Design and Implementation of Takagi-Sugeno Fuzzy Tracking Control for a DC-DC Buck Converter

Dhaouadi GUIZA[1], *Youcef SOUFI*[2], *Djamel OUNNAS*[2], *Abderrezak METATLA*[1]

[1]Department of Mechanical Engineering, Faculty of Technology,
University of Skikda, 26 Route El Hadaiek. 21000 Skikda, Algeria.
[2]LABGET Laboratory, Department of Electrical Engineering, Faculty of Science and Technology,
University of Tebessa, Route de Constantine, 12002 Tebessa, Algeria

d.guiza@univ-tebessa.dz, y_soufi@yahoo.fr, djamel.ounnas@univ-tebessa.dz, metatla21_abderrezak@yahoo.fr

DOI: 10.15598/aeee.v17i3.3126

Abstract. *This paper presents the design and implementation of a Takagi-Sugeno (T-S) fuzzy controller for a DC-DC buck converter using Arduino board. The proposed fuzzy controller is able to pilot the states of the buck converter to track a reference model. The T-S fuzzy model is employed, firstly, to represent exactly the dynamics of the nonlinear buck converter system, and then the considered controller is designed on the basis of a concept called Virtual Desired Variables (VDVs). In this case, a two-stage design procedure is developed: i) determine the reference model according to the desired output voltage, ii) determine the fuzzy controller gains by solving a set of Linear Matrix Inequalities (LMIs). A digital implementation of the proposed T-S fuzzy controller is carried out using the ATmega328P-based Microcontroller of the Arduino Uno board. Simulations and experimental results demonstrate the validity and effectiveness of the proposed control scheme.*

Keywords

Arduino board, DC-DC buck converter, T-S fuzzy model.

1. Introduction

DC-DC buck converters are widely used in industrial and home environment (mobile phone, computers, and home appliances). Thanks to their increasingly high efficiency, together with a reduced size, weight and cost, they have held an important place in connections to storage batteries, photovoltaic systems, wind turbines, hybrid systems [1], [2], [3] and [4]. However, the control of a buck converter is still a challenging task because such a system exhibits a nonlinear behavior with inherent uncertainties and disturbances. Thus, the linear control schemes cannot ensure satisfactory performances over a wide operating range [5]. To address this problem, nonlinear and advanced control design methods have been proposed, such as linearization control [6] and [7], sliding mode [8] and [9], adaptive control [10] and [11], backstepping control approach [12] and exact linearization methods [13].

The simplicity of design and the robustness of the sliding mode controller have made it the most used one [14] and [15]. But, these advantages are neutralized by the presence of an undesirable phenomenon known as 'chattering' (oscillations having finite frequency and amplitude) which is considered as the main obstacle for implementation [16] and [17]. In [18] and [19] an adaptive backstepping controller is proposed for DC-DC buck converters. But it also suffers from difficulties and limitations during the implementation stage. In [20] and [21], a state feedback exact linearization method is applied to DC-DC buck converters. However, in [20], the effects of the different parasitic elements are not taken into account, while in [21] the developed controller cannot be used in a wide range of variation because of the excessive output voltage overshoot.

In the field of fuzzy logic, much research has devoted to the application of fuzzy Mamdani controllers to converters [22] and [23]. These works are typically based on a small signal model using the state space averaging method; the model obtained by these methods is only useful for small variations around a specific operating point, whereas the application of Takagi-Sugeno (T-S) fuzzy models on buck converters is not sufficiently investigated. The T-S fuzzy models owe their popularity to their effectiveness in modeling and controlling nonlinear systems [24] and [25]. The T-S fuzzy model represents a nonlinear system by a set of fuzzy If-Then rules, which locally represents the input-output relationships of a system expressing each conclusion with a linear subsystem. The advantage of this type of fuzzy model lies in the stability of the fuzzy system which can be analyzed using the Lyapunov method, and then treated in terms of the feasibility of a set of Linear Matrix Inequalities (LMIs). In this case, the problem can be solved easily by numerical convex optimization techniques [26].

Recently, the T-S fuzzy tracking control problem has been addressed in many works based on a concept knwon as Virtual Desired Variables (VDVs) to simplify the development of the control law and reference model [27], [28], [29], [30], [31] and [32]. Furthermore, the VDVs concept allows converting easily the tracking problem into a stabilization one. The concept has been analyzed in a number of studies using the Lyapunov approach and successfully investigated in many control applications. For example, in [28], it was employed to control a wind energy conversion system. In [29], it was employed to control a Permanent Magnet Synchronous Machine (PMSM) while in [30], the same concept was used to control a photovoltaic system. In [31], it was used to develop a fuzzy torque observer for PMSM and in [32], it was combined with H infinity performance to design a T-S fuzzy controller for a PMSM.

In this paper, the purpose is to develop a T-S fuzzy tracking controller for a buck converter based on the VDVs concept. In this case, the proposed controller can be used to drive the system to follow the desired reference. First, the nonlinear buck converter system is represented by a T-S fuzzy model. Then, a fuzzy controller is developed based on a set of virtual desired variables to simplify the design of the reference model and control law. Next, the tracking performance of the enhanced fuzzy system is analyzed by the Lyapunov method which can be formulated into LMIs problems. Simulation tests are performed on a buck converter to verify the controller's efficiency. Finally, the proposed controller is implemented on an ATmega328P-based microcontroller of Arduino Uno.

The remainder of this paper is composed as follows: the Sec. 2. is devoted to details on the mathematical buck converter model. In the Sec. 3. the proposed fuzzy control method is introduced. It consists of three main blocks: The first part deals with the T-S fuzzy controller, the second part is dedicated to stability analysis conditions and the third one deals with the determination of the desired reference model and the nonlinear tracking controller. The results of the simulation and practical implementation of the proposed controller are given in Sec. 4. and Sec. 5. followed by a conclusion at the end of this work.

2. Mathematical Buck Converter Model

The buck converter can be represented by the following nonlinear state space system form:

$$\begin{cases} \dot{x}(t) = f(x(t)) + g(x(t))u(t) + \eta \\ y(t) = \varphi(x(t)) \end{cases}, \tag{1}$$

$$x(t) = \begin{bmatrix} i_L(t) \\ v_o(t) \end{bmatrix}, \quad \eta = \begin{bmatrix} -\frac{V_D}{L} \\ 0 \end{bmatrix}, \tag{2}$$

$$f(x(t)) =$$
$$= \begin{bmatrix} -\frac{1}{L}\left(R_L + \frac{RR_C}{R+R_c}\right) i_L(t) - \frac{R}{L(R+R_C)} v_o(t) \\ \left(\frac{R}{C(R+R_C)}\right) i_L(t) - \left(\frac{1}{C(R+R_C)}\right) v_o(t) \end{bmatrix}, \tag{3}$$

$$g(x(t)) = \begin{bmatrix} \left(\frac{1}{L} V_{in} + V_D - R_M i_L(t)\right) u(t) \\ 0 \end{bmatrix}, \tag{4}$$

$$\varphi(x(t)) = \left(\frac{RR_C}{R+R_c}\right) i_L(t) + \left(\frac{R}{R+R_c}\right) v_o(t), \tag{5}$$

where R_M is the resistance of the transistor (MOSFET), R_L is the winding resistance of the inductor, V_D is the threshold voltage of the diode, R_C is the equivalent series resistance of the filter capacitor and V_{in} is the input voltage. i_L, v_o and u represent, respectively, the inductance current, the output voltage and the duty cycle of the buck converter, as shown in Fig. 1. It should be mentioned that the internal resistance R_m, the diode's forward voltage V_D, the equivalent series resistance of the filter capacitor R_C and the winding resistance of inductor R_L have not been taken into account in many previous researches, which can perturb the control of the buck converter system. Consequently, this paper considers a more general case.

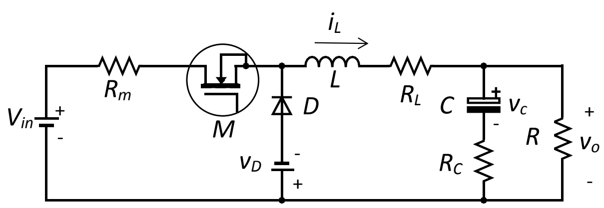


Fig. 1: Equivalent circuit of DC-DC buck converter.

3. Fuzzy Control Design

The goal of this paper is to develop a fuzzy controller that permits to pilot the states of a buck converter $x = \begin{bmatrix} i_L & v_o \end{bmatrix}^T$ to track a desired trajectory $x_d = \begin{bmatrix} i_{Ld} & v_{od} \end{bmatrix}^T$. Firstly, we design a fuzzy controller based on the T-S fuzzy model of a buck converter system and then develop a virtual reference model and nonlinear controller according to the desired output voltage. Thus, the fuzzy tracking control scheme shown in Fig. 2 is proposed.

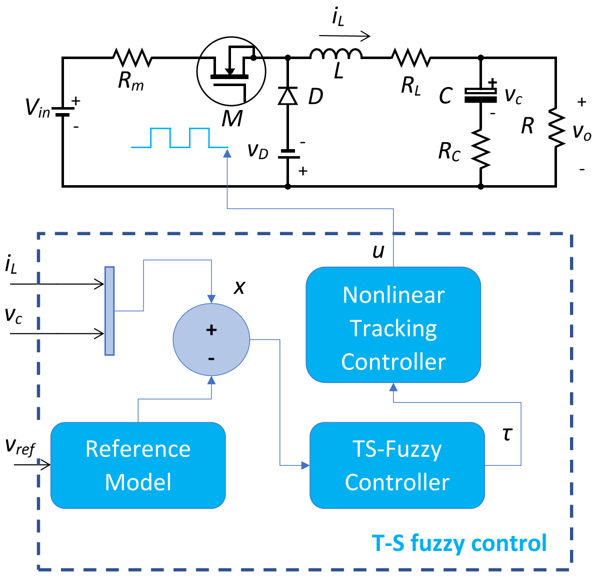


Fig. 2: Proposed fuzzy control scheme.

3.1. T-S Fuzzy Model of Buck Converter

The development of the proposed T-S fuzzy controller goes through the transformation of nonlinear model Eq. (1) into a fuzzy model by using the variable of the inductance current i_L as decision variable. The nonlinear state space of buck converter is given by the following form:

$$\begin{cases} \dot{x}(t) = Ax(t) + B(i_L)u(t) + E \\ y(t) = v_o = Cx(t)) \end{cases}, \tag{6}$$

where:

$$A = \begin{bmatrix} -\frac{1}{L}\left(R_L + \frac{RR_C}{R+R_c}\right) & -\frac{R}{L(R+R_C)} \\ \frac{R}{C(R+R_C)} & -\frac{1}{C(R+R_C)} \end{bmatrix}, \tag{7}$$

$$B(i_L) = \begin{bmatrix} \frac{1}{L}\left(V_{in} + V_D - R_M i_L(t)\right) \\ 0 \end{bmatrix}, \tag{8}$$

$$E = \begin{bmatrix} -\frac{V_D}{L} \\ 0 \end{bmatrix}, \quad C = \begin{bmatrix} \frac{RR_c}{R+R_C} & \frac{R}{R+R_C} \end{bmatrix}. \tag{9}$$

Assuming that the premiss variable $z(t) = i_L(t)$ is bounded as: $\underline{i}_L \leq i_L(t) \leq \bar{i}_L$ and using sector nonlinearity transformation [33], the nonlinear system Eq. (6) can be exactly represented by a T-S fuzzy model using the following two If-Then rules:

Rule1: If i_L is F_{11} Then $\dot{x}(t) = A_1 x(t) + B_1 u(t) + E_1$,
Rule2: If i_L is F_{12} Then $\dot{x}(t) = A_2 x(t) + B_2 u(t) + E_2$,

where F_{11} and F_{12} are the membership functions given by:

$$F_{11}(i_L) = \frac{i_L(t) - \underline{i}_L}{\bar{i}_L - \underline{i}_L}, \quad F_{12}(i_L) = 1 - F_{11}(i_L). \tag{10}$$

The sub-matrices are defined as:

$$A_1 = A_2 = \begin{bmatrix} -\frac{1}{L}\left(R_L + \frac{RR_C}{R+R_c}\right) & -\frac{R}{L(R+R_C)} \\ \frac{R}{C(R+R_C)} & -\frac{1}{C(R+R_C)} \end{bmatrix}, \tag{11}$$

$$B_1 = \begin{bmatrix} \frac{1}{L}\left(V_{in} + V_D - R_M \bar{i}_L\right) \\ 0 \end{bmatrix}, \tag{12}$$

$$B_2 = \begin{bmatrix} \frac{1}{L}\left(V_{in} + V_D - R_M \underline{i}_L\right) \\ 0 \end{bmatrix}, \quad E_1 = E_2 = \begin{bmatrix} -\frac{V_D}{L} \\ 0 \end{bmatrix}. \tag{13}$$

The final output of fuzzy model is inferred as follows:

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))\left(A_i x(t) + B_i u(t) + E\right), \tag{14}$$

where $h_i(z) = \omega_i(z)/\sum_{i=1}^{r}\omega_i(z)$, $\omega_i(z) = \prod_{j=1}^{n} F_{ij}(z_j)$ for all $t > 0$, $h_i(z) \geq 0$ and $\sum_{i=1}^{r} h_i(z) = 1$.

3.2. Control Design and Stability Analysis

The T-S fuzzy control is necessary to satisfy the following condition:

$$x(t) - x_d(t) \to 0 \quad as \quad t \to \infty, \tag{15}$$

where $x_d(t)$ represents the desired trajectory variable. Let us define the tracking error as $\tilde{x}(t) = x(t) - x_d(t)$. Then, its time derivative can be given by:

$$\dot{\tilde{x}}(t) = \dot{x}(t) - \dot{x}_d(t). \tag{16}$$

By substituting Eq. (14) into Eq. (16) and adding the term $\sum_{i=1}^{r} h_i(z)A_i(x_d(t) - x_d(t))$, Eq. (16) becomes:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} h_i(z)\left(A_i\tilde{x} + B_i u + A_i x_d(t) + E_i\right) - \dot{x}_d. \tag{17}$$

In Eq. (17), let us choose a new control variable $\tau(t)$ that satisfies the following condition:

$$\sum_{i=1}^{r} h_i B_i \tau = \sum_{i=1}^{r} h_i(z)\left(A_i x_d + B_i u + E\right) - \dot{x}_d. \tag{18}$$

By using Eq. (18), the tracking error derivative Eq. (17) can be rewritten as follows:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r} h_i(i_L(t))(A_i\tilde{x}(t) + B_i\tau(t)). \tag{19}$$

The new controllers are developed to deal with the fuzzy tracking control problem as:

Controller rule 1 : If $i_L(t)$ is F_{11} Then $\tau(t) = -K_1\tilde{x}(t)$,
Controller rule 2 : If $i_L(t)$ is F_{12} Then $\tau(t) = -K_2\tilde{x}(t)$.

The final fuzzy controller output is given by:

$$\tau(t) = -\sum_{i=1}^{r} h_i(z(t))K_i\tilde{x}(t). \quad (20)$$

By substituting Eq. (20) into Eq. (19), the final closed-loop system takes the following form:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t))h_j(z(t))(A_i - B_iK_j)\tilde{x}(t). \quad (21)$$

By letting $G_{ij} = (A_i - B_iK_j)$, Eq. (21) can be rewritten as follows:

$$\dot{\tilde{x}}(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} h_i(z(t))h_j(z(t))G_{ij}\tilde{x}(t). \quad (22)$$

Stability Analysis. Obtaining the fuzzy controller consists in determining the gains K_i satisfying the conditions of the following theorem [28] and [29]:

Theorem 1 *The continuous model Eq. (22) is asymptotically stable via the fuzzy controller Eq. (20), if there exists a diagonal matrix D, matrices Q_{ij} with: $Q_{ii} = Q_{ii}^T$ and $Q_{ji} = Q_{ij}^T$ for $i \neq j$, and a common positive definite matrix $P > 0$ such that:*

$$G_{ii}^TP + PG_{ii} + Q_{ii} + DPD < 0, \quad i = 1, ..., r, \quad (23)$$

$$\left(\frac{G_{ij}+G_{ji}}{2}\right)^T P + P\left(\frac{G_{ij}+G_{ji}}{2}\right) + Q_{ij} \leq 0, \quad i < j \leq r, \quad (24)$$

$$\begin{bmatrix} Q_{11} & Q_{12} & \dots & Q_{1r} \\ Q_{12} & Q_{22} & \dots & Q_{2r} \\ \vdots & \ddots & \vdots & \\ Q_{1r} & Q_{2r} & \dots & Q_{rr} \end{bmatrix} \equiv \tilde{Q} > 0, \quad (25)$$

for $i,\ j = 1,\dots,r$, s.t. the pairs $(i,\ j)$ such that: $h_i(z)h_j(z) = 0,\ \forall\ t$.

The determination of the fuzzy control gains requires changing the conditions of the previous theorem into an equivalent problem of linear matrix inequalities. This transformation corresponds to simple objective changes of variables $X = P^{-1}$, $K_i = M_iX^{-1}$ and the use of a congruence in inequalities Eq. (23), Eq. (24) and Eq. (25). Then, the following LMIs can be obtained.

$\exists\ X = X^T > 0, \exists\ Y_{ii} = Y_{ii}^T, \exists\ Y_{ij} = Y_{ji}^T, \exists\ M_i$:

$$\begin{bmatrix} XA_i^T + A_iX - B_iM_i - M_i^TB_i^T + Y_{ii} & XD^T \\ DX & -X \end{bmatrix} < 0, \quad (26)$$

$$XA_i^T + A_iX + XA_j^T + A_jX - B_iM_j - M_j^TB_i^T - B_jM_i - M_i^TB_j^T + 2Y_{ij} \leq 0, \quad i < i \leq r, \quad (27)$$

$$\begin{bmatrix} Y_{11} & Y_{12} & \dots & Y_{1r} \\ Y_{12} & Y_{22} & \dots & Y_{2r} \\ \vdots & \ddots & \vdots & \\ Y_{1r} & Y_{2r} & \dots & Y_{rr} \end{bmatrix} \equiv \tilde{Y} > 0. \quad (28)$$

3.3. Desired Reference Model and Nonlinear Controller

In order to determine the desired reference model x_d and nonlinear controller $u(t)$, we use Eq. (18) which can be rewritten as follows:

$$\sum_{i=1}^{r} h_iB_i(u-\tau) = -\sum_{i=1}^{r} h_iA_ix_d - \sum_{i=1}^{r} h_iE + \dot{x}_d. \quad (29)$$

Noting that:

$$A = \sum_{i=1}^{r} h_iA_i, \quad B = \sum_{i=1}^{r} h_iB_i, \quad E = \sum_{i=1}^{r} h_iE_i. \quad (30)$$

Then, Eq. (29) can be rewritten in the following form:

$$B(u(t) - \tau(t)) = -Ax_d(t) - E + \dot{x}_d(t). \quad (31)$$

Eq. (31) can be rewritten as follows:

$$\begin{bmatrix} \frac{1}{L}[V_{in} + V_D + R_Mi_L(t)] \\ 0 \end{bmatrix}(u(t) - \tau(t)) = = -\begin{bmatrix} \frac{1}{L}[R_L + \frac{RR_C}{R+R_c}] & -\frac{R}{L(R+R_C)} \\ \frac{R}{C(R+R_C)} & -\frac{1}{C(R+R_C)} \end{bmatrix}\begin{bmatrix} i_{Ld} \\ v_{cd} \end{bmatrix} + -\begin{bmatrix} -\frac{V_D}{L} \\ 0 \end{bmatrix} + \begin{bmatrix} \dot{i}_{Ld} \\ \dot{v}_{cd} \end{bmatrix}. \quad (32)$$

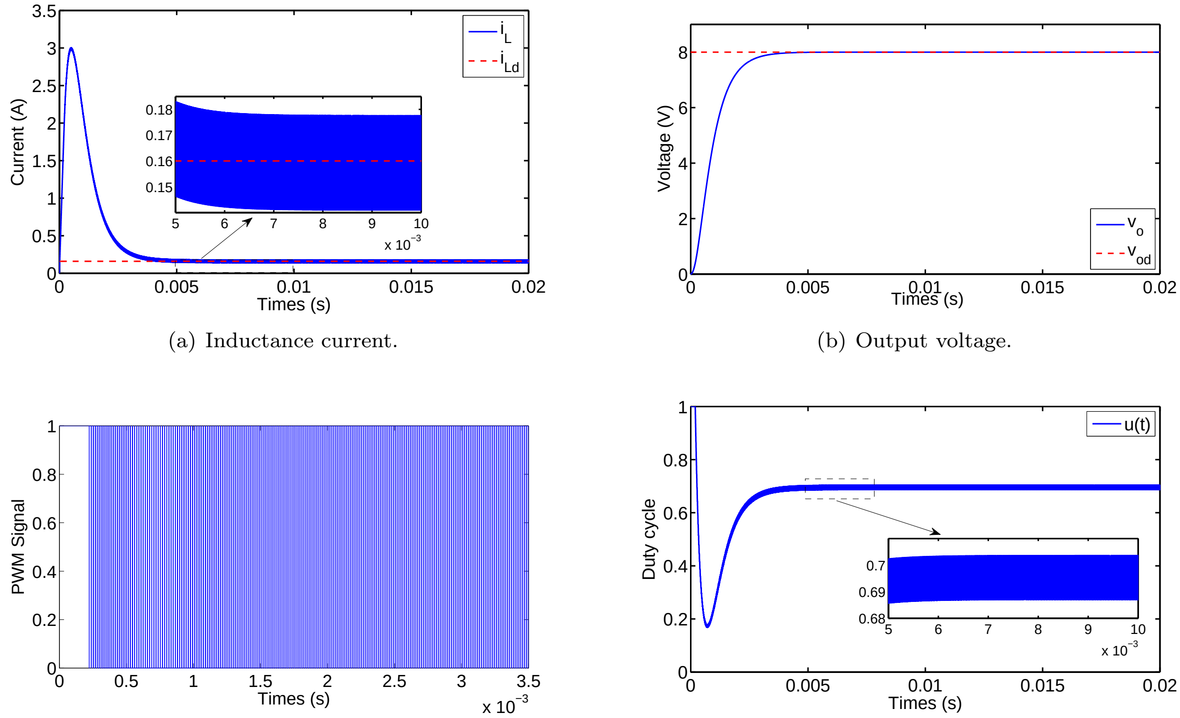
It should be mentioned that the nonlinear control law and the desired reference model will be calculated according to the desired output voltage.

From the second equation of Eq. 32, we obtain

$$-\frac{R}{C(R+R_C)}x_{1d} + \frac{1}{C(R+R_C)}x_{2d} = 0 \Rightarrow x_{1d} = \frac{x_{2d}}{R}. \quad (33)$$

From the first equation of Eq. 32, we can derive the nonlinear control law $u(t)$, as follows:

$$u(t) = \frac{(\frac{R_L}{R} + \frac{R_C}{R+R_C} + \frac{R}{R+R_C})x_{2d} + V_D}{V_{in} + V_D + R_Mi_L(t)}. \quad (34)$$



(a) Inductance current. (b) Output voltage.

(c) PWM signal. (d) Duty ratio.

Fig. 3: Simulation results for voltage reference $v_{od} = 8$ V.

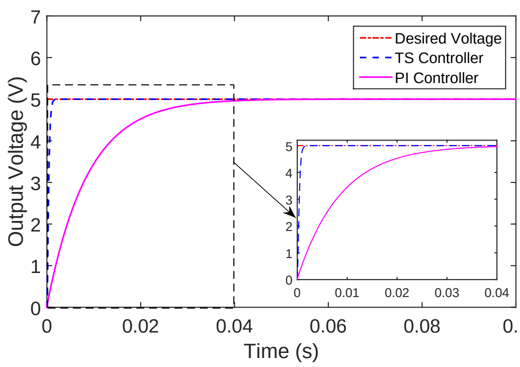


Fig. 4: Comparison between PI and T-S fuzzy controllers.

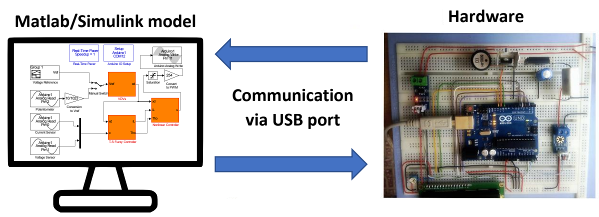


Fig. 5: Communication with an Arduino board using Matlab input/output package.

Tab. 1: Performances comparison between PI and T-S controllers.

Method	PI controller	T-S controller
Rise time (s)	0.0187	$6.6211 \cdot 10^{-4}$
Settling time (s)	0.0327	0.0012
Overshoot (%)	0.0264	0

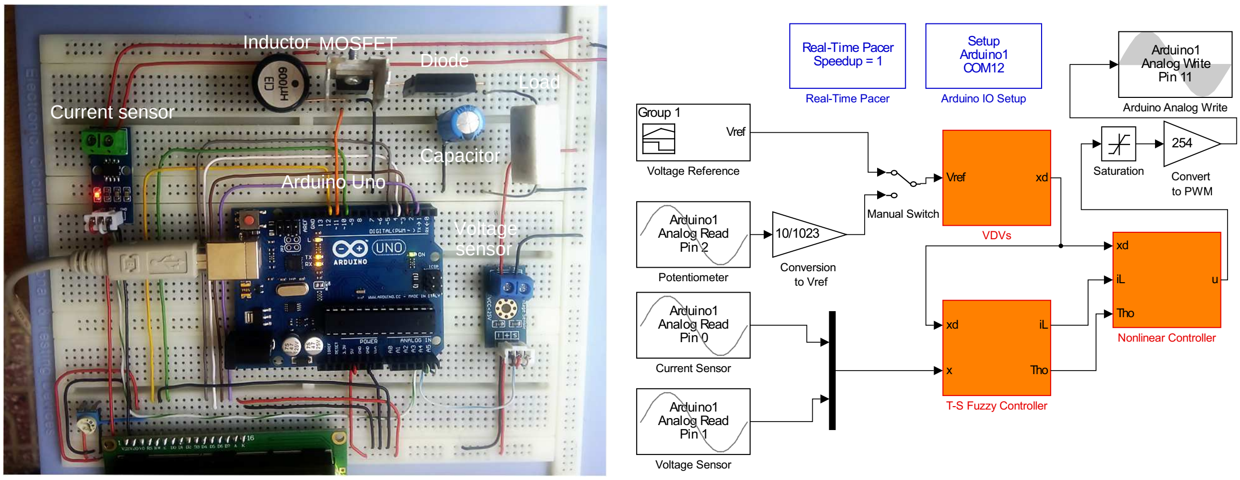
4. Simulation Results

In order to verify the performance of the proposed fuzzy tracking control, simulation test was carried out on a DC-DC buck converter. The controller gains are obtained by solving the LMIs Eq. (26), Eq. (27) and Eq. (28), as follows:

$$K_1 = \begin{bmatrix} 0.4829 & 0.1582 \end{bmatrix}, \quad (35)$$

$$K_2 = \begin{bmatrix} 0.4537 & 0.1345 \end{bmatrix}. \quad (36)$$

The first simulation is carried out in output voltage reference $v_{od} = 8$ V. The responses of the inductance current, output voltage, PWM signal and duty cycle are depicted in Fig. 3(a), Fig. 3(b), Fig. 3(c) and Fig. 3(d), respectively. The results indicate that the steady states track the desired trajectories perfectly. It is also shown that the time response required to follow the reference model is very short (0.0012 s). It can be concluded that the proposed T-S fuzzy control has a good tracking performance. In the second simulation test, the T-S fuzzy controller is compared with the base-line PI (Proportional Integrator) controller due to its popularity. The PI parameters (K_p and K_i) are calculated based on the following buck transfer function



(a) Hardware setup. (b) Simulink model using Matlab input/output package.

Fig. 6: Hardware implementation using Arduino Uno and Simulink model.

[36] and [37]:

$$G(s) = \frac{V_o}{u} = V_{in}\left(\frac{R}{R+R_L}\right)\left(\frac{\frac{s}{\omega_{ZERO}}+1}{\Omega(s)}\right), \quad (37)$$

where

$$\Omega(s) = \frac{s^2}{\omega_0^2} + \frac{s}{Q\omega_0} + 1, \quad (38)$$

$$\omega_0 = \frac{1}{\sqrt{LC\frac{R+R_c}{R+R_L}}}, \quad \omega_{ZERO} = \frac{1}{CR_c}, \quad (39)$$

$$Q = \frac{1}{\omega_0\left(\frac{L}{R+R_L} + \frac{RR_LC}{R+R_L} + R_cC\right)}. \quad (40)$$

The PI parameters (K_p and K_i) are obtained by using the known compensation method, as follows:

$$K_p = 0.195, \quad K_i = 9.88. \quad (41)$$

The response of the output voltage for $v_{od} = 5$ V rise time, the settling time and the overshoot for the two methods.

From Fig. 4 and Tab. 1, it can be confirmed that the T-S controller offers superior performance and fast dynamic response in terms of rapidity and limitation of overshoot.

5. Experimental Verification

To verify the simulation results, a special package known as input/output (I/O) support package is used with Matlab environment, which has been designed by MathWorks for microcontroller-based Arduino board to interface the Matlab/ Simulink with the hardware setup without any programming language [34]. This package is primarily used for real-time communication between Arduino board and Simulink, as shown in Fig. 5. The hardware consists of a buck converter, an Arduino Uno, a voltage sensor and a current sensor. The hardware and Simulink model used in this implementation stage are shown in Fig. 6(a) and Fig. 6(b), respectively. Note that the parameters given in Appendix A are considered for the development of a buck converter prototype.

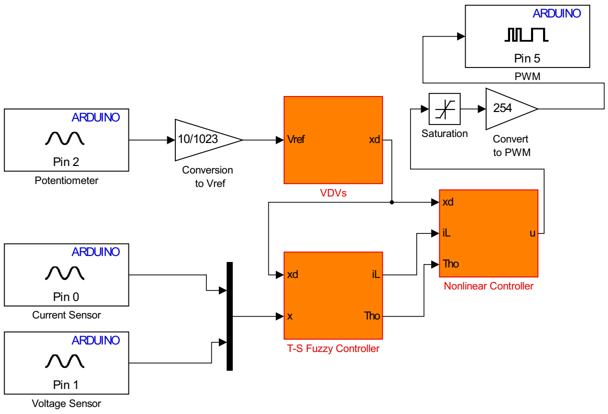
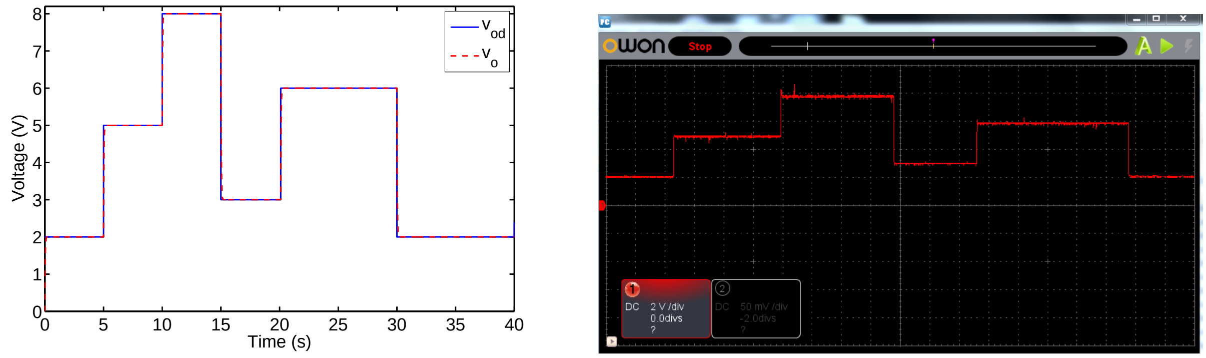


Fig. 7: Simulink model using Matlab support package.

The experiment is conducted with a multi-step voltage reference. The experimental waveform and simulation response of output voltage are illustrated in Fig. 8(a) and Fig. 8(b). It is obvious that the obtained results in both the simulation and the implementation are in good agreement.

After the previous verification and validation of the simulation results, the proposed system should be created as a standalone project that does not need to be



(a) Simulation results of output voltage. (b) Experimental waveform of output voltage.

Fig. 8: Simulation and experimental results for multi-step voltage reference.

connected to the Simulink (host computer) [35]. In this respect, it is necessary to deploy the proposed tracking control algorithm to the Arduino board. To achieve this, an Arduino support package is used, as shown in Fig. 7. The experimental waveforms of the output voltage and the duty cycle for a reference voltage $v_{od} = 5$ V are shown in Fig. 9.

These practical results demonstrate that buck converter can be controlled by the proposed method to flow exactly the desired output voltage.

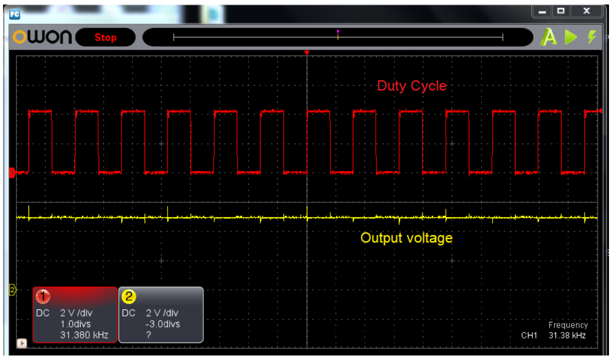


Fig. 9: Experimental results for desired voltage $v_{od} = 5$ V.

6. Conclusion

A T-S fuzzy tracking controller is proposed for a DC-DC buck converter which is able to pilot the system to follow a desired reference model. The controller gains are obtained based on sufficient conditions formulated into LMIs form and solved using optimization tools. Experimental and simulation results show that the buck converter can be controlled effectively at different operating regions by the proposed method and can overcome the limitations of classical controllers.

References

[1] OUNIS, F. and N. GOLEA. PID, 2-DOF PID and Mixed Sensitivity Loop-Shaping Based Robust Voltage Control of Quadratic Buck DC-DC Converter. *Advances in Electrical and Electronic Engineering*. 2016, vol. 14, iss. 6, pp. 551–561. ISSN 1804-3119. DOI: 10.15598/aeee.v14i5.1821.

[2] SIVAKUMAR, S., M. J. SATHIK, P. S. MANOJ and G. SUNDARARAJAN. An assessment on performance of DC–DC converters for renewable energy applications. *Renewable and Sustainable Energy Reviews*. 2016, vol. 58, iss. 1, pp. 1475–1485. ISSN 2278–9472. DOI: 10.1016/j.rser.2015.12.057.

[3] OVAHED, A. M., H. T. SHANDIZ and S. K. HOSSEINI SANI. Comparison of Fractional Order Modelling and Integer Order Modelling of Fractional Order Buck Converter in Continuous Condition Mode Operation. *Advances in Electrical and Electronic Engineering*. 2016, vol. 14, iss. 5, pp. 531–542. ISSN 1804-3119. DOI: 10.15598/aeee.v14i5.1635.

[4] WANG, L., M. ZHAO, X. WU, X. GONG and L. YANG. Fully integrated high-efficiency high step-down ratio DC–DC buck converter with predictive over-current protection scheme. *IET Power Electronics*. 2017, vol. 10, iss. 14, pp. 1959–1965. ISSN 1755-4535. DOI: 10.1049/iet-pel.2017.0087.

[5] AL-BAIDHANI, H. and M. K. KAZIMIERCZUK. Nonlinear modeling and PWM-based sliding-mode control of DC-DC buck converter for CCM. In: *Energy Society Innovative Smart Grid Technologies Conference*. Washington: IEEE, 2018, pp. 1–5. ISBN 978-1-5386-2453-1. DOI: 10.1109/ISGT.2018.8403392.

[6] LINARES-FLORES, J., J. L. BARAHONA-AVALOS, H. SIRA-RAMIREZ and M. A. CONTRERAS-ORDAZ. Robust passivity-based control of a Buck-Boost-converter/DC-motor system: An active disturbance rejection approach. *IEEE Transactions on Industry Applications*. 2014, vol. 48, iss. 6, pp. 2362–2371. ISSN 1939-9367.

[7] SON, Y. I. and I. H. KIM. Complementary PID controller to passivity-based nonlinear control of boost converters with inductor resistance. *IEEE Transactions on control systems technology*. 2012, vol. 20, iss. 3, pp. 826–834. ISSN 1558-0865. DOI: 10.1109/TCST.2011.2134099.

[8] ALSMADI, Y. M., V. UTKIN, M. A. HAJ-AHMED and L. XU. Sliding mode control of power converters: DC/DC converters. *International Journal of Control*. 2017, vol. 90, iss. 1, pp. 1–22. ISSN 0020-7179. DOI: 10.1080/00207179.2017.1306112.

[9] PANDEY, S. K., S. L. PATIL and S. B. PHADKE. Comment on PWM-Based Adaptive Sliding-Mode Control for Boost DC–DC Converters. *IEEE Transactions on Industrial Electronics*. 2018, vol. 65, iss. 6, pp. 5078–5080. ISSN 1557-9948. DOI: 10.1109/TIE.2017.2764872.

[10] LINARES-FLORES, J., A. HERNANDEZ MENDEZ, C. GARCIA-RODRIGUEZ and H. SIRA-RAMIREZ. Robust Nonlinear Adaptive Control of a "Boost" Converter via Algebraic Parameter Identification. *IEEE Transactions on Industrial Electronics*. 2014, vol. 61, iss. 8, pp. 4105–4114. ISSN 1557-9948. DOI: 10.1109/TIE.2013.2284150.

[11] OUCHERIAH, S. and L. GUO. PWM-Based Adaptive Sliding-Mode Control for Boost DC–DC Converters. *IEEE Transactions on Industrial Electronics*. 2013, vol. 60, iss. 8, pp. 3291–3294. ISSN 1557-9948. DOI: 10.1109/TIE.2012.2203769.

[12] NIZAMI, T. K. and C. MAHANTA. An intelligent adaptive control of DC–DC buck converters. *Journal of the Franklin Institute*. 2016, vol. 335, iss. 12, pp. 2588–2613. ISSN 0016-0032. DOI: 10.1016/j.jfranklin.2016.04.008.

[13] MERABET, A., L. LABIB, A. M. GHIAS, C. GHENAI and T. SALAMEH. Robust Feedback Linearizing Control With Sliding Mode Compensation for a Grid-Connected Photovoltaic Inverter System Under Unbalanced Grid Voltages. *IEEE Journal of Photovoltaics*. 2017, vol. 7, iss. 3, pp. 1473–1482. ISSN 2156-3403. DOI: 10.1109/JPHOTOV.2017.2667724.

[14] SALIMI, M., A. ZAKIPOUR, N. R. ABJADI and J. SOLTANI. Hyper-plane sliding mode control of the DC–DC buck/boost converter in continuous and discontinuous conduction modes of operation. *ET Power Electronics*. 2015, vol. 8, iss. 8, pp. 3291–3294. ISSN 1755-4543. DOI: 10.1049/iet-pel.2014.0578.

[15] AL-BAIDHANI, H. and M. K. KAZIMIERCZUK. PWM-based proportional-integral sliding-mode current control of DC-DC boost converter. In: *IEEE Texas Power and Energy Conference*. College Station: IEEE, 2018, pp. 1–6. ISBN 978-1-5386-1006-0. DOI: 10.1109/TPEC.2018.8312062.

[16] CHEN, Z. PI and Sliding Mode Control of a Cuk Converter. *IEEE Transactions on Power Electronics*. 2012, vol. 27, iss. 8, pp. 3635–3703. ISSN 1941-0107. DOI: 10.1109/TPEL.2012.2183891.

[17] WANG, B., G. MA, D. XU, L. ZHANG and J. ZHOU. Switching sliding-mode control strategy based on multi-type restrictive condition for voltage control of buck converter in auxiliary energy source. *Applied Energy*. 2018, vol. 228, iss. 1, pp. 1373–1384. ISSN 0306-2619. DOI: 10.1016/j.apenergy.2018.06.141.

[18] NIZAMI, T. K., A. CHAKRAVARTY and C. MAHANTA. Analysis and experimental investigation into a finite time current observer based adaptive backstepping control of buck converters. *Journal of the Franklin Institute*. 2018, vol. 335, iss. 12, pp. 4996–5017. ISSN 1941-0107. DOI: 10.1016/j.jfranklin.2018.05.026.

[19] ROZALI, S. M., N. S. FARHANA, M. N. KAMARUDIN, A. F. Z. ABIDIN, M. F. RAHMAT and C. C. SOON. Robust Control Design of Nonlinear System via Backstepping-PSO with Sliding Mode Techniques. In: *17th Asia Simulation Conference*. Melaka: IEEE, 2017, pp. 27–37. ISBN 978-981-10-6463-0. DOI: 10.1007/978-981-10-6463-0_3.

[20] FANG, Z., J. WANG, S. DUAN, K. LIU and T. CAI. Control of an LLC Resonant Converter Using Load Feedback Linearization. *IEEE Transactions on Power Electronics*. 2018, vol. 33, iss. 1, pp. 887–898. ISSN 0885-8993. DOI: 10.1109/TPEL.2017.2672731.

[21] SHUAI, D., Y. XIE and X. WANG. Optimal control of Buck converter by state feedback linearization. In: *7th World Congress on Intelligent Control and Automation*. Chongqing: IEEE, 2008, pp. 2265–2270. ISBN 978-1-4244-2114-5. DOI: 10.1109/WCICA.2008.4593275.

[22] FERNANDEZ, M. Z. R., R. L. A. MALABANAN, M. J. M. PIZON, J. J. A. QUIATCHON, J. M. SERRANO and L. XU. Design and Development of Fuzzy Logic Algorithm with Varying Setpoints for Fan Speed Control System Using Arduino Microcontroller. *LPU-Laguna Journal of Engineering and Computer Studies*. 2015, vol. 3, iss. 1, pp. 70–84. ISSN 2467-5172.

[23] GUESMI, K., A. HAMZAOUI and J. ZAYTOON. Control of nonlinear phenomena in DC–DC converters: Fuzzy logic approach. *International Journal of Circuit Theory and Applications*. 2008, vol. 36, iss. 7, pp. 857–874. ISSN 1097-007X. DOI: 10.1002/cta.468.

[24] RAM, J. P., T. S. BABU and N. RAJASEKAR. A comprehensive review on solar PV maximum power point tracking techniques. *Renewable and Sustainable Energy Reviews*. 2017, vol. 67, iss. 1, pp. 826–847. ISSN 1364-0321. DOI: 10.1016/j.rser.2016.09.076.

[25] RAM, J. P., T. S. BABU, N. RAJASEKAR, M. RAKHSHAN, N. VAFAMAND, M. KHOOBAN and F. BLAABJERG. Maximum Power Point Tracking Control of Photovoltaic Systems: A Polynomial Fuzzy Model-Based Approach. *IEEE Journal of Emerging and Selected Topics in Power Electronics*. 2018, vol. 6, iss. 1, pp. 292–299. ISSN 2168-6785. DOI: 10.1109/JESTPE.2017.2708815.

[26] TANAKA, K. and O. W. HUA. *Fuzzy control systems design and analysis: a linear matrix inequality approach*. 1st ed. New York: John Wiley & Sons, 2004. ISBN 978-0-4713-2324-2.

[27] LIAN, K. Y. and J. LIOU. Output Tracking Control for Fuzzy Systems via Output Feedback Design. *IEEE Transactions on Fuzzy Systems*. 2006, vol. 14, iss. 5, pp. 628–639. ISSN 1941-0034. DOI: 10.1109/TFUZZ.2006.876725

[28] OUNNAS, D., M. RAMDANI, S. CHENIKHER and T. BOUKTIR. Optimal Reference Model Based Fuzzy Tracking Control for Wind Energy Conversion System. *International Journal of Renewable Energy Research*. 2016, vol. 6, no. 3, pp. 1129–1136. ISSN 1309-0127.

[29] LIAN, K. Y., C. H. CHIANG and H. W. TU. LMI-Based Sensorless Control of Permanent-Magnet Synchronous Motors. *IEEE Transactions on Industrial Electronics*. 2007, vol. 54, iss. 5, pp. 2769–2777. ISSN 0278-0046. DOI: 10.1109/TIE.2007.899829.

[30] OUNNAS, D., M. RAMDANI, S. CHENIKHER and T. BOUKTIR. An Efficient Maximum Power Point Tracking Controller for Photovoltaic Systems Using Takagi–Sugeno Fuzzy Models. *Arabian Journal for Science and Engineering*. 2017, vol. 42, iss. 12, pp. 4971–4982. ISSN 2191-4281. DOI: 10.1007/s13369-017-2532-0.

[31] JUNG, J. W., T. H. KIM and H. H. CHOI. Speed control of a permanent magnet synchronous motor with a torque observer: a fuzzy approach. *IET control theory and applications*. 2010, vol. 4, iss. 12, pp. 2971–2981. ISSN 1751-8652. DOI: 10.1049/iet-cta.2009.0469.

[32] OUNNAS, D., M. RAMDANI, S. CHENIKHER and T. BOUKTIR. A Combined Methodology of H Fuzzy Tracking Control and Virtual Reference Model for a PMSM. *Advances in Electrical and Electronic Engineering*. 2015, vol. 13, iss. 3, pp. 212–222. ISSN 1804-3119. DOI: 10.15598/aeee.v13i3.1331.

[33] OHTAKE, H., K. TANAKA and H. O. WANG. Fuzzy Modeling via Sector Nonlinearity Concept. *Integrated Computer-Aided Engineering*. 2003, vol. 10, no. 4, pp. 333–341. ISSN 1875-8835. DOI: 10.3233/ICA-2003-10404.

[34] BARBER, R., M. HORRA and J. CRESPO. Control Practices using Simulink with Arduino as Low Cost Hardware. *IFAC Proceedings*. 2013, vol. 46, iss. 17, pp. 250–255. ISSN 2405-8963. DOI: 10.3182/20130828-3-UK-2039.00057.

[35] TEIKARI, P., R. P. NAJJAR, H. MALKKI, K. KNOBLAUCH, D. DUMORTIER, C. GRONFIER and H. M. COOPER. An inexpensive Arduino-based LED stimulator system for vision research. *Journal of neuroscience methods*. 2012, vol. 211, iss. 2, pp. 227–236. ISSN 0165-0270. DOI: 10.1016/j.jneumeth.2012.09.012.

[36] ABBAS, G., J. GU, U. FAROOQ, M. ABID, A. RAZA, M. ASAD, V. BALAS and M. BALAS. Optimized Digital Controllers for Switching-Mode DC-DC Step-Down Converter. *Electronics*. 2018, vol. 7, iss. 12, pp. 1–25. ISSN 2079-9292. DOI: 10.3390/electronics7120412.

[37] TIAN, S., F. C. LEE, Q. LI and Y. YAN. Unified Equivalent Circuit Model and Optimal Design of V^2 Controlled Buck Converters. *IEEE Transactions on Power Electronics*. 2016, vol. 31, iss. 2, pp. 1734–1744. ISSN 1941-0107. DOI: 10.1109/TPEL.2015.2424913.

About Authors

Dhaouadi GUIZA was born in Tebessa, Algeria. He received a B.Sc. degree in Elecrtonics from

Skikda University, Algeria in 2001, Magister degree in electronic components and system from Constantine University, Algeria in 2009. He is currently a research fellow and Ph.D. candidate at Skikda Universitiy (Algeria). His research interests include fuzzy control of electrical drives, energy conversion and power control, practical electronics and Drives.

Youcef SOUFI was born in Tebessa, Algeria. He received a B.Sc. degree and Doctorate degrees from the University of Annaba, Algeria, in 1991 and 2012 respectively. and a Magister degree in 1997 in Electrical Engineering from Tebessa University, Algeria. Currently, he is a Professor in the department of Electrical Engineering, Faculty of Sciences and Technology, Larbi Tebessi University, Tebessa, Algeria. His research interests include electrical machines, diagnostics, wind and solar energy, power electronics and drives applied to renewable and sustainable energy.

Djamel OUNNAS was born in Tebessa, Algeria. He received a B.Sc. degree in electronic from Tebessa University, Algeria in 2007, Magister degree in automatic from Biskra University in 2011. He graduated with Ph.D. degree in Automatic from Setif University, Algeria in 2017. Currently he is a Professor in the department of Electrical Engineering, Faculty of Sciences and Technology, Larbi Tebessi University, Tebessa, Algeria. His research interests include fault detection and diagnosis in industrial systems, fuzzy control of electrical drives, energy conversion and power control.

Abderrezak METATLA received the Engineer, Magister and Ph.D. degrees in electromechanical engineering from Badji Mokhtar University in Annaba, Algeria in 2004, 2009. Since 2004, he has been in the Electromechanical Department of Skikda University, Algeria where he is currently a Professor of electrical engineering. His main research fields include electrical machines, control systems and renewable energy.

Appendix A
Buck Converter Parameters

Circuit parameters	Value
MOSFET resistance R_m	0.1 Ω
Threshold voltage of the diode V_D	0.8 V
Output capacitor C	270 µF
Output capacitor resistance R_c	0.18 Ω
Inductor L	600 µH
Winding resistance of inductor R_L	0.1 Ω
Resistance load R	30 Ω
Input voltage V_{in}	10 V
Switching frequency f_s	31.38 kHz