European Journal of Technique

journal homepage: https://dergipark.org.tr/en/pub/ejt

Vol.11, No.1, 2021

Designing a Control Interface and PID Controller of CUK Converter

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ARTICLE INFO

Received: Nov., 04. 2020
Revised: May, 20. 2021
Accepted: May, 26. 2021

Keywords:
CUK Converter
PID Controller
Transfer function

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ISSN: *2536-5010* | e-ISSN: *2536-5134*

DOI: https://doi.org/10.17694/ejt.821257

ABSTRACT

The system of CUK converter, which is controlled by PI controller, is unstable due to excessive oscillations caused by excessive integrations. To remove this instability, a converter controlled with a proportional-integral-differential (PID) controller is used. The dynamic model of the system is found by the mathematical analysis of the converter. In this article, PID design and control of CUK converter has been implemented. A fourth-order parametric transfer function is obtained here. The converter is simulated in virtual environment by using the obtained parameters. To find the control parameters of the system, an interface design is carried out. The control parameters (P, PI and PID) of the system are obtained by using the Ziegler-Nichols method. The results were evaluated by simulating the system as uncontrolled, PID controlled and Regulated PID controlled. The performance of CUK converter at different values of parameters by using PID controller is found more effective than PI controller.

1. INTRODUCTION

Maximum power point tracking technique (MPPT) is used to make the most of solar cells and solar panels [1-2]. In order to obtain the maximum efficiency, the solar panel is wanted (required) to be operated at maximum power. This situation is only possible if the system remains at a certain voltage and current level. It also determines the MPP tracking performance of DC-DC (Direct Current - Direct Current) converter topologies [3].

The CUK converter topology allows the dc voltage source to be stepped up or stepped down through a single switching control. A variety of classical control methods have been applied to the CUK converter including PI/PID [25], linear state feedback [4-5], fuzzy-logic [6], and sliding mode control [7-8].

DC-DC CUK converter is one of the power converters used in many studies. The static and dynamic properties of CUK converters have been widely discussed in the literature, where powerful tools for analysis, modeling and design are available [9-14]. CUK converters feature excellent properties (capacitive energy transfer, integrity of magnetic components and use of full transformers) and good steady-state performances (wide conversion ratio, smooth input and output currents).

In this study, the design and control of the CUK converter has been carried out. Mathematical analysis of the CUK converter has been done. Then, the state-space averaging technique has applied to find the dynamic model. A fourth-order parametric transfer function has been obtained here. Using the obtained parameters, the CUK converter was simulated in virtual environment and the results were evaluated. The transfer function has been done by using the Graphical User Interface (GUI) editor in the virtual environment. Here, an interface has been designed to find out the necessary control parameters of the system. The transfer function was created by entering the parameters of the converter with the designed interface. The control parameters (P, PI and PID) of the system were obtained by using the Ziegler-Nichols method. Uncontrolled and PID controlled simulation of the system was made and the results were evaluated. Finally, the effects based on the PID controller performance at different values of parameters of the CUK converter were examined. Optimal control values for the system were observed.

In order to control the fourth order system of the CUK converter, it must be reduced to the second-order [15]. With

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the designed interface, control parameter values were calculated very quickly without reducing the degree of the system. In addition, the user can adjust the input parameters of the circuit to the desired values and display the results numerically and graphically on the same interface. The results obtained from the simulation are presented to the user in a short time and in integrity. Thus, it is thought that it will be beneficial to a certain extent in eliminating problems such as time constraints encountered in converter applications. In addition, the output of this study has the potential to make an important contribution to the electric vehicles, industry, communication and renewable energy sectors [16].

Excessive integration, which is one of the disadvantages of PI controller in previous studies, leads the system to instability. PID controller is most widely used in power converter control [17]. With the derivative factor and filter coefficient in PID control, it has been found to be more suitable for eliminating unwanted oscillations and instability. This study emphasizes filtering one of the disadvantages of PID's sensitivity to noise at the most appropriate value. In the study, the situations at different values of the switching frequency, which is one of the important parameters in converter design, were observed and system analysis was made.

2. CUK Converter

The CUK converter circuit is shown in Figure 1. The output voltage can be greater or smaller than the input voltage. There is a reverse polarity at the output. Here, the converter works according to the open and closed state of the switch. It can be applied where very low input and output noise is required [18].

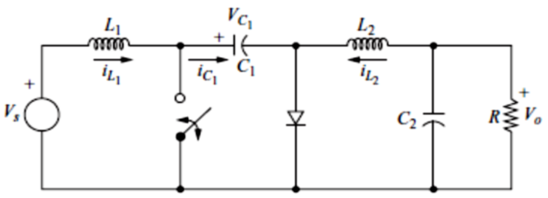

Figure 1. CUK Converter Circuit

The open state matrix (A1) and the closed state matrix (A2) of the switch are shown in Equation (1).

$$A_1=\begin{bmatrix}0 & 0 & 0 & 0\\ 0 & 0 & \frac{1}{L_2} & -\frac{1}{L_2}\\ 0 & -\frac{1}{C_1} & 0 & 0\\ 0 & \frac{1}{C_1} & 0 & -\frac{1}{RC_2}\end{bmatrix}\quad A_2=\begin{bmatrix}0 & 0 & -\frac{1}{L_2} & 0\\ 0 & 0 & 0 & -\frac{1}{L_2}\\ \frac{1}{C_1} & 0 & 0 & 0\\ 0 & \frac{1}{C_2} & 0 & -\frac{1}{RC_2}\end{bmatrix}\quad (1)$$

The transfer function calculated from the state-space equation in Equation (2) is shown below parametrically.

2.1. PID Control

The PID controller has optimum control dynamics such as zero steady-state error, fast response (short rise time), minimum oscillation and higher stability. The necessity to use a derivative gain component in addition to the PI controller is to eliminate overshoots and oscillations that occur in the output response of the system. One of the main advantages of PID controller is that it can be used with higher-level processes involving more than single energy storage [19].

PID controllers are considered as the best controllers in the control system family. Nichols Minorsky has published a theoretical analysis paper on the PID controller. The operating signal for PID control consists of the proportional error signal added by the derivative and integral of the error signal [20].

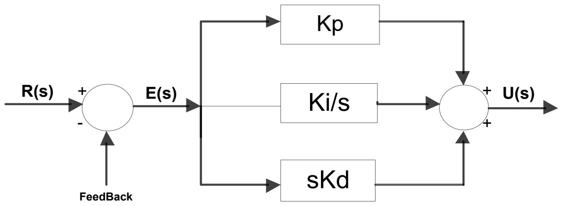

Figure 2. PID Control Block Diagram

Equation (3) contains the mathematical representation of the relationship between the input and output of the PID controller.

$$\frac{Eo(s)}{Ei(s)}=\left(Kp+\left(\frac{K\,i}{s}\right)+s\,Kd\right)=Kp\left(1+\left(\frac{K\,i}{s\,K\,p}\right)+\left(s\frac{K\,d}{K\,p}\right)\right)\quad (3)$$

2.2 Interface Design to Control and Calculate the Control Parameters

In this study, a graphical user interface was designed to simulate the CUK converter circuit from DC-DC converters by using the Graphical User Interface (GUI) editor included in the MATLAB program [21]. The transfer function of the system in the designed interface and the critical gain and critical time period of the transfer function created by using the Ziegler-Nichols method were calculated. The required control parameter values (P, PI, PID) for controlling the system were calculated with the calculated critical gain and critical time period.

In the system, the user will be able to adjust the input parameters of the circuit to the desired values and display the results numerically and graphically on the same interface. Thus, the simulation process and the results obtained will be presented to the user in a short time and in integrity, and it is thought that it will be beneficial in solving the problems such as time constraints encountered in converter circuit applications. The designed interface is shown in Figure 3.

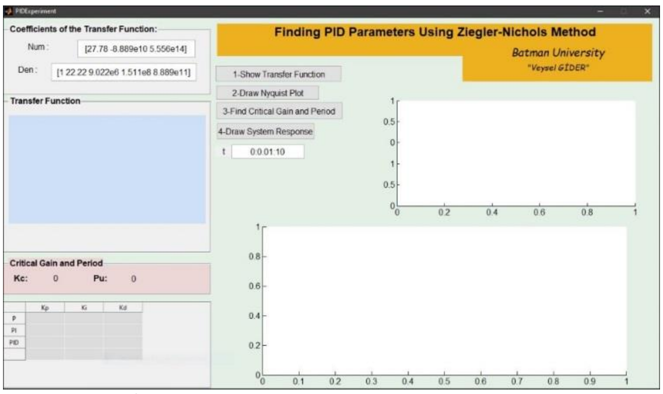

Figure 3. Interface created with MATLAB GUI

In the design, the transfer function is created automatically by writing the desired parameters in the code section. D (operation) ratio required for the system is automatically calculated according to the input / output voltage value.

2.3. Ziegler-Nichols Method

PID controller is faster and less oscillating than PI controller. But with small changes in the input set point, the PID controller tends to be more unstable than PI controller even in the case of distortion. The Ziegler-Nichols Method is one of the most effective methods to increase the use of PID controllers. First, it is checked whether the desired proportional control gain is positive or negative [22]. This critical Kp value is reached as "Critical Gain", Kc, and the period in which the oscillation occurs is called Pu "Critical Time Period". As a result, the whole process depends on two variables and other control parameters are calculated according to Table 1. Ziegler-Nichols method values used in the calculation for control parameters are shown in the table below.

TABLE 1.
ZIEGLER-NICHOLS METHOD

Control Type	Kp	Ki	Kd
P	0.5 * Kc	-	-
PI	0.45 * Kc	1.2 * Kp/Pu	-
PID	0.6 * Kc	.2 * Kp/Pu	Kp / Ku/8

3. Analysis And Results Of The Simulation System

The parameters in Table 2 below were used for the CUK Converter. First, the mathematical analysis of the converter was done. Then the CUK converter was simulated and the results were observed. In order to control the designed interface transfer function and the system, necessary control parameters have been calculated.

TABLE 2.
CUK CONVERTER SYSTEM PARAMETERS

Parameters	V_i	L_1	C_1	L_2	C_2	R	V_0	f_s	Duty
Values	25V	1mH	100µF	1mH	450µF	100Ω	100V	5kHz	0,8

The output voltage and current values of the system are found as follows. The output voltage, the output current on the load resistor and the output power on the load are calculated by putting the values into the Equation (4), Equation (5) and Equation (6).

$$V_{0} = -V_s.\frac{D}{1-D} = -25.\frac{0.8}{0.2} = -100\ V \quad (4)$$

$$I_0 = \frac{-V_0}{R} = \frac{-100\ V}{100} = -1A \quad (5)$$

$$P_{0} = I_0{}^2 R = 1^2 100 = 100W \quad (6)$$

The currents on the L1 and L2 coils are calculated by putting the values into the Equation (7) and (8). Here, the average power supplied by the source should be the same as the average power dissipated by the load [18].

$$I_{L1} = \frac{P_s}{V_s} = \frac{100w}{25V} = 4A \quad (7)$$

$$I_{L2} = \frac{P_0}{-V_0} = \frac{100w}{-100V} = -1A \quad (8)$$

3.1. Uncontrolled Simulation Results of CUK Converter

At this stage, uncontrolled system analysis of the CUK converter was made.

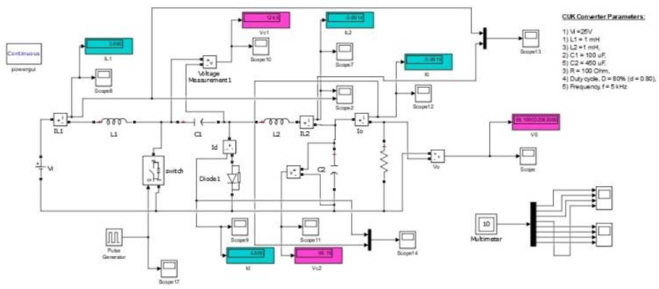

Figure 4. Uncontrolled CUK converter simulation of the created system

The output voltage and current values of the system were found as follows.

$$V_{0} = -99.189\ V$$
$$I_{L1} = 3.995\ A$$
$$I_{L2} = -0.6914\ A$$
$$I_0 = -0.9919\ A$$

Here, the average power (Ps) provided by the source and the power (Po) consumed by the load were calculated.

$$P_{s} = I_{L1} * V_s \quad (9)$$
$$P_{s} = 3.995\ A * 25\ V = 99.875\ W$$
$$P_{o} = I_{L2} * (-V_o) \quad (10)$$
$$P_{o} = -0.6914\ A * 99.189\ V = -68.57\ W$$

The current and voltage output graphs of the uncontrolled system of the CUK converter are as follows.

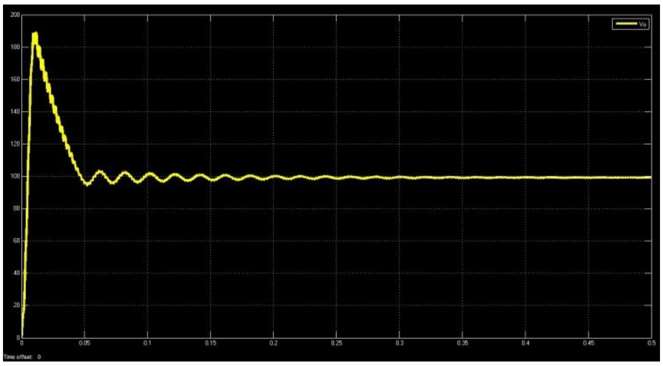

Figure 5. Output voltage (Vo) of uncontrolled CUK converter

Results of the mathematical analysis of the CUK converter and uncontrolled simulation are shown in Table 3, and power values are shown in Table 4.

TABLE 3.
Mathematical Analysis and Uncontrolled CUK Converter Results

	Mathematical Analysis	Uncontrolled Result
$I_{L1}(A)$	4	3.995
$I_{L2}(A))$	-1	-0.6914
$Io(A)$	-1	-0.9919
$Vo(V)$	-100	-99.189

 ISSN 2536-5010 | **e-ISSN** 2536-5134

TABLE 4.
Mathematical Analysis and Uncontrolled CUK converter Power values

	Mathematical Analysis	Uncontrolled Result
$P_s(W)$	100	99.875
$Po(W)$	-100	-68.57

As seen in Figure 5, the output voltage of the uncontrolled CUK converter value is 99.189 with a large amount of percentage(approximately more than 90%). This is also an undesirable and oscillating situation. A Control design is needed to eliminate overshoots and oscillations [23].

3.2. Finding the Transfer Function, Control Parameters and Their Results from the Interface

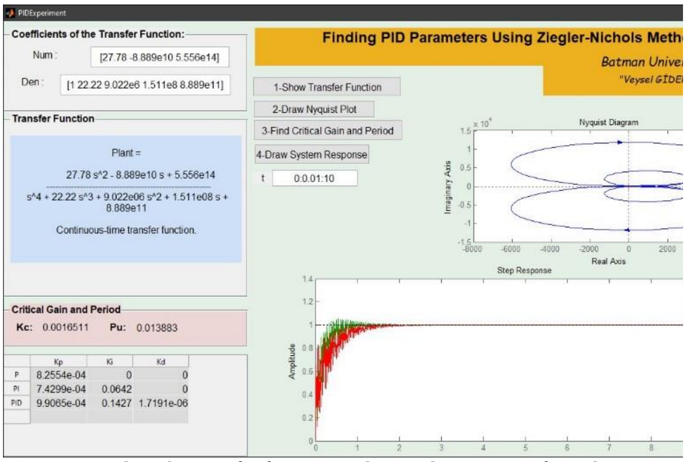

Figure 6. Finding the transfer function and control parameters from the interface

The transfer function of the system of which parameters are given in Equation (11) as seen below.

$$\frac{V_0(s)}{d(s)} = \frac{27.78s^2 - 8.889x10^{10}s + 5.556x10^{14}}{s^4 + 22.22s^3 + 9.022x10^6s^2 + 1.511x10^8s + 8.889x10^{11}} \quad (11)$$

The transfer function of the system is calculated in the designed interface. The critical gain of the transfer function generated by using the Ziegler-Nichols method was calculated as (Kc) = 0.0016511, critical time period (Pu) = 0.013883. The required control parameter values (P, PI, PID) for system control were calculated with the critical gain and critical time period calculated before. The values of PID controller parameters were selected as Proportional gain (Kp) = 0.00099065, Integral gain (Ki) = 0.1427, Derivative gain (Kd) = 0.0000017191, Filter coefficient (N) = 1000.

3.3. Simulation Results of CUK Converter with PID Controller

As seen in Figure 7, the system has been analyzed by performing the PID control process with the calculated Kp, Ki, Kd and N values of the CUK converter. The output voltage of the PID controlled circuit of the CUK converter is V0 = 100.089 V, current values IL1 = 2.228 A, IL2 = 1.029 A, I0 = 1.001 A.

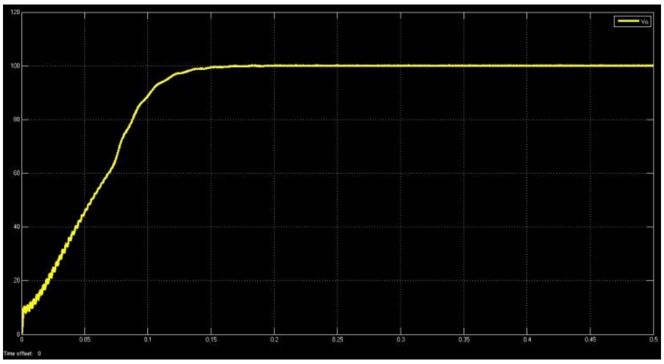
Figure 8. Output voltage (Vo) graph of PID controlled CUK converter

The output voltage (Vo) graph of the PID controlled CUK converter is shown in Figure 8.

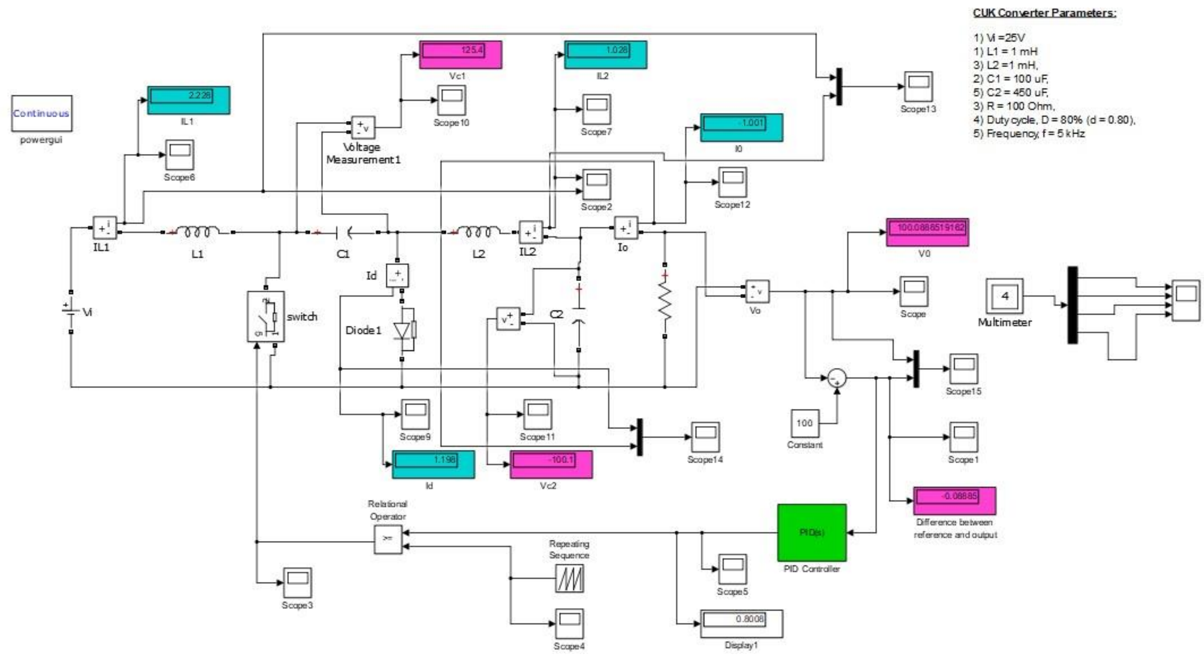

Figure 7. The CUK converter circuit with PID controller

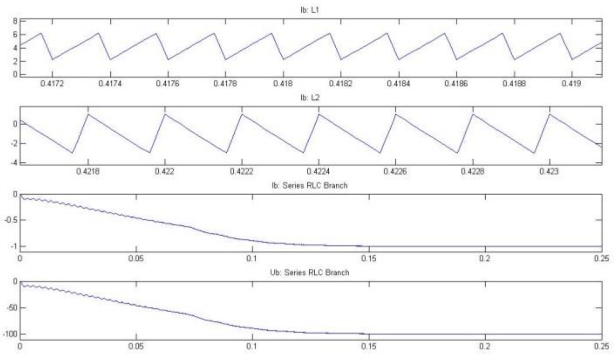

Figure 9. Graphs of current and output voltage (Vo) on L_1, L_2, R (I_{L1}, I_{L2}, Io) of PID controlled CUK converter

Mathematical analysis results of CUK converter, uncontrolled and PID controlled results are compared in table 5.

TABLE 5.
Mathematical Analysis and Uncontrolled and PID Controlled

	Mathematical Analysis	Uncontrolled Result	PID Controlled Result
$I_{L1}(A)$		3.995	2.228
$I_{L2}(A))$		-0.6914	1.029
$Io(A)$		-0.9919	1.001
$Vo(V)$		99.189	100.1

The purpose of designing a controller for the CUK converter is to both ensure the stability of the system and achieve a less steady-state error with minimal overshoot despite distortions in the input voltage. It is to regulate the output voltage by monitoring the set point value [24].

In the PID Controller block, the Filter coefficient (N) is the bandwidth of the low pass filter on the derivative. Pure derivatives are practically avoided as they increase the measurement noise. This low pass filter made by the PID controller block should be used. In order to get as close to the pure derivative as possible, the default filter coefficient values from 100 to 10000 are given.

In CUK converter with PI controller, the system is unstable due to the high oscillation caused by excessive integration. During system analysis with variables such as Kp, Ki, Kd in PID control, the filter coefficient that affects the Kd factor should be selected at the most appropriate value. One of the disadvantages of PID controller is that it is very sensitive to noise. The filter coefficient affects the steady-state error (e) of the system. The steady-state error is the difference between the reference input value and the output value. This difference is desired to be zero.

Figure 10-15 shows the comparison of the PID Tuner values in Simulink and the PID control parameters of the converter calculated at the interface. Here, how the different filter coefficient affects the system is examined.

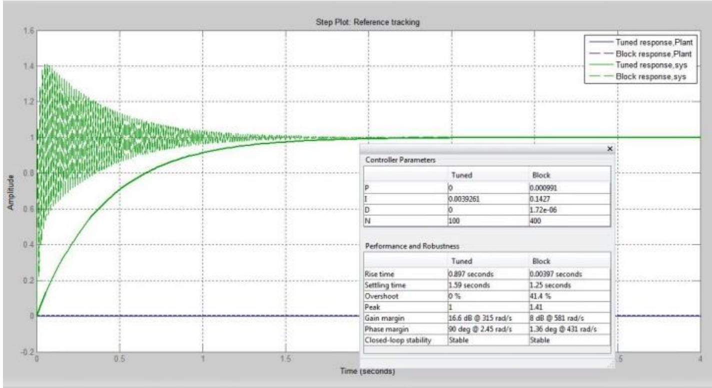

Figure 10. For filter coefficient N = 400

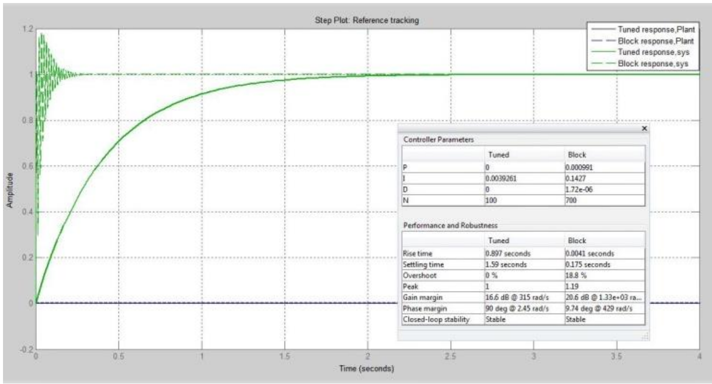

Figure 11. For filter coefficient N = 700

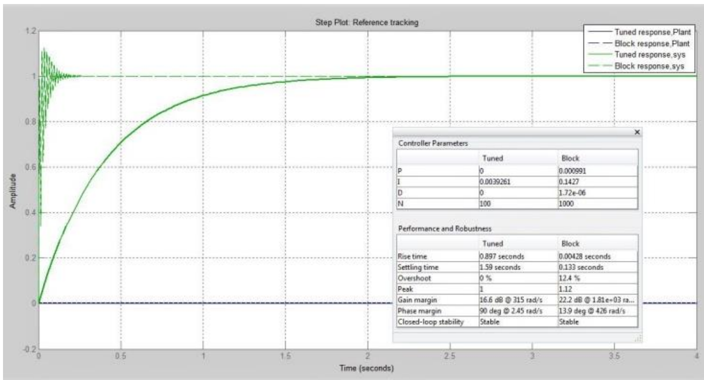

Figure 12. For filter coefficient N = 1000

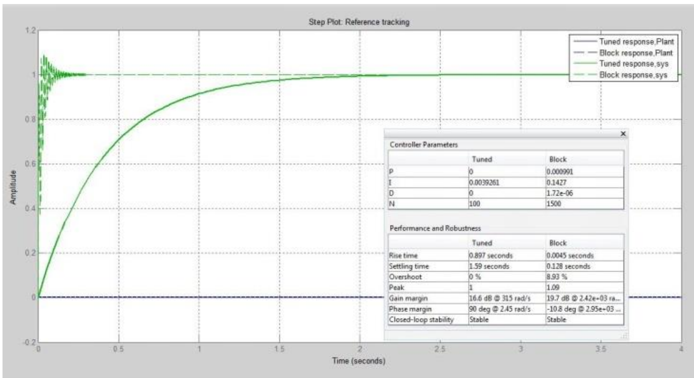

Figure 13. For filter coefficient N = 1500

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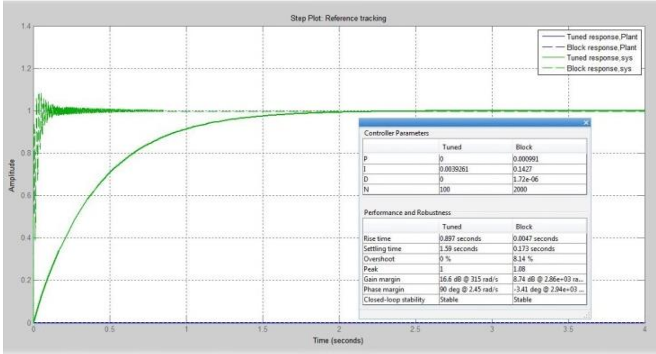

Figure 14. For filter coefficient N = 2000

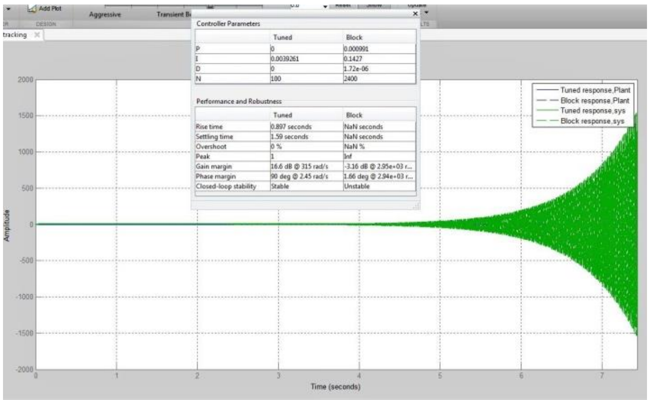

Figure 15. For filter coefficient N = 2400

The comparison of settlement time, rise time and overshoot values for different filter coefficients formed in Table 6 is included.

TABLE 6.
The Comparison of settlement time, rise time and overshoot values for different filter coefficients

Filter Coefficient N	Kp	Ki	Kd	Settlement time(sn)	Rise Time (sn)	Overshoot%
400	0,000991	0,1427	0,00000172	1,25	0,00397	41,4
500	0,000991	0,1427	0,00000172	0,343	0,004	29
600	0,000991	0,1427	0,00000172	0,22	0,00405	22,9
700	0,000991	0,1427	0,00000172	0,175	0,0041	18,8
800	0,000991	0,1427	0,00000172	0,155	0,00416	15,9
900	0,000991	0,1427	0,00000172	0,141	0,00422	13,9
1000	0,000991	0,1427	0,00000172	0,133	0,00428	12,4
1500	0,000991	0,1427	0,00000172	0,128	0,0045	8,93
2000	0,000991	0,1427	0,00000172	0,173	0,0047	8,14
2200	0,000991	0,1427	0,00000172	0,733	0,00474	8,37
2300	0,000991	0,1427	0,00000172	Unstable	Unstable	Unstable
2400	0,000991	0,1427	0,00000172	Unstable	Unstable	Unstable

Displayed in red are the reference parameter results used for system analysis.

When Table 6 and Figure 10-15 are examined; as the filter coefficient increases from N = 400 to N = 2000, the settlement time decreases, the rise time increases and the overrun decreases. At N = 2200, the rise time increases, although the overrun decreases, the sitting time increases. The system becomes unstable after N = 2300.

3.4. Input-Output Power Values for Different Switching Frequency Values (fs)

Table 7 shows the effects of different switching frequencies on coil currents. As the switching frequency increases, the "switching" losses of the switch also increase. In the study, the optimum switching frequency value can be selected from the table so that the average power value supplied by the source and the average power value consumed by the load are the closest values to the power values in the mathematical analysis results. According to the chart, it is the value where the power supplied by the source and the power consumed by the load are closest to each other, fs = 6.7 kHz.

TABLE 7.
The effect of different switching frequency (fs) values on input and output powers

Frequency fs(kHz)	Vi (V)	I_{L1} (A)	$Input\ Power$ (W) $(Vg * I_{L1})$	Vo (V)	I_{L2} (A)	$Output\ Power$ (W) $(Vo * I_{L2})$
1	25	2.117	52.295	101.376	-0.4669	-47.332
2	25	1.633	40.825	99.764	1.653	164.909
3	25	5.791	144.775	99.873	-2.682	-267.859
4	25	1.725	43.125	100.139	1.547	154.915
5	25	2.228	55.700	100.089	1.029	102.991
6	25	3.399	84.975	99.968	-0.164	-16.394
6.7	25	3.994	99.850	99.9977	-0.976	-97.597
7	25	4.233	105.825	99.954	-1.008	-100.7536
7.5	25	3.737	93.425	100.056	-0.4918	-49.2075
8	25	2.982	74.550	100.034	0.2607	26.0788
9	25	1.412	106.525	100.262	-3.646	-365.555

Displayed in red are the reference parameter results used for system analysis.

3.5. New System Regulated with Analysis

According to the study, many observations were made to select the system parameters at the most appropriate values. As a result of the observations, the organized state of the system parameters and PID controller parameter values has shown in the chart. Looking at Table 8, different from the previous system parameter, L_1, L_2 coil values and fs switching frequency values selected as a result of the analyzes have been changed. The system was analyzed again according to the changed values and results close to the desired values were obtained.

TABLE 8.
The parameters of the regulated CUK Converter system

Parameters	V_i	L_1	C_1	L_2	C_2	R	V_0	f_s	D
Values	25V	5mH	100μF	50mH	450μF	100Ω	100V	6.7kHz	0,8

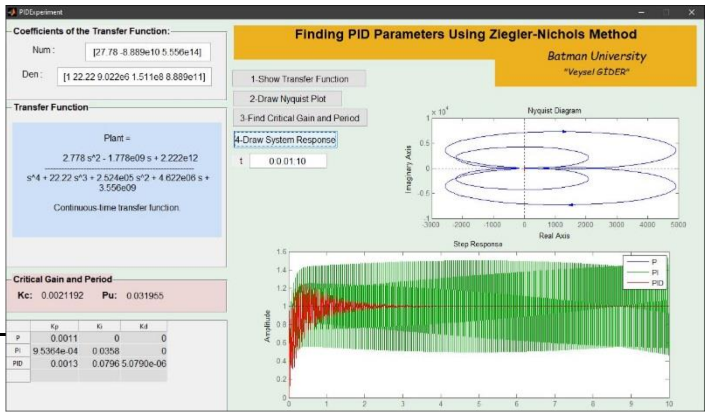

Figure 16. Finding the Transfer function and control parameters of the system regulated from the interface

The transfer functions and control parameter values of this regulated system are calculated from the designed interface.

The transfer function of the regulated system whose parameters are given is as in equation (12) below.

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$$\frac{V_0(s)}{d(s)} = \frac{2.778s^2 - 1.778x10^9 s + 2.222x10^{12}}{s^4 + 22.22s^3 + 2.524x10^5 s^2 + 4.622x10^6 s + 3.556x10^9} \quad (12)$$

PID values calculated from the interface of the regulated system were found to be Proportional gain (Kp) = 0.0013, Integral gain (Ki) = 0.0796, Derivative gain (Kd) = 0.0000050790, Filter coefficient (N) = 350. CUK converter circuit made with PID controller with regulated system parameters and its results are shown in Figure 16 below.

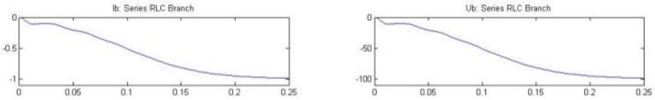

Figure 19. Graph of output current and voltage on the load resistance (Io, Vo) of the PID controlled CUK converter of the regulated system

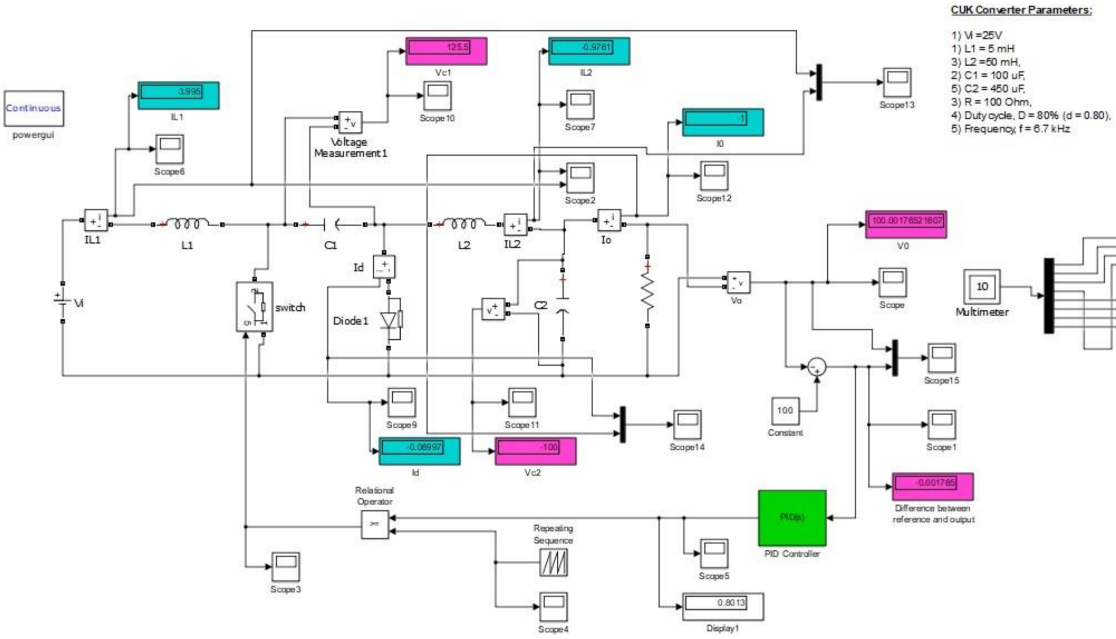

Figure 17. PID controlled circuit of the regulated system of the CUK converter.

The output voltage and current values of the PID controlled circuit of the regulated system of the created CUK converter were found as follows.

$V_{0=}100.001772\ V$
$I_{L1} = 3.995\ A$
$I_{L2} = -0.9761\ A$
$I_0 = -1\ A$

Here, the average power P_s supplied by the source and the power P_o consumed by the load are calculated.

$P_{s=}I_{L1} \cdot V_s$ (13)
$P_{s=}3.995\ A \cdot 25\ V = 99.875\ W$
$P_{o=}I_{L2} \cdot (-V_o)$ (14)
$P_{s=} -0.9761\ A \cdot (100.001772\ )V = -97.612\ W$

The output voltage (Vo) graph of the PID controlled CUK converter of the regulated system is shown in Figure 18.

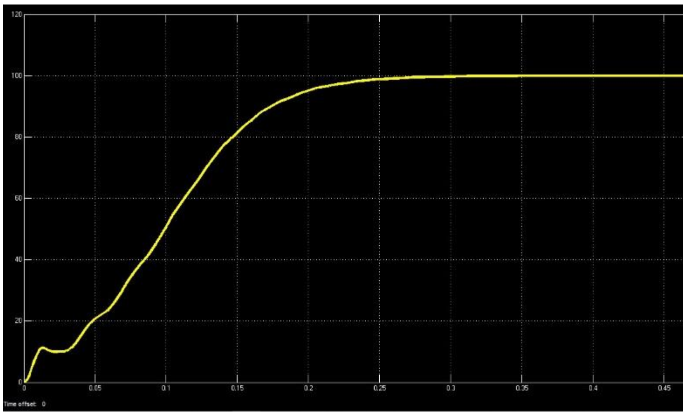

Figure 18. Output voltage graph of the PID controlled CUK converter of the regulated system

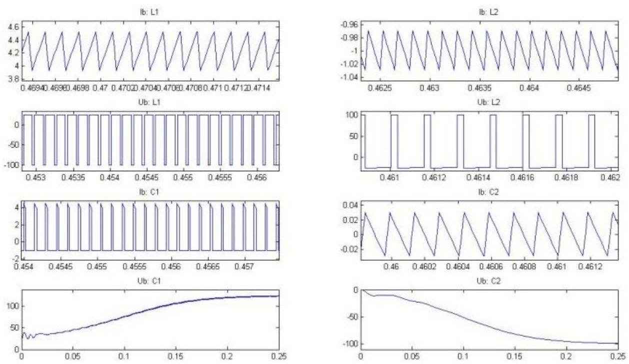

Figure 20. L_1 of the regulated system's PID controlled CUK converter Current and voltage graph on L_2 and C_1, C_2, (I_{L1}, I_{L2}, V_{C1}, V_{C2})

Mathematical analysis results, uncontrolled, regulated system PID controlled CUK converter current, voltage and power results are compared in Table 9 below.

TABLE 9.
Mathematical Analysis, Uncontrolled, Regulated System and PID Controlled CUK Converter Results

	Mathematical Analysis	Uncontrolled Result	Regulated System PID Control Result
$I_{L1}(A)$	4	3.995	3.995
$I_{L2}(A))$	-1	-0.6914	-0.9761
$Io(A)$	-1	-0.9919	-1
$Vo(V)$	-100	-99.189	-100
$P_s(W)$	100	99.875	99.875
$Po(W)$	-100	-68.57	-97.612

4. CONCLUSION

In PI-controlled CUK converter, the system is unstable due to excessive integration. In this article, proportional-integral-differential (PID) controller is used to eliminate the instability of the CUK converter. By simulating the converter in a virtual environment, the interface design was realized to find the control parameters of the system. The effect of CUK converter on PID control parameters is observed according to different component values. With these varying parameters, the effect of the system on rise time, residence time, overrun value, current and voltage values were investigated. In addition, different values of the filter coefficient in PID control and its effect on the controller have been observed. Comparisons of the PID control block diagram of the transfer function with the PID-controlled result and steady-state error of the CUK circuit were also made. It has been found that PID control performance is more effective than the PI control at different parameter values of CUK converter.

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