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Design and control of a DC-DC buck converter using discrete Takagi-Sugeno fuzzy models

Introduction. *A DC-DC buck converter plays a crucial role in industrial applications by efficiently stepping down voltage levels to power various electronic components and systems. However, controlling a buck converter is challenging due to its inherently nonlinear behavior. This paper presents a novel fuzzy tracking control approach for the buck converter, based on the combination of time-discrete Takagi-Sugeno (T-S) fuzzy models and the concept of virtual desired variables (VDVs).* ***Originality****. This paper introduces an innovative fuzzy tracking control that integrates time-discrete T-S models and VDVs concept to develop an efficient digital controller.* ***Goal.*** *The proposed fuzzy control strategy aims to regulate the output voltage regardless of sudden change in setpoint, load variation and change in input voltage.* ***Methodology****. The proposed control strategy aims to regulate the output voltage of a DC-DC buck converter. The design starts with a discrete T-S fuzzy controller based on the nonlinear model of the buck converter. A nonlinear tracking controller is developed using a virtual reference model that incorporates the VDVs concept. System stability is analyzed via Lyapunov's method and expressed through linear matrix inequalities.* ***Results****. Simulation tests under varying conditions validate the accuracy and effectiveness of the controller in achieving superior voltage tracking performance. Comparative analysis with a conventional PID controller highlights faster dynamic response and better tracking, showcasing the advantages of the proposed approach.* ***Practical value****. The practical value of this research lies in the development of a robust voltage control strategy for DC-DC buck converters and the establishment of reliable and efficient electrical systems using discrete-time fuzzy T-S control. This work also opens up the prospect for future implementation in experimental prototypes.* References 30, table 2, figures 7.

Key words: **discrete-time Takagi–Sugeno fuzzy models, DC-DC buck converter, linear matrix inequalities.**

Вступ*. Понижуючий DC-DC перетворювач відіграє важливу роль у промисловості, ефективно знижуючи рівні напруги живлення різних електронних компонентів і систем. Однак управління понижуючим перетворювачем є складним завданням через його початковий нелінійний характер. У статті представлено новий підхід до управління нечітким відстеженням для понижуючого перетворювача, заснований на поєднанні дискретних за часом нечітких моделей Такагі-Сугено (T-S) та концепції бажаних віртуальних змінних (VDV).* ***Оригінальність****. У статті наведено інноваційний підхід до управління нечітким відстеженням, який поєднує дискретні за часом моделі T-S та концепцію VDV для розробки ефективного цифрового контролера.* ***Мета****. Запропонована стратегія нечіткого управління спрямована на регулювання вихідної напруги незалежно від раптової зміни уставки, зміни навантаження та зміни вхідної напруги.* ***Методологія****. Запропонована стратегія управління спрямована на регулювання вихідної напруги понижуючого DC-DC перетворювача. Проєктування починається з дискретного нечіткого контролера T-S на основі нелінійної моделі знижувального перетворювача. Нелінійний контролер відстеження розроблено з використанням віртуальної еталонної моделі, що включає концепцію VDV. Стійкість системи аналізується за допомогою методу Ляпунова та виражається через лінійні матричні нерівності.* ***Результати****. Тести моделювання в різних умовах підтверджують точність та ефективність контролера у досягненні високої продуктивності відстеження напруги. Порівняльний аналіз із традиційним PID-регулятором підкреслює швидшу динамічну реакцію та краще відстеження, демонструючи переваги запропонованого підходу.* ***Практична цінність*** *цього дослідження полягає у розробці надійної стратегії управління напругою для понижуючих DC-DC перетворювачів та створення надійних та ефективних електричних систем з використанням дискретного часу нечіткого управління T-S. Ця робота також відкриває перспективи майбутньої реалізації у експериментальних прототипах.* Бібл. 30, табл. 2, рис. 7.

Ключові слова: **дискретні нечіткі моделі Takagi–Sugeno, понижуючий DC-DC перетворювач, лінійні матричні нерівності.**

Introduction. A DC-DC buck converter is an electrical device designed to reduce a DC voltage level to a lower one. It plays a crucial role in contemporary electronics, facilitating effective power control and voltage regulation in many applications. Because of its user-friendly nature, exceptional effectiveness, and adaptability, as well as its ability to work independently and interact harmoniously with energy storage and renewable energy systems, it is used in a diverse array of fields, such as providing power for industrial and residential settings [1–5].

The DC-DC buck converter exhibits considerable nonlinearity and varies structurally throughout each switching period. These characteristics can pose challenges when designing the controller, rendering conventional linear control approaches such as P, PI and PID inadequate for ensuring satisfactory performance across a broad operational spectrum [6, 7]. To tackle this problem, several advanced nonlinear control design strategies have been suggested.

The authors in [8] suggest an active damping method to provide a virtual resistance, thereby modulating the buck converter's output voltage. Active damping offers system stability and results without further power loss, but it comes at the cost of lower output voltage. In [9], a nonlinear feedback linearization technique is introduced to control the buck converter's output voltage of a system that provides power to a constant load. This strong controller does not require a disturbance sensor. However, this approach has disadvantages, such as low precision and slow processing speed. The sliding mode controller's design simplicity and adaptability have established it as the most widely utilized controller [10] and [11]. Nevertheless, the benefits of these improvements are counteracted by an undesired occurrence referred to as «chattering», which involves oscillations with a specific frequency and amplitude. This phenomenon is widely recognized as the primary hindrance to achieving real-time implementation [12, 13].

The use of fuzzy logic control solved the shortcomings of the previous methods [14–17]. Nevertheless, this method sometimes lacks precision because it heavily depends on assumptions. Creating fuzzy rules and membership functions presents a tough task [18]. The authors in [19, 20] describe developing and implementing a robust fuzzy logic control for a DC-DC buck converter. This controller is designed to utilize measurements of the inductor current and output voltage but requires an additional sensor, which inevitably increases the cost and reduces the system's reliability. Several methods were proposed to address this problem based on Takagi-Sugeno (T-S) fuzzy models [21, 22].

T-S fuzzy model employs a collection of fuzzy rules to represent a nonlinear system by utilizing a series of local linear models seamlessly linked together by fuzzy membership functions. T-S fuzzy model has gained significant popularity due to its utilization of an affine dynamic model in its consequence section instead of a fuzzy set. It possesses the subsequent benefits:

1) Numerous established robust tools, such as the Lyapunov's method, can be employed for stability analysis and controller synthesis;

2) T-S fuzzy model is less affected by the problem of high dimensionality compared to other fuzzy models;

3) The structure of the model and the properties of local models can be readily linked to the physical characteristics of the system [23–25].

The accuracy of the mathematical model is crucial for designing a robust controller for the DC-DC buck converter. Thus, accurate modelling of switching DC-DC converters is needed to predict stability and design a suitable controller with enhanced stability and performance. There is currently a revived interest in discrete-time analysis and modeling to aid the implementation of practical digital control for high-frequency DC-DC converters on microcontroller boards. This is driven by the desire to eliminate delay effects in averaged models.

Goal. This paper deals with the design of a new controller for a buck converter system using T-S fuzzy models. The proposed fuzzy control strategy aims to regulate the output voltage, despite changes in reference voltage, load variations, and changes in input voltage. Many simulation tests were conducted under various load and input voltage situations to validate the precision and efficiency of the suggested controller in operating the DC-DC buck converter to drive the desired reference voltage.

Developed fuzzy control scheme. The objective of this work is to construct a T-S fuzzy controller capable of efficiently controlling buck converter states $x = [i_L\ v_o]^T$ to track a specific trajectory $x = [i_{Ld}\ v_{od}]^T$. At first, we construct a digital fuzzy controller utilizing the discrete-time T-S fuzzy model of a buck converter system. Afterward, we create a virtual reference model and a nonlinear controller that drives the considered system to track the desired voltage. The proposed control scheme is illustrated in Fig 1.

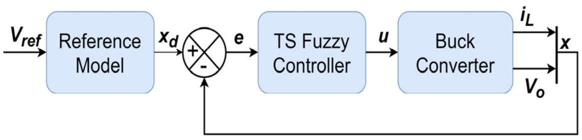


Fig. 1. Proposed fuzzy tracking control scheme

Nonlinear state space system model. Figure 2 depicts the buck converter's schematic, illustrating the components such as the input voltage V_{in}, electronic switch (MOSFET), diode D, capacitor C, load resistor R and inductor L.

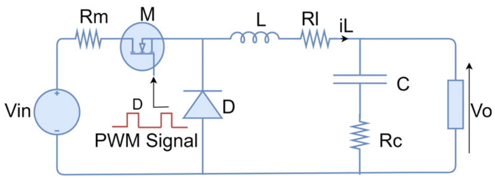


Fig. 2. Schematic representation of a DC-DC buck converter

To represent the buck converter, we use the nonlinear state space system form shown below [21]:

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

where

$$x(t) = \begin{bmatrix} i_L(t) \\ v_o(t) \end{bmatrix}, \delta = \begin{bmatrix} -\frac{V_D}{L} \\ 0 \end{bmatrix}, \quad g(x(t)) = \begin{bmatrix} \frac{1}{L} v_{in} + v_D - R_M i_L(t) \\ 0 \end{bmatrix};$$

$$f(x(t)) = \begin{bmatrix} -\frac{1}{L}\left(R_L + \frac{RR_c}{R+R_c}\right) i_L(t) - \frac{R}{L(R+R_c)} v_o(t) \\ \left(\frac{R}{C(R+R_c)}\right) i_L(t) - \left(\frac{1}{C(R+R_c)}\right) v_o(t) \end{bmatrix};$$

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

where R_L is the inductor's winding resistance; V_D is the diode's threshold voltage; R_C is the filter capacitor's equivalent series resistance; R_M is the transistor's resistance (MOSFET). Current flowing through the inductance, voltage at the output, and duty ratio are represented by the variables i_L, v_o and u, correspondingly.

Discreet-time T-S fuzzy model. The creation of the suggested T-S fuzzy controller necessitated the conversion of the nonlinear model into a fuzzy model, utilizing the current of inductance i_L as the decision variable. The nonlinear state space of the buck converter is expressed in a nonlinear manner:

$$\begin{cases} \dot{x} = A_c x(t) + B_c(i_L)u(t) + E_c; \\ y(t) = v_o = C_c x(t), \end{cases} \quad (2)$$

where

$$A_c = \begin{bmatrix} -\frac{1}{L}\left(R_L + \frac{RR_c}{R+R_c}\right) & -\frac{R}{L(R+R_c)} \\ \frac{R}{C(R+R_c)} & -\frac{1}{C(R+R_c)} \end{bmatrix}; E_c = \begin{bmatrix} -\frac{V_D}{L} \\ 0 \end{bmatrix};$$

$$C_c = \begin{bmatrix} \frac{RR_c}{R+R_c} & \frac{R}{R+R_c} \end{bmatrix}; B_c(i_L) = \begin{bmatrix} \frac{1}{L}(V_{in} + V_D - R_M i_L(t)) \\ 0 \end{bmatrix}.$$

The suggested control strategy necessitates a discrete-time model, which can be obtained from the nonlinear model of the system. This is done assuming that the switching period is significantly less than the time constants of the buck converter circuit. The forward Euler approximation is used to derive the following discrete-time model:

$$\begin{cases} x(k+1) = (I + T_s A_c)x(k) + T_s B_c u(k) + T_s E_c; \\ y(k) = T_s C_c x(k). \end{cases} \quad (3)$$

The T-S discrete-time state-space model of the buck converter can be derived based on this assumption:

$$\begin{cases} x(k+1) = A_d x(k) + B_d u(k) + E_d; \\ y(k) = C_d x(k), \end{cases} \quad (4)$$

where

$$x(k) = \begin{bmatrix} i_L(k) \\ v_o(k) \end{bmatrix}; E_d = \begin{bmatrix} -\frac{T_s V_D}{L} \\ 0 \end{bmatrix};$$

$$A_d=\begin{bmatrix}1-\frac{1}{L}\left(R_L+\frac{RR_c}{R+R_c}\right)T_s & -\frac{RT_s}{L(R+R_c)}\\ \frac{RT_s}{C(R+R_c)} & 1-\frac{T_d}{C(R+R_c)}\end{bmatrix};$$

$$B_d(i_L(k))=\begin{bmatrix}\frac{T_s}{L}(V_{in}+V_D-R_M i_L(k))\\ 0\end{bmatrix};\ C_d=\begin{bmatrix}\frac{T_sRR_c}{R+R_c} & \frac{T_sR}{R+R_c}\end{bmatrix}.$$

Suppose the premise variable $z(k) = i_L(k)$ has borders as: $\underline{i_L} \le i_L \le \overline{i_L}$. In addition, by using the sector nonlinearity transformation [26], the nonlinear system given by (1) can be accurately indicated by a discrete T-S fuzzy model with the inclusion of the subsequent two *If-Then* rules:

$$\begin{aligned}&Rule\ 1: IF\ i_L\ is\ F_{11}\ THEN\\ &\begin{cases}x(k+1)=A_1x(k)+B_1u(k)+E_1;\\ y=C_1x(k).\end{cases}\\ &Rule\ 2: IF\ i_L\ is\ F_{12}\ THEN\\ &\begin{cases}x(k+1)=A_2x(k)+B_2u(k)+E_2;\\ y=C_2x(k).\end{cases}\end{aligned} \quad (5)$$

The membership functions F_{11} and F_{12} are obtained by:

$$F_{11}=\frac{i_L(k)-\underline{i_L}}{\overline{i_L}-\underline{i_L}};\quad F_{12}(i_L)=1-F_{11}. \quad (6)$$

The ultimate result of the fuzzy model is deduced in the following manner:

$$\begin{cases}x(k+1)=\sum_{i=1}^{r}h_i(z(k))(A_ix(k)+B_iu(k)+E);\\ y(k)=\sum_{i=1}^{r}h_i(z(k))C_ix(k),\end{cases} \quad (7)$$

where

$$A_1=A_2=\begin{bmatrix}1-\frac{1}{L}\left(R_L+\frac{RR_c}{R+R_c}\right)T_s & -\frac{RT_s}{L(R+R_c)}\\ \frac{RT_s}{C(R+R_c)} & 1-\frac{T_d}{C(R+R_c)}\end{bmatrix};$$

$$B_1=\begin{bmatrix}\frac{T_s}{L}(V_{in}+V_D-R_M\overline{i_L})\\ 0\end{bmatrix};\ B_2=\begin{bmatrix}\frac{T_s}{L}(V_{in}+V_D-R_M\underline{i_L})\\ 0\end{bmatrix};$$

$$C_1=C_2=\begin{bmatrix}\frac{T_sRR_c}{R+R_c} & \frac{T_sR}{R+R_c}\end{bmatrix};\ E_1=E_2=\begin{bmatrix}\frac{-T_sV_D}{L}\\ 0\end{bmatrix};$$

$$h_i(z)=\omega_i(z)/\sum_{i=1}^{r}\omega_i(z);\ \omega_i(z)=\prod_{j=1}^{n}F_{ij}(z_j);$$

$$\text{for all } k>0,\ h_i(z)\ge 0 \text{ and } \sum_{i=1}^{r}h_i(z)=1.$$

Control design and stability analysis. The following requirements must be met to design T-S fuzzy control:

$$x(k)-x_d(k)\to 0 \text{ as } k\to\infty, \quad (8)$$

where $x_d(k)$ is the desired trajectory variable.

Let us establish the tracking error as:

$$\tilde{x}(k)=x(k)-x_d(k).$$

Subsequently, its equivalent discrete-time derivative can be expressed as:

$$\tilde{x}(k+1)=x(k+1)-x_d(k+1). \quad (9)$$

By replacing (7) with (9) and including the term:

$$\sum_{i=1}^{r}h_i(z)A_i(x_d(k)-x_d(k)). \quad (10)$$

The first equation of (7) becomes:

$$\tilde{x}(k+1)=\sum_{i=1}^{r}h_i(z)(A_i\tilde{x}(k)+B_iu(k)+A_ix_d(k)+E_i)-x_d(k+1). \quad (11)$$

Let's select a new control variable for (11) that meets the requirements listed below:

$$\sum_{i=1}^{r}h_iB_i\lambda(k)=\sum_{i=1}^{r}h_i(z)(A_ix_d(k)+B_iu(k)+E_i)-x_d(K+1). \quad (12)$$

By employing (12), the discrete derivative of the tracking error, as expressed in (11), can be reformulated in a following manner:

$$\tilde{x}(k+1)=\sum_{i=1}^{r}h_i(i_L(k))(A_i\tilde{x}(k)+B_i\lambda(k)). \quad (13)$$

The fuzzy tracking control problem is addressed by the novel controllers, which are designed to:

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

The final output of the fuzzy controller is as follows:

$$\lambda(k)=\sum_{i=1}^{r}h_i(z(k))K_i\tilde{x}(k). \quad (14)$$

The closed-loop system is represented as follows by substituting (14) into (13):

$$\tilde{x}(k+1)=\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(z)h_j(z)(A_i-B_iK_j)\tilde{x}(k). \quad (15)$$

By permitting $G_{ij} = (A_i - B_iK_j)$, equation (15) can be restated in the following manner:

$$\tilde{x}(k+1)=\sum_{i=1}^{r}\sum_{j=1}^{r}h_i(z)h_j(z)G_{ij}\tilde{x}(k). \quad (16)$$

Stability analysis. The process of acquiring the fuzzy controller involves identifying the gains that meet the conditions stated in the subsequent theorem [27]:

Theorem 1. The system represented by (16) achieves global asymptotic stability if there exist matrices $X=X^T>0, S_{ii}=S_{ii}^T, S_{ij}=S_{ij}^T, Y_i$, verifying the following linear matrix inequalities: $\forall i,j\in\{1,.......r\}$:

$$\begin{bmatrix}-X+S_{ii} & XA_i^T+Y_i^TB_i^T\\ A_iX+B_iY_i & -X\end{bmatrix}<0; \quad (17)$$

$$\begin{bmatrix}-2X+S_{ij}+S_{ij}^T & XA_i^T+Y_j^TB_i^T+XA_j^T+Y_i^TB_j^T\\ * & -2X\end{bmatrix}<0, i<j; \quad (18)$$

$$\begin{bmatrix}S_{11} & S_{12} & \dots & S_{1r}\\ S_{12} & S_{22} & \dots & S_{2r}\\ \vdots & \ddots & \vdots & .\\ S_{1r} & S_{2r} & \dots & S_{rr}\end{bmatrix}>0. \quad (19)$$

The gains of the control law are: $K_i = Y_iX^{-1}$.

Virtual desired variables and control law. The virtual desired variables and tracking control law for the buck converter system may be determined by (12), which can be expressed in the following manner:

$$\sum_{i=1}^{r} h_i B_i (u(k)-\lambda(k)) = -\sum_{i=1}^{r} h_i A_i x_d(k) - \sum_{i=1}^{r} h_i E_i + x_d(k+1) \, . \quad (20)$$

Let's define aggregated matrices as follows:

$$B=\sum_{i=1}^{r} h_i(z) B_i \, , A=\sum_{i=1}^{r} h_i(z) A_i \, , E=\sum_{i=1}^{r} h_i(z) E_i \, . \quad (21)$$

Subsequently, equation (20) can be restated in a concise manner as:

$$B(u(k)-\lambda(k)) = -A x_d(k) - E + x_d(k+1) \, . \quad (22)$$

By applying (22) to the buck converter model, we obtain the following matrix form:

$$\begin{bmatrix} \frac{T_s}{L}(V_{in}+V_D-R_M i_L(k)) \\ 0 \end{bmatrix} [u(k)-\lambda](k) =$$

$$= -\begin{bmatrix} 1-\frac{1}{L}\left(R_L+\frac{RR_c}{R+R_c}\right)T_s & -\frac{RT_s}{L(R+R_c)} \\ \frac{RT_s}{C(R+R_c)} & 1-\frac{T_s}{C(R+R_c)} \end{bmatrix} \begin{bmatrix} i_{Ld}(k) \\ v_{od}(k) \end{bmatrix} - \quad (23)$$

$$-\begin{bmatrix} -\frac{T_s V_D}{L} \\ 0 \end{bmatrix} + \begin{bmatrix} i_{Ld}(k+1) \\ v_{od}(k+1) \end{bmatrix} .$$

From (23) it can be extracted the reference inductor current as:

$$i_{Ld}(k) = \frac{\left(1-\frac{T_s}{C(R+R_C)}\right)v_{od}(k)+v_{od}(k+1)}{\frac{RT_s}{C(R+R_C)}} \, . \quad (24)$$

Also from (23) it can be extracted the tracking control law as:

$$u(k) = \frac{\left(\frac{T_s}{L}\left(R_L+\frac{RR_C}{R+R_C}\right)-1\right)i_{Ld}(k)+\frac{RT_s}{L(R+R_C)}v_{od}(k)}{\frac{T_s}{L}(V_m+V_D-R_M i_L(k))} + \quad (25)$$

$$+\frac{\frac{T_s V_D}{L}+i_{Ld}(k+1)}{\frac{T_s}{L}(V_m+V_D-R_M i_L(k))}+\lambda(k).$$

Simulation results. Several simulation tests were carried out at different load and input voltage conditions to prove the accuracy of the suggested controller for a DC-DC buck converter. The used parameters are shown in Table 1.

Table 1

Buck converter parameters

Parameter	Values
MOSFET resistance R_m, Ω	0.1
Threshold voltage of the diode V_D, V	0.8
Output capacitor C, μF	270
Output capacitor resistance R_C, Ω	0.18
Inductor L, μH	180
Winding resistance of inductor R_L, Ω	0.1
Resistance load R, Ω	25
Input voltage V_{in}, V	12
Switching frequency f, kHz	31

The first test used a constant reference voltage of 6 V. The output voltage, inductor current, duty ratio and PWM signal responses are depicted in Fig. 3,*a*–*d*, respectively.

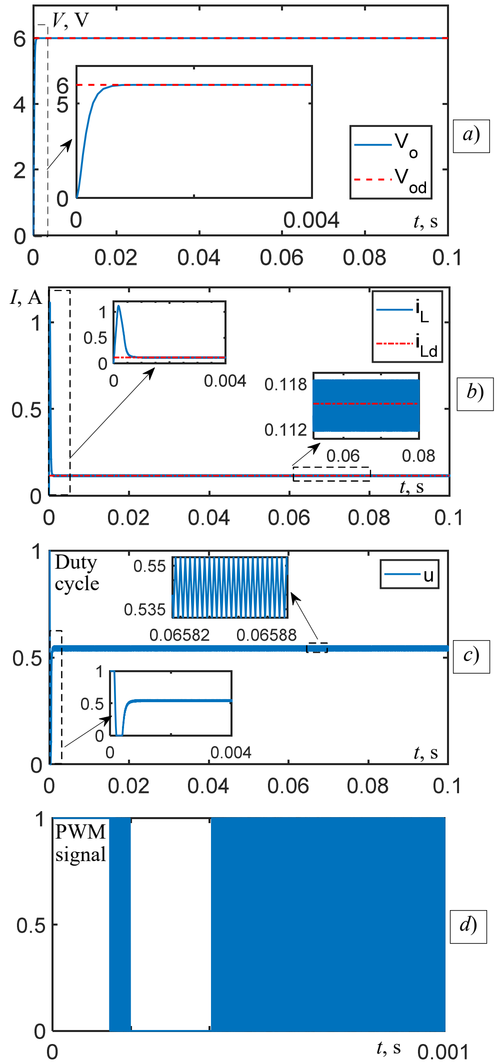
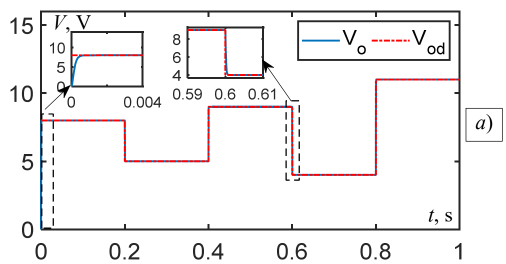


Fig. 3. Simulation results for a fix reference voltage:
a – output voltage; *b* – inductor current voltage;
c – duty ratio; d – PWM signal

These results show that the output voltage precisely follows the wished trajectory. Additionally, it has been demonstrated that the time necessary for the system to respond to the reference model is brief, specifically 0.4 ms.

In the second test, a variable reference voltage was used. The output voltage, inductor current, and duty ratio responses are depicted in Fig. 4,*a*–*c*, respectively. From these results, we notice that despite the random change in the chosen voltage, the output voltage always follows the desired voltage with a minimal response time and limitation of overshoot.



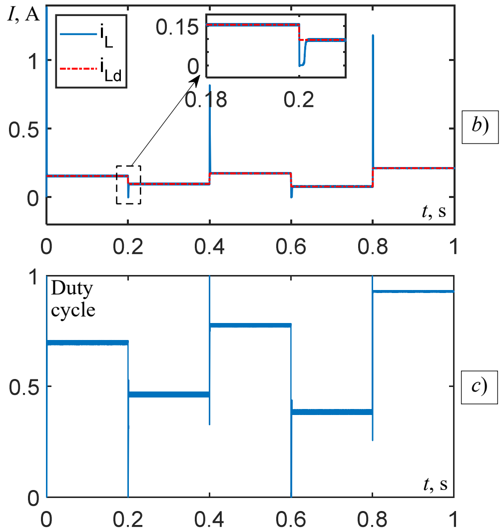


Fig. 4. Simulation results for variable reference voltages: *a* – output voltage; *b* – inductor current voltage; *c* – duty ratio

In the third test, another scenario is used to prove the effectiveness of the proposed controller. A variable voltage is applied to the input of the buck converter, and observing of the response of the output voltage. Figure 5 shows the output voltage response under input voltage variations. Initially, the input voltage was set to 12 V, and the desired output voltage was set to a constant 8 V at t = 15 ms. These results show that the output voltage matches the chosen level quickly and remains constant even when the input voltage changes.

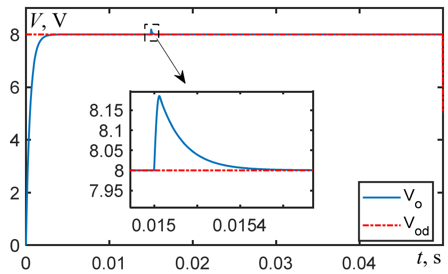


Fig. 5. Responses of the output voltage for input voltage variable

In the fourth test, we randomly changed the load resistance value and noted the output voltage response and how well it followed the desired voltage (Fig. 6).

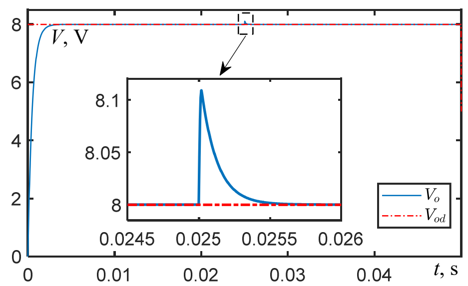


Fig. 6. Responses for resistor load variable

In the next scenario, the reference voltage is kept at 8 V. At time t = 0 s, the converter functions with a load resistance of 25 Ω. Then, at time t = 2.5 ms, the load resistance is modified to 30 Ω. The overshoot in a transient condition is observed to be brief. Subsequently, the output voltage remains constant at 8 V. The results produced by the T-S fuzzy controller, in the last test, are compared to those obtained by the PID controller [28–30] (Fig. 7).

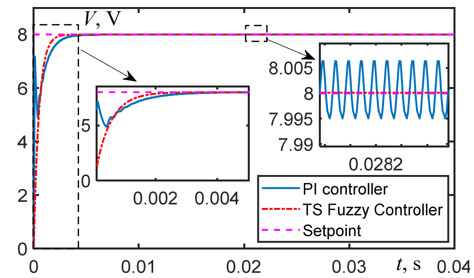


Fig. 7. Performances comparison between PID and T-S controllers

Table 2 presents the comparison results. The performances of the both controllers are evaluate based on the specified parameters of overshoot (efficiency), settling time (accuracy and stability), and rise time (speed).

Table 2

Results of the comparison and evaluation between T-S fuzzy and PID controllers

Method	PID controller	Proposed method
Overshoot, %	0	0
Settling time, ms	4	25
Rise time, ms	28	2

The comparison results indicate that the developed controller provides superior performance and a faster response compared to the conventional PID controller, which has numerous drawbacks, such as a slow response to accurately track the required voltage and significant oscillations around the desired voltage, particularly during variations in the resistor load and input voltage.

Conclusions. This paper presents the control of the output voltage of a DC-DC buck converter. A discrete-time T-S fuzzy model is used to represent the considered system's dynamic and then employed to develop a fuzzy controller. The concept of virtual desired variables is used to extract the desired reference model and nonlinear control law. Sufficient conditions for stability are derived from Lyapunov's method, and then they are converted into linear matrix inequalities to find the controller gains. The simulation results show that the proposed control can drive the output voltage to track its reference exactly with a shorter response time and without any overshooting. A comparison of the suggested controller with the conventional PID shows its superiority in terms of time response and tracking. Exploring practical application and robustness challenges will take center stage in an upcoming research endeavor.

Conflict of interest. The authors declare that they have no conflicts of interest.

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