Simple formula for designing the PID controller of a DC-DC buck converter

Ahmad Saudi Samosir[1], Tole Sutikno[2,3], Luthfiyyatun Mardiyah[1]
[1]Department of Electrical Engineering, Faculty of Engineering, Universitas Lampung, Bandar Lampung, Indonesia
[2]Department of Electrical Engineering, Faculty of Industrial Technology, Universitas Ahmad Dahlan (UAD), Yogyakarta, Indonesia
[3]Embedded System and Power Electronic Research Group (ESPERG), Yogyakarta, Indonesia

Article Info

Article history:

Received Oct 5, 2022
Revised Dec 10, 2022
Accepted Dec 19, 2022

Keywords:

Buck converter
Close loop control
PID controller
Simple PID design
State space model

ABSTRACT

This paper proposes a simple way to design a proportional integral derivative proportional integral derivative (PID) controller for a DC-DC buck converter. This work concerns getting the formula to calculate Kp, Ki, and Kd parameters from a PID controller easily. The main advantage of this formula is that the tuning process of the K_P, K_I and K_D parameters of the PID controller will be simplified just by entering the R, L, and C component values of the buck converter into the formula. The synthesis process of the formula is explained step by step. State space analysis is used to model the equations and transfer functions of the buck converter. The transfer function of the PID controller and buck converter was analyzed to obtain the Buck Converter system's closed loop transfer function. The formula for calculating the parameters K_P, K_I and K_D of the PID controller is derived from the closed loop transfer function of the buck converter system. Numerical simulations are provided to confirm the effectiveness of the proposed PID controller. The performance of the buck converter controlled by the proposed PID controller was tested under various load conditions.

Corresponding Author:

Ahmad Saudi Samosir
Department of Electrical Engineering, Faculty of Engineering, Universitas Lampung
No. 1, Sumantri Brojonegoro St. Bandar Lampung, Indonesia
Email: saudi.ahmad@gmail.com

1. INTRODUCTION

A DC-DC converter is an electronic circuit that converts a DC voltage source from one DC voltage level to another DC voltage level. DC-DC converters are widely used in many electronic industrial applications because they have high efficiency and can provide adjustable voltage output [1]–[4]. The DC-DC converters are often used as dc motor drives [5], [6]. DC-DC converters are also widely used in supporting devices in renewable energy generation, such as output voltage stabilizers from renewable energy devices such as photovoltaic (PV) [7]–[9]. Many researchers have studied and designed DC-DC converters to get high performance and higher power efficiency [10]–[13].

One of the topologies for DC-DC converters that is used the most frequently is called a buck converter. This particular converter is used to bring high DC voltage down to a more manageable level. The buck converter has a straightforward construction. Components such as MOSFETs and diodes that perform the function of switching are active, while components such as inductors and capacitors that perform the function of output filtering are passive. The active components make up the main circuit. Buck converters, when they contain components such as inductors, capacitors, and switching elements, transform into nonlinear, second-order systems [14], [15].

The buck converter requires a good controller that can control the MOSFET switching signal to produce the appropriate duty cycle in order for it to be able to produce stable output with a quick response. In this case, the control technique that is utilized is a significant factor that plays a role in determining the performance of the switching converter [12], [15]. A good controller needs to be efficient, providing solutions that are straightforward and realistic, so that it can achieve desirable levels of performance despite the presence of disturbances and uncertainties in the system.

A wide variety of controllers, such as proportional integral derivative (PID) controllers, sliding mode control [16], [17], internal model control [18], [19], dynamic evolution control [13], and several types of adaptive control, have been used to accomplish the goal of high performance and high power efficiency. A controller known as a proportional integral derivative (PID) controller is one of the types of controllers that are frequently used in industry. Because of its straightforward construction, reliable performance, and user-friendliness, the PID controller has emerged as a de facto standard across many industries. The selection of the parameters proportional gain (K_P), integral gain (K_I), and derivative gain (K_D) has a significant impact on the performance of the PID controller, which is one of the challenges associated with making use of a PID controller. It is essential to determine the values of the parameters K_P, K_I and K_D because incorrect values will result in a response from the system that is less than ideal. Because the process of calculating the values of K_P, K_I and K_D typically involves the use of complicated formulas, the values of K_P, K_I and K_D are typically obtained through the use of a tuning process.

Conventional tuning methods such as trial-and-error, gain scheduling, Ziegler-Nichols [20], the genetic algorithm [21], and the particle swarm optimization algorithm [22]–[24] are frequently used in the process of determining PID parameters. Other common tuning methods include gain scheduling, Ziegler-Nichols [20], and the genetic algorithm [21]. These conventional PID tuning methods are regarded as being less than optimal, and performing calculations using this method is considered to be relatively challenging.

A straightforward formula that can be used to determine the K_P, K_I and K_D values of the PID controller for a buck converter is going to be proposed in this article. Without having to go through a difficult and time-consuming process of tuning, the parameter values of K_P, K_I and K_D can be quickly and easily calculated with the help of this formula. To calculate the values of K_P, K_I and K_D, all that needs to be done is plug the component values of R, L, and C derived from the buck converter into the appropriate spaces in the formula. Under a wide variety of load conditions, the performance of the buck converter that was controlled by the proposed PID controller was evaluated. The environment of MATLAB and simulink was utilized for the carrying out of the experiments.

2. MODELING AND ANALYSIS OF DC-DC BUCK CONVERTER SYSTEM

2.1. Operation and modelling of DC-DC buck converter

Buck converters are a type of power electronic converter that take a direct current voltage at one level and convert it to a lower level at the output. Buck converters are also known as “bucking converters”. The primary circuit of a buck converter is comprised of two static switches, which are typically a mosfet and a diode, and is then followed by an inductor-capacitor filter. Figure 1 presents the buck converter's circuit diagram in the form of a schematic. The functionality of the buck converter can be broken down into two distinct mode states, which are referred to respectively as the switch ON state and the switch OFF state, as shown in Figure 2.

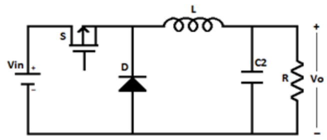

Figure 1. DC-DC buck converter schematic diagram

(a) (b)

Figure 2. DC-DC buck converter operation mode (a) ON state and (b) OFF state

2.1.1. Switch ON state

The operation modes during the switch-on state are shown in Figure 2(a). When switch S is in the ON state, the input voltage Vin is connected to the inductor and diode. Current flows to the load through the inductor. During this stage, the inductor current increases linearly. The diode is reverse biased, resulting in no current flowing through the diode. By applying Kirchhoff's voltage law to the circuit diagram of Figure 2(a), obtained in (1) and (2).

$$V_{in} - \frac{di_L}{dt} - V_C = 0 \tag{1}$$

$$\frac{di_L}{dt} = \frac{V_{in} - V_C}{L} \tag{2}$$

By applying Kirchhoff's current law in the circuit diagram of Figure 2(a), obtained in (3) and (4).

$$\frac{V_C}{R} + C\frac{dV_C}{dt} = i_L \tag{3}$$

$$\frac{dV_C}{dt} = \frac{i_L}{C} - \frac{V_C}{RC} \tag{4}$$

2.1.2. Switch OFF state

The operation modes during the switch-off state are shown in Figure 2(b). When switch S is in the OFF state, the input voltage Vin is released from the inductor. The current from the input voltage is cut off. The inductor transfers the stored energy to the load. The inductor delivers current to the load. During this stage, the inductor current decreases linearly. The diode is forward-biased and delivers current from the load back to the inductor. By applying Kirchhoff's voltage law to the circuit diagram of Figure 2(b), obtained in (5) and (6).

$$L\frac{di_L}{dt} + V_C = 0 \tag{5}$$

$$\frac{di_L}{dt} = -\frac{V_C}{L} \tag{6}$$

By applying Kirchhoff's current law in the circuit diagram of Figure 2(b), obtained in (7) and (8).

$$\frac{V_C}{R} + C\frac{dV_C}{dt} = i_L \tag{7}$$

$$\frac{dV_C}{dt} = \frac{i_L}{C} - \frac{V_C}{RC} \tag{8}$$

2.2. State space model of DC-DC buck converter

The state-space model is a linear presentation of a dynamic system. The state-space model describes a time-invariant linear system in the form of a matrix equation. State-space models are often used to model the performance of a linear or nonlinear system [25]–[27]. A Buck converter is a system that operates in a switching mode. This causes the Buck converter to become a non-linear system. The state space averaging method is a powerful method for analyzing non-linear systems such as Buck converters [28].

The state space model of buck converter during switch ON state are derived using (2) and (4). From (2) and (4), the equation of the switch ON state condition can be written in matrix form as (9).

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} V_{in} \tag{9}$$

The state space model of buck converter during switches OFF state are derived using (6) and (8). From (6) and (8), the equation of the switch OFF state condition can be written in matrix form as (10).

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \end{bmatrix} V_{in} \tag{10}$$

From (9) and (10), the state space model of the buck converter during switch ON state and switch OFF states can be written as (11) and (12).

During switch ON: $\dot{X} = A_1.X + B_1.U$ (11)

During switch OFF: $\dot{X} = A_2.X + B_2.U$ (12)

With the values of matrices X, A_1, A_2, B_1, B_2, U are:

$$X = \begin{bmatrix} i_L \\ V_C \end{bmatrix}, \qquad \dot{X} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dV_C}{dt} \end{bmatrix}, \qquad U = V_{in}$$

$$A_1 = A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$$

$$B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}, \qquad B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

the state space averaging technique is then applied to obtain the equivalent matrices A and B for the buck converter system. Matrices A and B are calculated using (13) and (14):

$$A = A_1.d + A_2.(1-d) \tag{13}$$

$$B = B_1.d + B_2.(1-d) \tag{14}$$

where '*d*' and '(1-*d*)' are the duty cycle for ON and OFF stages respectively [28]-[30].

Since the output voltage of the buck converter is the same as the output capacitor voltage, the output voltage equation can be written in matrix form:

$$V_O = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ V_C \end{bmatrix}$$

finally, the complete state space model of the buck converter system is written as (15) and (16).

$$\dot{X} = A.X + B.U \tag{15}$$

$$Y = C.X + D.U \tag{16}$$

Where Y and U are the output and input voltages, respectively. The values of matrices A, B and C in state space model of the buck converter system are:

$$A = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}, B = \begin{bmatrix} \frac{d}{L} \\ 0 \end{bmatrix}, C = \begin{bmatrix} 0 & 1 \end{bmatrix},$$

and 'D' represents the feed forward gain matrix and its value is '0' for this system.

2.3. Buck converter transfer function

The transfer function of the buck converter system can be derived based on the state-space model in (15) and (16). The Laplace transform of the state (15) produces in (17) and (18).

$$sX = A.X + B.U \tag{17}$$

$$X = (sI - A)^{-1}.BU \tag{18}$$

By substituting (18) into (16), the output voltage equation can be written as (19).

$$Y = C.(sI - A)^{-1}.BU + DU \tag{19}$$

Hence, the transfer function of the system converter buck can be written as (20).

$$\frac{Y}{U} = C.(sI - A)^{-1}.B + D \tag{20}$$

After substitution of the values of the A, B, and C matrices into (20), the transfer function of the buck converter is described by (21) and (22).

$$\frac{V_o(s)}{V_{in}(s)} = \frac{d}{LCS^2 + \frac{L}{R}s + 1} \tag{21}$$

$$\frac{V_o(s)}{d(s)} = \frac{V_{in}}{LCS^2 + \frac{L}{R}s + 1} \tag{22}$$

3. FORMULA TO DETERMINE PID CONTROL PARAMETERS FOR DC–DC BUCK CONVERTER

In this work, a closed-loop controller for a buck converter will be designed using a PID controller. The PID controller's control mechanism includes a feedback cycle that corrects the error value between the measured system output and a predetermined set point value. The difference in the resulting value is calculated to provide a control action to achieve the set value. The PID Controller involves three separate parameters, namely proportional gain (K_P), integral gain (K_I), and derivative gain (K_D), as shown in Figure 3.

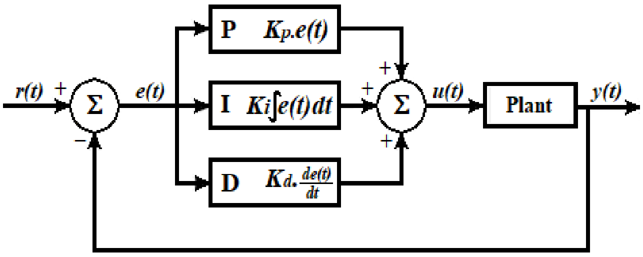

Figure 3. PID Controller block diagram

The PID controller equation can be written in the time domain as in (23).

$$U(t) = K_P.e(t) + K_I \int e(t)\,dt + K_D \frac{de(t)}{dt} \tag{23}$$

The PID controller equation can also be written in the frequency domain as in (24).

$$U(s) = \left[K_P + \frac{K_I}{s} + K_D.s\right].E(s) \tag{24}$$

The PID controller transfer function can be written as in (25) and (26).

$$\frac{U(s)}{E(s)} = K_P + \frac{K_I}{s} + K_D.s \tag{25}$$

$$\frac{U(s)}{E(s)} = \frac{K_D.s^2 + K_P s + K_I}{s} \tag{26}$$

Block diagram of the PID controller for DC-DC Buck Converter can be described as in Figure 4.

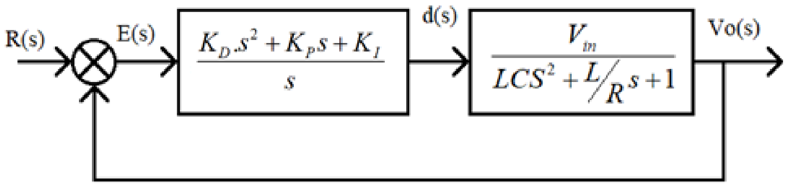

Figure 4. Block diagram of the PID controlled DC-DC buck converter

Open loop transfer function of buck converter system:

$$\frac{V_O(s)}{E(s)} = \frac{K_D.s^2+K_Ps+K_I}{s}.\frac{V_{in}}{LCS^2+\frac{L}{R}s+1}$$

$$\frac{V_O(s)}{E(s)} = \frac{(K_Ds^2+K_Ps+K_I).V_{in}}{\left(LCs^2+\frac{L}{R}s+1\right).s} \quad (27)$$

close loop transfer function of buck converter system is:

$$\frac{V_O(s)}{V_{ref}(s)} = \frac{\frac{(K_Ds^2+K_Ps+K_I).V_{in}}{\left(LCs^2+\frac{L}{R}s+1\right).s}}{1+\frac{(K_Ds^2+K_Ps+K_I).V_{in}}{\left(LCs^2+\frac{L}{R}s+1\right).s}}$$

$$\frac{V_O(s)}{V_{ref}(s)} = \frac{(K_Ds^2+K_Ps+K_I).V_{in}}{\left(LCs^2+\frac{L}{R}s+1\right).s+(K_Ds^2+K_Ps+K_I).V_{in}} \quad (28)$$

to get a simpler buck converter transfer function, it can be done by making the coefficients of the $(K_Ds^2 + K_Ps + K_I)$ and $\left(LCs^2 + \frac{L}{R}s + 1\right)$ parts to be equal.

$$(K_Ds^2 + K_Ps + K_I) = \left(LCs^2 + \frac{L}{R}s + 1\right) \quad (29)$$

Hence:

$$K_D = LC \quad (30)$$

$$K_P = \frac{L}{R} \quad (31)$$

$$K_I = 1 \quad (32)$$

by selecting the values of K_P, K_I and K_D as above, then the closed loop transfer function of the buck converter system will be simple as (33):

$$\frac{V_O(s)}{V_{ref}(s)} = \frac{V_{in}}{s+V_{in}} \quad (33)$$

in order to get faster controller response, the value of K_P, K_I and K_D must be multiplied by a certain Gain. In this paper, the Gain value of 50 was chosen. So, the formula to determine K_P, K_I and K_D as (34)-(36):

$$K_D = 50.LC \quad (34)$$

$$K_P = 50.\frac{L}{R} \quad (35)$$

$$K_I = 50 \quad (36)$$

4. IMPLEMENTATION OF PID CONTROL FOR DC–DC BUCK CONVERTER SYSTEM

4.1. Determination of PID controller parameters

To investigate the performance of the proposed control system, a PID-controlled buck converter has been implemented. A DC-DC buck converter has been modeled, complete with a PID controller. The specifications of the buck converter system are listed in Table 1. The implementation of PID control for the dc–dc buck converter system begins with the calculation of the PID parameters using the proposed formula. Based on Table 1, a PID-controlled buck converter is taken as an example for experimental verification with the following circuit parameters: $L = 50\ \mu H$, $C = 220\ \mu F$, and $R = 10\ \Omega$.

The mathematical formula to determine the PID parameter of the buck converter is: $K_P = 50 \cdot \frac{L}{R}$, $K_I = 50$, and $K_D = 50 \cdot LC$. By using this formula, the values of K_P, K_I and K_D can be obtained easily by substituting the values of the components L, C and R on the buck converter into the formula. From the calculation, the values of K_P, K_I and K_D that will be used are: $K_P = 2.5 \times 10^{-4}$, $K_I = 50$, and $K_D = 5 \times 10^{-7}$.

Table 1. Buck converter specification

Parameter	Value	Unit
Input voltage	12	V
Output voltage	5	V
Inductor	50	uH
Capacitor	220	uF
Load Resistance	10	ohm
Switching Frequency	22	kHz

4.2. Simulation results

A buck converter system has been modeled in MATLAB SIMULINK to test how well the proposed formula-based PID controller works. Figure 5 shows the Simulink model of a buck converter that is controlled by a formula-based PID controller. In this experiment, the buck converter is supplied with an input voltage of 12 volt, and the reference voltage is set to 5 volt. This means the buck converter is expected to produce an output voltage of 5V from an input voltage of 12 volt. The PID controller parameters are set with value of $K_P = 2.5 \times 10^{-4}$, $K_I = 50$, and $K_D = 5 \times 10^{-7}$ as shown in Figure 6.

The simulation results of the buck converter system controlled by the formula-based PID are shown in Figure 7. The output voltage waveforms of a DC-DC buck converter are shown in Figure 7. By providing a constant input voltage of 12 volt to the buck converter and setting the reference voltage to 5 volt, the buck converter produces an output voltage of 4,978 volt, which is very close to 5 volt. At the initial start, there is an overshoot at the output voltage with a peak of 5.3 volt. The output voltage of the buck converter reaches a steady state within 10ms with a ripple voltage of 50 mV. These results indicate that the proposed formula-based PID controller can control the output voltage of the buck converter with very good accuracy.

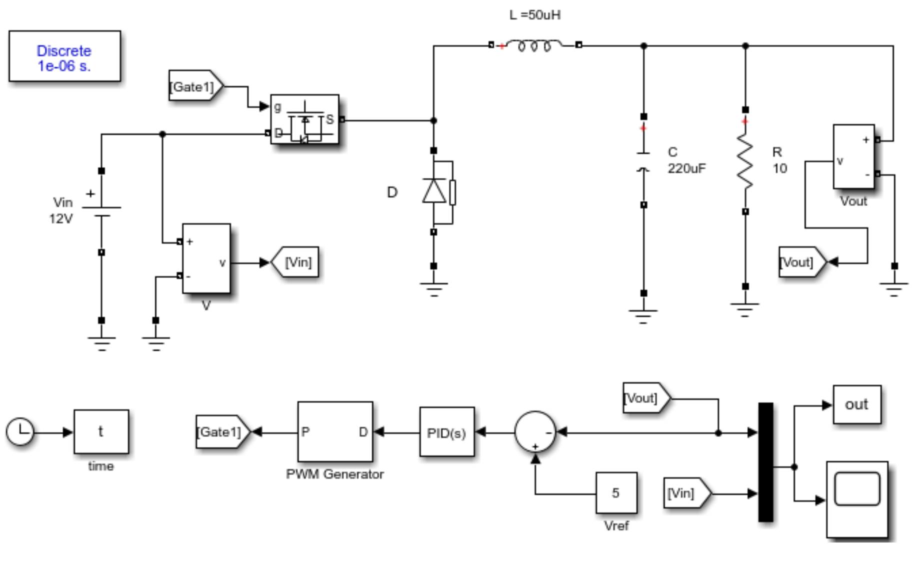

Figure 5. Simulink model of a PID-controlled buck converter system

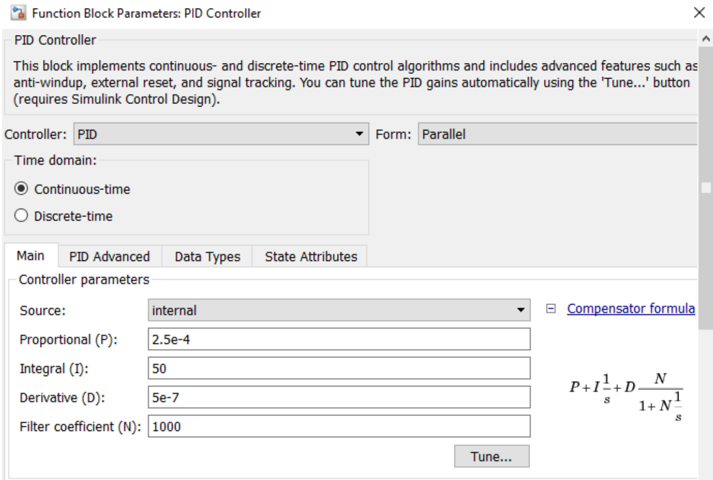

Figure 6. Setting of block parameter PID controller in MATLAB Simulink

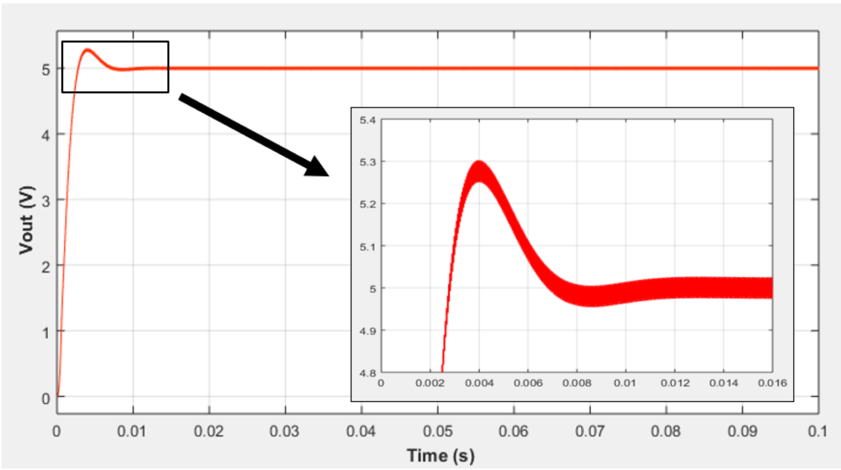

Figure 7. Output voltage waveform of the buck converter

4.3. Various load test

In this experiment, a buck converter controlled by a formula-based PID has been tested with various loads. The buck converter is loaded with a resistive load whose value varies from 5 Ω to 50 Ω. A constant of 12 volts is applied to the input voltage. The reference voltage is set to 5 V. The experimental results are shown in Table 2. The experimental results show that the proposed PID controller has the ability to control the Buck Converter to produce a very accurate output voltage. The resulting output voltage is very close to the set reference voltage. The biggest error percentage is 0.78% at load $R = 5\ \Omega$, while the smallest error percentage is 0.16% at load $R = 50\ \Omega$. The average error percentage in this test is 0.35%. These results show the average accuracy is 99.65%.

Table 2. Test results at various load with 5V reference voltage

Load (Ω)	Output voltage (volt)	Error (%)
5	4,961	0.78
10	4,971	0.58
15	4,978	0.44
20	4,982	0.36
25	4,985	0.30
30	4,987	0.26
35	4,989	0.22
40	4,990	0.20
45	4,991	0.18
50	4,992	0.16

5. CONCLUSION

In this paper, the DC-DC buck converter control system is discussed and analyzed step by step. It is proposed that a straightforward formula could be used in the development of a PID controller for a DC-DC buck converter. The procedure for formula synthesis is broken down into its component parts. The formula that produced in this proposed research was $\mathrm{K_P} = 2.5 \times 10^{-4}$, $\mathrm{K_I} = 50$, and $\mathrm{K_D} = 5 \times 10^{-7}$. The performance of the buck converter, which is controlled by the proposed PID controller, has been investigated under a variety of load conditions. From the simulation results it was found that The biggest error percentage is 0.78% at load $R = 5\ \Omega$, while the smallest error percentage is 0.16% at load $R = 50\ \Omega$. The average error percentage in this test is 0.35%. These results show the average accuracy is 99.65%. The findings from the simulation demonstrate that the PID controller that was proposed is capable of controlling the Buck Converter in an effective manner and very good accuracy.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the University of Lampung for providing research facilities and funding. This research was also supported by the World Class Professor Program 2022, Decree No. 3252/E4/DT.04.03/2022, of the Directorate General of Higher Education, Research, and Technology of the Ministry of Education, Culture, Research, and Technology of the Republic of Indonesia.

REFERENCES

[1] H. H. Chou, W. H. Luo, H. L. Chen, and S. F. Wang, “A novel buck converter with dual loops control mechanism,” *Electronics*, vol. 11, no. 8, pp. 1256, 2022, doi:10.3390/ electronics11081256.

[2] G. Zhou, J. Xu and J. Wang, “Constant-frequency peak-ripple-based control of buck converter in CCM: review, unification, and duality,” *IEEE Transactions on Industrial Electronics*, vol. 61, no. 3, pp. 1280-1291, 2014, doi: 10.1109/TIE.2013.2257143.

[3] M. Veerachary, “Two-switch semiquadratic buck converter,” *IEEE Transactions on Industrial Electronics*, vol. 64, no. 2, pp. 1185-1194, Feb. 2017, doi: 10.1109/TIE.2016.2611571.

[4] K. Karaket and C. Bunlaksananusorn, “Modeling of a quadratic buck converter,” *The 8th Electrical Engineering/ Electronics, Computer, Telecommunications and Information Technology (ECTI) Association of Thailand - Conference* 2, 2011, pp. 764-767, doi: 10.1109/ECTICON.2011.5947952.

[5] A. A. A. Ismail and A. Elnady, “Advanced drive system for DC motor using multilevel DC/DC buck converter circuit,” *IEEE Access*, vol. 7, pp. 54167-54178, 2019, doi: 10.1109/ACCESS.2019.2912315.

[6] G.C. Ioannidis *et.al*., “AC-DC & DC-DC converters for DC motor drives review of basic topologies,” *Proceedings of the 2013 International Conference on Electronics and Communication Systems*, 2013.

[7] N.H. Baharudin, T. M. N. T. Mansur, F. A. Hamid, R. Ali and M. I. Misrun, “Topologies of DC-DC converter in solar PV applications,” *Indonesian Journal of Electrical Engineering and Computer Science*, vol. 8, no. 2, pp. 368-374, 2017, doi: 10.11591/ijeecs.v8.i2.pp368-374.

[8] A. S. Samosir, S. Purwiyanti, H. Gusmedi and M. Susanto, “Design of DC to DC converter for solar photovoltaic power plant applications,” *International Conference on Converging Technology in Electrical and Information Engineering (ICCTEIE)*, 2021, pp. 132-137, doi: 10.1109/ICCTEIE54047.2021.9650639.

[9] B.S. Revathi and M. Prabhakar, “Non isolated high gain DC-DC converter topologies for pv applications – a comprehensive review,” *Renewable and Sustainable Energy Reviews*, vol. 66, pp. 920-933, 2016, doi: 10.1016/j.rser.2016.08.057.

[10] S. Abdelmalek, A. Dali, A. Bakdi and M. Bettayeb, “Design and experimental implementation of a new robust observer-based nonlinear controller for DC-DC Buck Converters,” *Energy*, vol. 213, pp. 118816, 2020, doi: 10.1016/j.energy.2020.118816.

[11] M. Z. Hossain, N. A. Rahim, S. Jeyraj, “Recent progress and development on power DC-DC converter topology, control, design and applications: a review,” *Renewable and Sustainable Energy Reviews*, vol. 81, pp. 205-230, 2018, doi: 10.1016/j.rser.2017.07.017.

[12] M. Saoudi, A. El-Sayed and H. Metwally, “Design and implementation of closed-loop control system for buck converter using different techniques,” *IEEE Aerospace and Electronic Systems Magazine*, vol. 32, no. 3, pp. 30-39, 2017, doi: 10.1109/MAES.2017.150261.

[13] A.S. Samosir, and A. H. M. Yatim, “Dynamic evolution control for synchronous buck DC–DC converter: Theory, model and simulation,” *Simulation Modelling Practice and Theory*, vol. 18, no. 5, pp. 663-676, 2010, doi: 10.1016/j.simpat.2010.01.010.

[14] J. A. Solsona, S. G. Jorge and C. A. Busada, “Nonlinear control of a buck converter which feeds a constant power load,” *IEEE Transactions on Power Electronics*, vol. 30, no. 12, pp. 7193-7201, 2015, doi: 10.1109/TPEL.2015.2392371.

[15] M. Gheisarnejad, H. Farsizadeh and M. H. Khooban, “A novel nonlinear deep reinforcement learning controller for DC–DC Power buck converters,” *IEEE Transactions on Industrial Electronics*, vol. 68, no. 8, pp. 6849-6858, 2021, doi: 10.1109/TIE.2020.3005071.

[16] S. Ding, W. X. Zheng, J. Sun and J. Wang, “Second-order sliding-mode controller design and its implementation for buck converters,” *IEEE Transactions on Industrial Informatics*, vol. 14, no. 5, pp. 1990-2000, 2018, doi: 10.1109/TII.2017.2758263.

[17] L. Liu, W. X. Zheng and S. Ding, “An adaptive SOSM controller design by using a sliding-mode-based filter and its application to buck converter,” *IEEE Transactions on Circuits and Systems I: Regular Papers*, vol. 67, no. 7, pp. 2409-2418, 2020, doi: 10.1109/TCSI.2020.2973254.

[18] A. Ghosh, M. Prakash, S. Pradhan and S. Banerjee, “A comparison among PID, sliding mode and internal model control for a buck converter,” *IECON 2014 - 40th Annual Conference of the IEEE Industrial Electronics Society*, 2014, pp. 1001-1006, doi: 10.1109/IECON.2014.7048624.

[19] K. G. Shankar, D. Jena and R. Reddivari, “Comparative overview of internal model control based PID, state feedback integral, and sliding mode controllers for buck converter,” *IEEE International Conference on Distributed Computing, VLSI, Electrical Circuits and Robotics (DISCOVER)*, 2019, pp. 1-6, doi: 10.1109/DISCOVER47552.2019.9008056.

[20] E. K. Anto, J. A. Asumadu and P. Y. Okyere, “PID control for improving P&O-MPPT performance of a grid-connected solar PV

system with Ziegler-Nichols tuning method," *IEEE 11th Conference on Industrial Electronics and Applications (ICIEA)*, 2016, pp. 1847-1852, doi: 10.1109/ICIEA.2016.7603888.

[21] A. Chlaihawi, "Genetic algorithm error criteria as applied to PID controller DC-DC buck converter parameters: an investigation," *IOP Conference Series: Materials Science and Engineering*, 2020, vol. 671, doi: 10.1088/1757-899X/671/1/012032.

[22] E. Mirzaei and H. Mojallali, "Auto tuning PID controller using chaotic PSO algorithm for a boost converter," *13th Iranian Conference on Fuzzy Systems (IFSC)*, 2013, pp. 1-6, doi: 10.1109/IFSC.2013.6675643.

[23] K. L. Sowjanya and L. R. Srinivas, "Tuning of PID controllers using particle swarm optimization," *International Journal of Industrial Electronics and Electrical Engineering*, vol. 3, no. 2, pp. 17-22, 2015.

[24] M. F. Aranza, J. Kustija, B. Trisno, and D. L. Hakim, "Tuning pid controller using particle swarm optimization algorithm on automatic voltage regulator system," *IOP Conference Series: Materials Science and Engineering*, 2016, vol. 128, doi: 10.1088/1757-899X/128/1/012038.

[25] R. H. G. Tan and L. Y. H. Hoo, "DC-DC converter modeling and simulation using state space approach," *IEEE Conference on Energy Conversion (CENCON)*, 2015, pp. 42-47, doi: 10.1109/CENCON.2015.7409511.

[26] A. Sarwar, A. Shahid, A. Hudaif, U. Gupta and M. Wahab, "Generalized state-space model for an n-phase interleaved buck-boost converter," *4th IEEE Uttar Pradesh Section International Conference on Electrical, Computer and Electronics (UPCON)*, 2017, pp. 62-67, doi: 10.1109/UPCON.2017.8251023.

[27] U. Javaid and D. Dujić, "Arbitrary order generalized state space average modeling of switching converters," *IEEE Energy Conversion Congress and Exposition (ECCE)*, 2015, pp. 6399-6406, doi: 10.1109/ECCE.2015.7310556.

[28] G. Suman, B. V. S. P. Kumar, M. S. Kumar, B. C. Babu and K. R. Subhashini, "Modeling, analysis and design of synchronous buck converter using state space averaging technique for PV energy system," *International Symposium on Electronic System Design (ISED)*, 2012, pp. 281-285, doi: 10.1109/ISED.2012.27.

[29] P. Azer and A. Emadi, "Generalized state space average model for multi-phase interleaved buck, boost and buck-boost DC-DC converters: transient, steady-state and switching dynamics," *IEEE Access*, vol. 8, pp. 77735-77745, 2020, doi: 10.1109/ACCESS.2020.2987277.

[30] A. C. Schittler, D. Pappis, C. Rech, A. Campos and M. A. D. Costa, "Generalized state-space model for the interleaved buck converter," *XI Brazilian Power Electronics Conference*, 2011, pp. 451-457, doi: 10.1109/COBEP.2011.6085305.

BIOGRAPHIES OF AUTHORS

Ahmad Saudi Samosir is a lecturer in Electrical Engineering Department at the Universitas Lampung, Lampung, Indonesia. He received his B.Eng., M.Eng. and Ph.D. degrees in in Electrical Engineering from Universitas Sumatera Utara, Institut Teknologi Bandung and Universiti Teknologi Malaysia, in 1995, 1999 and 2010, respectively. He has been a Professor in Universitas Lampung Indonesia since 2017. He is currently a Dean of Postgraduate Faculty of Universitas Lampung. His research interests include power electronics design, controller and its applications in renewable energy, electric vehicle and industrial applications. He can be contacted at email: ahmad.saudi@eng.unila.ac.id.

Tole Sutikno is a lecturer in Electrical Engineering Department at the Universitas Ahmad Dahlan (UAD), Yogyakarta, Indonesia. He received his B.Eng., M.Eng. and Ph.D. degrees in Electrical Engineering from Universitas Diponegoro, Universitas Gadjah Mada and Universiti Teknologi Malaysia, in 1999, 2004 and 2016, respectively. He has been an Associate Professor in UAD, Yogyakarta, Indonesia since 2008. He is currently an Editor-in-Chief of the TELKOMNIKA and the Head of the Embedded Systems and Power Electronics Research Group (ESPERG). His research interests include the field of digital design, industrial applications, industrial electronics, industrial informatics, power electronics, motor drives, renewable energy, FPGA applications, embedded system, artificial intelligence, intelligent control, information technology and digital library. He can be contacted at email: tole@te.uad.ac.id, tole@ee.uad.ac.id.

Luthfiyyatun Mardiyah is a fresh graduate in Electrical Engineering Department at the Universitas Lampung, Lampung, Indonesia. She received her B.Eng. in 2022. Her research interests include power electronics, controller, and its applications. She can be contacted at email: luthfi.mardiah@gmail.com.