eliminate oscillations. The P-D controller is used to increase the stability of a system, but the D controller also directly amplifies the noise. P-I-D controller is the most optimal controller since the response is fast, does not produce oscillations, and has high stability [8].

PID controllers have been widely applied due to its simplicity and effectiveness to compensate for errors resulting from the difference between the set point and the feedback voltage on the power converter. The PID controller has demonstrated its ability to maintain the output voltage so that the value remains constant and matches the desired value even though the input voltage and load change. The PID controller also has the ability and fast response to control the performance of a DC-DC converter [9,10].

Conventional PID controllers are widely used in the industrial world because of their simplicity and ease of design [11]. However, the disadvantage of the PID controller is that it is difficult to get the control performance because of the nonlinearity, delay time, and interference encountered in the nonlinear system parameters. In this study, the fuzzy logic controller is explored to improve the performance a PID control method. Fuzzy logic is a technology widely used to develop the intelligent control and information systems.

Penalty is important for PID controllers. There are several tuning methods in PID controllers such as Ziegler-Nichols and Cohen-Coons tuning, but the tuning methods themselves contain some limitations [12, 13]. In this study, the fuzzy-PID controller is envisaged to perform the tuning of the PID controller and to improve the response of the PID controller. The purpose of the controller is to make the Ćuk converter maintain the generated output voltage constant, regardless of the change in input voltage and load condition.

2. Ćuk Converter

Ćuk converter is a DC-DC converter where the output voltage can be greater or smaller than the input voltage, as shown in Fig.2. The output voltage of this converter has a negative polarity with respect to the input voltage.

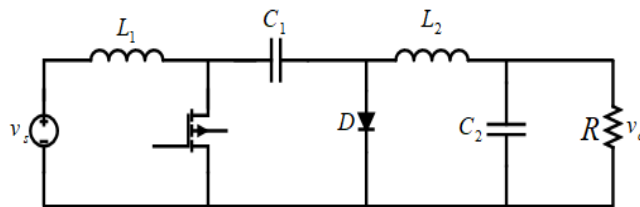


Fig. 2. Ćuk converter equivalent circuit

The operation of a Ćuk converter can be understood using the circuit shown in Fig. 3a) during the ON-state condition, and Fig. 3b) during the OFF-state condition.

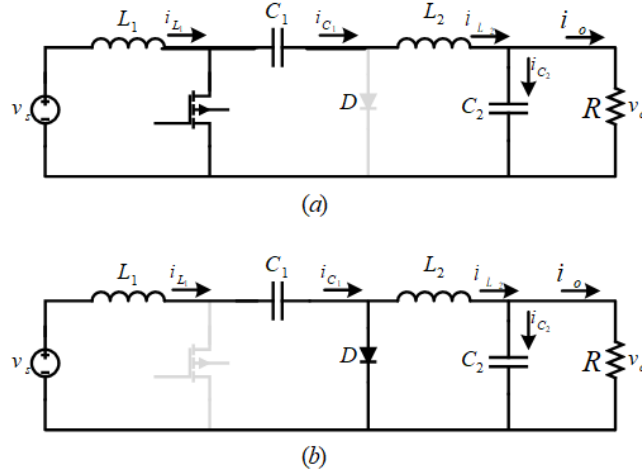


Fig. 3. Ćuk converter operation during (a) ON state (b) OFF state

When the switch is ON, the prevailing circuit equation can be expressed in a form of state-space equation in (1),

$$\dot{x} = A_1 x + B_1 u \quad (1)$$

which can also be stated as in (2).

$$\begin{bmatrix} \dot{i}_{L1} \\ \dot{i}_{L2} \\ \dot{v}_{C1} \\ \dot{v}_{C2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1/L_2 & -1/L_2 \\ 0 & 1/C_1 & 0 & 0 \\ 0 & 1/C_2 & 0 & -1/RC_2 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_s] \quad (2)$$

When the switch is OFF, the prevailing circuit equation can be expressed in a form of state-space equation in (3),

$$\dot{x} = A_2 x + B_2 u \quad (3)$$

which can also be stated as in (4).

$$\begin{bmatrix} \dot{i}_{L1} \\ \dot{i}_{L2} \\ \dot{v}_{C1} \\ \dot{v}_{C2} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & -1/L_1 & -1/L_2 \\ 1/C_1 & 0 & 0 & 0 \\ 0 & 1/C_2 & 0 & -1/RC_2 \end{bmatrix} \begin{bmatrix} i_{L1} \\ i_{L2} \\ v_{C1} \\ v_{C2} \end{bmatrix} + \begin{bmatrix} 1/L_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} [V_s] \quad (4)$$

In order to make the mathematical model of the Ćuk converter, the State-Space Averaging (SSA) technique is adopted as given in (5) and (6)

$$\dot{x} = Ax + Bu \quad (5)$$

$$V_o = Cx + Du \quad (6)$$

where,

$$A = A_{(on)}d + A_{(off)}(1-d) \quad (7)$$

$$B = B_{(on)}d + B_{(off)}(1-d) \quad (8)$$

By substituting the equations when the switch is closed and the switch is open into the SSA method, the following equations are obtained.

$$\dot{i}_{L1} = -\frac{(1-d)x_3}{L_1} - \frac{V_s}{L_1} \quad (9)$$

$$\dot{i}_{L2} = -\frac{dx_3}{L_2} - \frac{x_4}{L_2} \quad (10)$$

$$\dot{V}_{C1} = \frac{(1-d)x_1}{C_1} + \frac{dx_2}{C_1} \quad (11)$$

$$\dot{V}_{C2} = \frac{x_2}{C_2} - \frac{x_4}{C_2} \quad (12)$$

3. Proposed Method

The circuit of Ćuk converter model is shown in Fig. 4. It is built based on the state-space equation in (5)-(10). The next step is to simulate the converter in the open-loop condition.

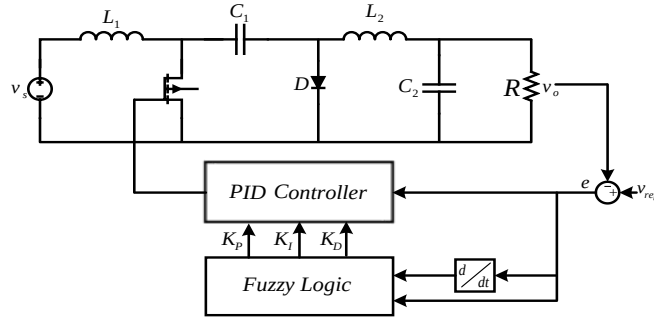


Fig. 4. Proposed method diagram

What needs to be observed in the simulation is the time needed to reach the steady-state condition, the overshoot, the oscillations, and the resulting output voltage. A second-order system approach is adopted in the design of the PID controller.

3.1. PID control method

Determination of the correct PID parameters (K_p , K_i , and K_d) is very important. The more precise the calculation of the PID parameters, the closer will be the obtained results to the desired criteria. The parameters of the PID controller in this system is obtained through mathematical calculations.

The first step to do is determining the value of the settling time (t_s) in the open loop condition. The desired t_s will be determined within the range of $\pm 5\%$. For this controller design, a faster response time is expected to be 0.0074 s, so that the desired settling time value can be obtained as follows

$$t_s (\pm 5\%) = 0.0074s = 3\tau^* \quad (13)$$

resulting in the settling time of $\tau^* = 0.02467s$.

Determining the PID parameters also requires the value of system gain (K), the system damping ratio (ξ) and the natural frequency (ω_n) of the system modeling at a duty cycle of 0.67. The obtained values of those three constants are $K = -72.7273$, $\xi = 0.192894$, and $\omega_n = 1753.479 \text{ rad/s}$.

The next calculation is to determine the constant τ_i using equation (14),

$$\tau_i = \frac{2\xi}{\omega_n} \quad (14)$$

giving the value of

$$\tau_i = \frac{2 \cdot (0.192894)}{1753.479} = 2.2 \times 10^{-4}$$

Calculation of the constant τ_d is done by substituting the values of ω_n and τ_i using equation (15),

$$\tau_d = \frac{1}{(\tau_i)(\omega_n^2)} \quad (15)$$

resulting in

$$\tau_d = \frac{1}{(2.2 \times 10^{-4})(3074689)} = 0.00147826$$

The proportional gain (K_p) is obtained by substituting the values of τ_i and τ^* into equation (16),

$$K_p = \frac{\tau_i}{K \cdot \tau^*} \quad (16)$$

giving

$$K_p = \frac{2.2 \times 10^{-4}}{(-72.7164)(0.002467)} = -0.00123$$

After getting the value of K_p , the value of K_i (integral gain) and K_d (differential gain) can be calculated.

$$K_i = \frac{K_p}{\tau_i} \quad (17)$$

$$K_d = K_p \times \tau_d \quad (18)$$

Giving the value of $K_i = -5.57516$ and $K_d = -1.8 \times 10^{-6}$.

3.2. Fuzzy logic method

After obtaining the values of PID control parameters, the next step is to determine the fuzzy-PID control parameters. The numerical data of input parameters are made into fuzzy data by turning it into a linguistic form during the fuzzification stage. It is to determine the functions for the error and delta error, as shown in Fig. 5. Both parameters are obtained from the Ćuk converter in open-loop condition. Error is the difference between the overshoot voltage value and the desired reference voltage, while delta error is the difference between the error voltage at the first point and the error voltage at the following point. In Fig. 6, the determination of the membership function during the fuzzification process is used to determine the values of K_p , K_i , and K_d .

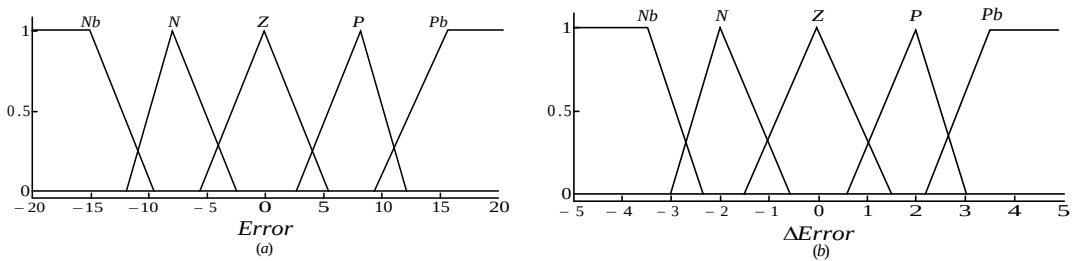


Fig. 5. Membership function for (a) Error and (b) Δ Error.

Using 5 linguistic terms, the rule base to determine each of the gain constants K_p , K_i , and K_d comprises 25 rules as presented in Table 1.

Table 1. Rule base for K_p , K_i , and K_d

$\begin{matrix} e \\ de \end{matrix}$	NB	NS	ZO	PS	PB
NB	NB	NB	PB	NB	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 rule base of K_d is constructed using the relationship between error and delta error and the decision making. Decisions made on this rule base still refer to the value of the K_d parameter obtained in the PID controller design.

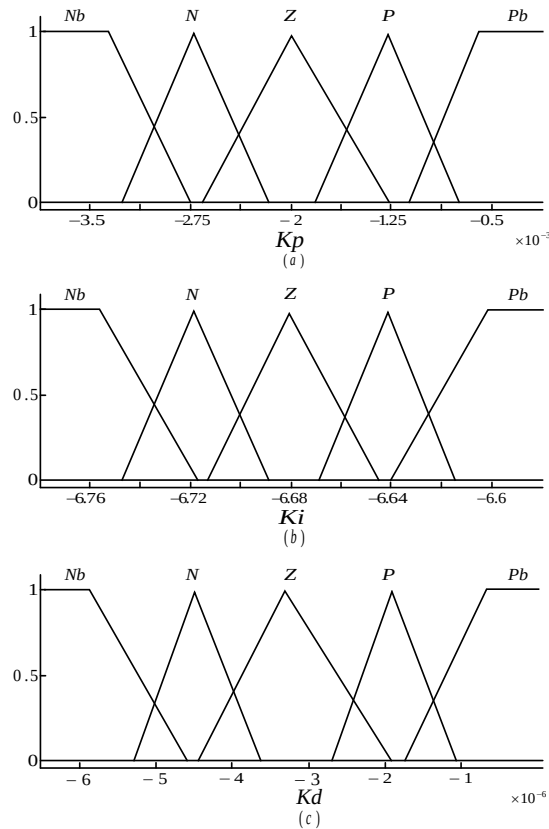


Fig. 6. Membership function for (a) K_p , (b) K_i , and (c) K_d

4. Results and Discussion

The component and parameter specification of Ćuk converter considered in this paper are given in Table 2. Observation to the converter control performance has been carried out using simulation by changing the reference voltage (V_{ref}), input voltage (V_{in}) and load (R).

Table 2. Specifications of Ćuk Converter

Parameter	Symbol	Value
Input Voltage	V_s	18-80 V
Output Voltage	V_o	-48 V
Frequency	f	20000 Hz
Resistor Load	R	100 Ω
Inductor 1	L_1	5 mH
Inductor 2	L_2	5 mH
Capacitor 1	C_1	4.7 μ F
Capacitor 2	C_2	4.7 μ F

By giving a certain disturbance to the system, the comparison of simulation results of both control methods implementation is presented. By providing disturbances in the form of changes in the value of V_{ref} , V_{in} , and R , the controlled converter performances are observed.

4.1. Simulation results with the change in reference voltage

The simulation has been conducted by varying the reference voltage while keeping constant the input voltage (18V) and load (100 Ω). The reference voltage values used are -12 V, -24 V, -36 V, -54 V, and -60 V. From the simulation results, the recovery time value (t_{rec}) and the voltage deviation value (ΔV) can be observed in Fig. 7 and Fig. 8 subsequently for the reference voltage of -54 V and -60 V. The complete results of observation for all reference voltage values considered are given in Table 3.

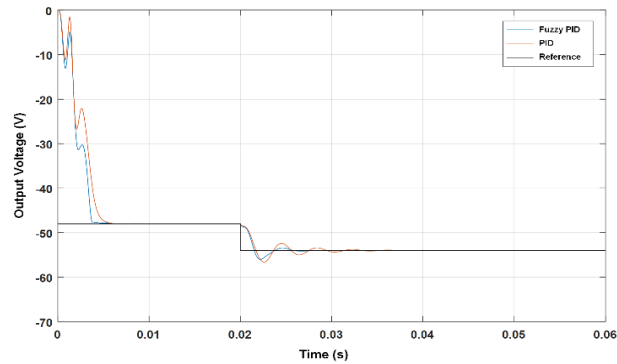


Fig. 7. Output voltage with the change in reference voltage to -54V

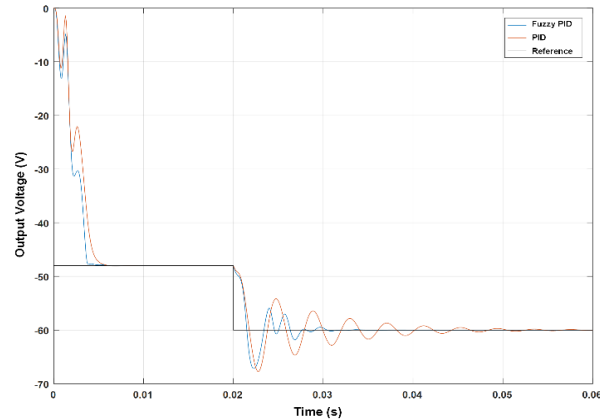


Fig. 8. Output voltage with changes in reference voltage to -60V

Table 3. Comparison of Both Control Methods on the Ćuk Converter

No	V_{ref} (V)	PID		Fuzzy PID	
		t_{rec} (s)	$ \Delta V $ (V)	t_{rec} (s)	$ \Delta V $ (V)
1	-12	0.046	0	0.0414	0
2	-24	0.027	4.06	0.0235	2.54
3	-36	0.0248	1.85	0.0225	1.12
4	-54	0.0265	2.64	0.0222	2.01
5	-60	0.0391	7.57	0.0279	6.96

4.2. Simulation results with the change in input voltage

The simulation has been conducted by varying the input voltage using 6 variations, which are 18 V, 21 V, 60 V, 72 V, and 80 V. The reference voltage set in 48V and 100 Ω in load resistance. The resulting output voltages with respect to input voltage change to 18 V and 21 V are shown in Fig. 9 and 10 respectively. The obtained recovery time value (t_{rec}) and the voltage deviation value (ΔV) for the whole considered values of input voltage are presented in Table 4.

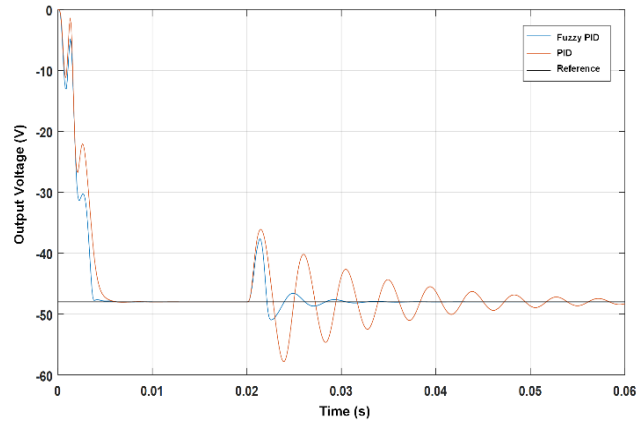


Fig. 9. Output voltage with the change in input voltage to 18V

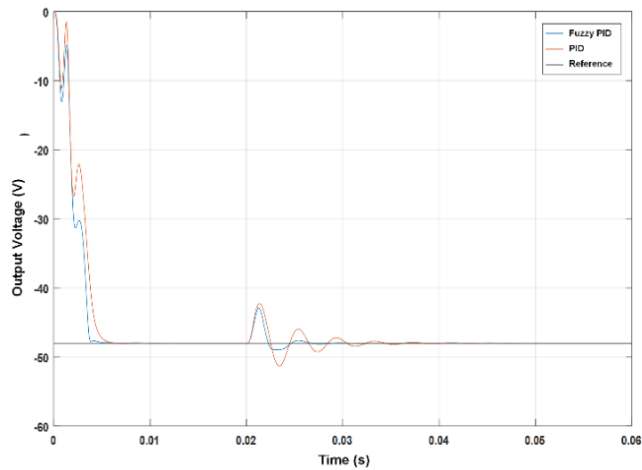


Fig. 10. Output voltage with the change in input voltage to 21 V

Table 4. Comparison of both control methods on the Ćuk converter

No	V_{in} (V)	PID		Fuzzy PID	
		t_{rec} (s)	ΔV (V)	t_{rec} (s)	$ \Delta V $ (V)
1	18	0.0505	11.89	0.0271	10.37
2	21	0.0293	5.75	0.0228	5.13
3	60	0.0255	46.58	0.0248	42.17
4	72	0.0272	55.8	0.0252	41.88
5	80	0.0282	60.7	0.0263	45.27

4.3. Simulation results with the change in load resistor

The considered load resistor values during simulation were 80 Ω , 90 Ω , 200 Ω , 300 Ω , and 400 Ω . The resulting output voltage response with the load resistor values of 200 Ω and 400 Ω are given in Fig. 11 and 12, respectively. The observed values are the recovery time value (t_{rec}) and the voltage deviation value (ΔV) of other load resistor according to the specific input voltage (18V) and reference voltage (48V) are presented in Table 5.

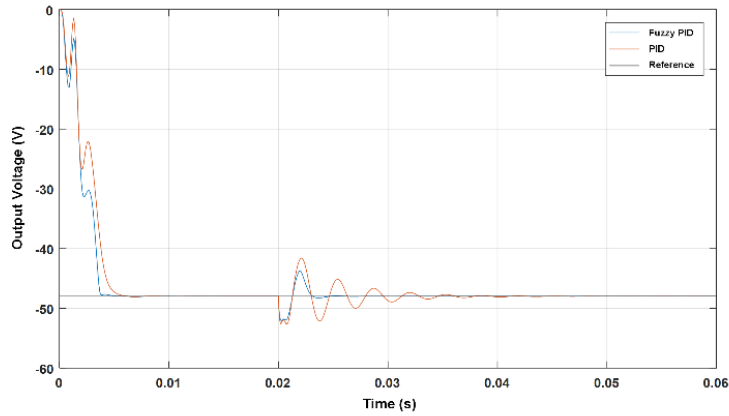
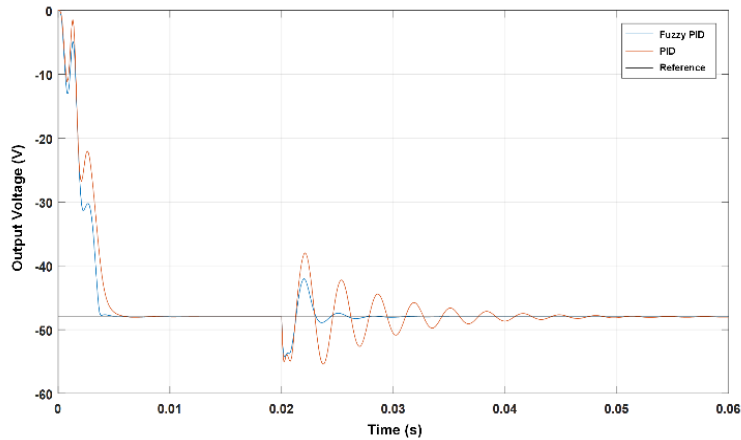
Fig. 11. Output voltage with the change in load resistor to 200 Ω Fig. 12. Output voltage with the change in load resistor to 400 Ω

Table 5. Comparison of both control methods on the Ćuk converter

No	R (Ω)	PID		Fuzzy PID	
		t_{rec} (s)	ΔV (V)	t_{rec} (s)	ΔV (V)
1	80	0.0260	2.79	0.0229	2.41
2	90	0.0239	1.23	0.0230	1.03
3	200	0.0303	6.41	0.0236	4.29
4	300	0.0351	8.76	0.0236	5.42
5	400	0.0399	10.01	0.0236	5.99

5. Conclusion

Based on the comparison analysis of simulation results from both the PID and the fuzzy-PID methods to control the output voltage of Ćuk converter, it can be concluded that in order to obtain the value of PID parameters by the direct synthesis method, the settling time and certain duty-cycle in open-loop condition are required. The determination of the fuzzy-PID controller parameters is based on the PID parameters previously obtained. The fuzzy logic method is used to tune the PID control parameters to improve its output response. Comparison of results obtained from simulation with the variations of reference voltage, input voltage, and load resistor, confirms and brings to a conclusion that the fuzzy-PID method performs better than the original PID method in controlling the output voltage of Ćuk converter, as indicated by a smaller voltage deviation (ΔV) value and a faster recovery time (t_{rec}).

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

The first author conducted the controller design, analyzed the data and wrote the paper; the second author was the supervisor and conducted the research; the third and fourth authors conducted the control system design and perform verification of the model; all authors had approved the final version.

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