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Study of Fuzzy Logic Control of Dc-Dc Buck Converter

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Abstract

Because of unspecified transfer function of dc-dc converters fuzzy controllers can be used instead of classical controllers. The design of fuzzy controllers does not require an exact mathematical model. Instead they are designed based on general knowledge of the plant. In this paper, a fuzzy logic controller for a dc-dc buck converter is designed. The designed controlled system is simulated in MATLAB/Simulink software. Different parameters such as input voltage and output load are varied and the responses of fuzzy controller to these variations have been studied and investigated in order to evaluate the designed controller performance. The simulation results are presented. Fast dynamic response of the output voltage and robustness to load and input voltage variations are obtained.

Keywords: Fuzzy logic controller, Dc-dc converter, Buck converter.

Dc-Dc Düşürücü Dönüştürücünün Bulanık Mantık Denetimi Üzerine Çalışma

Özet

Dc-dc dönüştürücülerin transfer fonksiyonunun tam olarak belirlenemediği durumda, klasik denetleyiciler yerine bulanık denetleyiciler kullanılabilir. Bulanık denetleyicilerin tasarımı tam bir matematiksel model gerektirmez. Bunun yerine denetlenecek sistemin genel bilgisine dayanarak tasarlanırlar. Bu çalışmada, dc-dc düşürücü dönüştürücü için bulanık mantık denetleyicisi tasarlanmıştır. Tasarlanan kontrollü sistemin MATLAB/Simulink ortamında benzetimi yapılmıştır. Giriş gerilimi ve çıkış yükü gibi farklı parametreler değiştirilerek bulanık denetleyicinin bu değişikliklere olan tepkisi incelenmiş ve tasarlanan kontrolörün performansını değerlendirilmiştir. Elde edilen benzetim sonuçları sunulmuştur. Çıkış geriliminin hızlı dinamik cevabı ve yük değişiklikleri ile giriş gerilimi değişimlerine karşı dayanıklılığı görülmüştür.

Anahtar Kelimeler: Bulanık mantık denetleyici, Dc-dc çevirici, Düşürücü çevirici.

1. Introduction

In some applications, it is necessary to convert the constant dc voltage value to a variable dc voltage. In power electronics, the circuits that perform this operation are called dc-dc converters. The dc-dc converters can also be called as a dc-chopper. A converter can be thought of as a dc equivalent circuit of a transformer with a continuously adjustable winding ratio. As transformers can reduce or increase AC voltage, dc-dc converters can also reduce or increase the voltage value of the dc source. Dc-dc converters are widely used in many office appliances, personal computer power supplies, spacecraft power systems, laptops, communication devices, speed control and braking in dc motors, mine hammers, freight elevators, trolleys and electric automobiles. The block diagram of a converter can be given as shown in Figure 1.

At the inputs of these converters, there is the constant dc voltage obtained by rectifying the mains voltage. Therefore, fluctuations in input voltage occur due to change of line voltage. That is, the input voltage at the dc-dc converters is an unregulated dc voltage. The inverter output is a regulated DC voltage whose amplitude and polarity are different from the input voltage.

Switched dc-dc converters are used to convert an unregulated dc input to a controlled dc output at the desired voltage range.

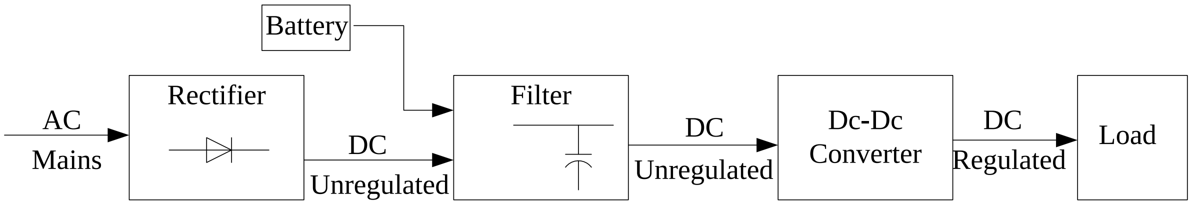


Figure 1. Converter block diagram

In practice, the efficiency of dc-dc converters is about 70-95%. High efficiency can be achieved by the use of switching elements which consume less power and are controlled at higher frequencies. Parallel to the developments in electronics, BJT, MOSFET and IGBT are used as switching elements in dc-dc converters in recent years. However, igbt and MOSFETs are preferred in high-power converter applications [1].

The basic energy required for the operation of the electronic circuits is provided by dc power supplies which convert the AC input signal to the dc output signal. There are basically two types of DC power supply.

- Linear power supplies
- Switched dc power supplies

The basic operating principle of the switched-mode voltage regulator is based on transferring the high frequency switching of the DC voltage applied to the input to the output. For this operation, the input voltage is chopped and the pulse duty ratio is changed. In short, pulse width modulation (PWM) is performed. This process makes the regulator output independent of changes in load and input voltage.

Advantages and disadvantages:

- The structure is complex and high costs.
- There is a need to filter the output due to noise and distortion.
- The efficiencies are quite high.
- Since the operating frequencies are very high, the dimensions of the circuit elements such as coil and transformer are smaller.
- Multiple outputs can be obtained and the poles of the output voltage can be changed.

The most important feature in power electronic systems is efficiency. So, as a rule, power electronic systems do not use resistances as a power electronics circuit element. Voltage drop and current flow are realized with the help of switches.

There is no voltage drop when an ideal switch is in the on state, and no current through when it is in the off state. Thus a switch can be thought of as an effective loss-free resistor depending on duty ratio.

Conversion of the power dc to dc is done with switched-mode power converters. It consists of reactive and switching elements. The operating principle is based on by setting the on and off times of the switching elements used in the circuit. If the frequency of the load-supplying voltage is large, practically dc power transmission is possible without interruption to the load. Thus, the design of the converters can be designed depending on the proper configuration of the reactive elements and the switching methods.

Switched dc-dc converters are nonlinear and time-varying systems due to the inductance behavior of their structures. Dc-dc Converters can be classified in many different ways. However, in terms of the functions performed by the converters, the dc-dc converters can be classified as follows;

Step-Down converter, (Buck)

Step-Up converter (Boost)

Step–Down/ Up converter (Buck-Boost)

Cuk converter

Full Bridge converter

Buck and boost converters are basic converters. The buck-boost and cuk converters are formed by the use of basic converters. Full bridge converters are a different application of step down converter. The converter variants are also referred to as switched DC power supplies in certain applications [2].

The buck type dc-dc converters are used when a lower voltage than the source voltage is needed. Different control algorithms are applied to to control the output voltage of dc-dc converters. Voltage- Mode Control and Current-Mode Control are two traditional methods to control dc-dc converters [3]. The transient responses of voltage-mode control is robust to disturbances, but are slow. Current-mode control improves the speed of transient responses. The disadvantages with this method are its instability when the duty-cycle is greater than one half and the need for a ramp compensation circuit to avoid this problem [4]. Current-Mode Control has more complex and expensive circuit structures to be implemented when compared Voltage-Mode Control.

If classical linear control techniques are used, the small signal model is derived by linearization around an operating point from the state space average model [1]. The classical controllers are simple to implement however, it is difficult to account the variation of system parameters, because of the dependence of small signal model parameters on the converter operating point [2]. Large signal and system parameter variations cannot be easily dealt with these techniques. The intrinsic nonlinearity and wide input voltage and load variations must be cope with the control technique, while ensuring stability and providing fast transient response in any operating condition. To achieve the desired performance, the classical control methods for dc-dc converters require the transfer function of the converter which is usually a complicated task.

Another method for control of converters is fuzzy controller which has an acceptable level of efficiency regarding the nonlinear model of converters. In fuzzy control method, the control action is based on some linguistic rules which can decrease the complexity of the nonlinear model and does not require an accurate mathematical modeling of the systems and computational complexity [5, 6]

Its design philosophy deviates from all the previous methods by accommodating expert knowledge in controller design. This control technique is based on the human ability to understand the system behavior and it is also based on controlling qualitative rules. This control technique can extend the ability to control large signals since each operating point will have a specific driver without changing the circuit structure.

The use of fuzzy logic control enables to improve and overcome the deficiency of the control method based on small signal models. Fuzzy logic control improves the dynamic behavior of the system, and becomes very useful when the system mathematical model is difficult to obtain. Unlike other robust schemes, which are computationally intensive linear methods, implementaion of fuzzy logic is simple.

In this study, a fuzzy logic controller is used to control a Buck converter which will have a constant output voltage under load and input voltage variations. For this topology, the tests on load regulation and line regulation are carried out to evaluate the controller's performance.

2. The Mathematical Model of Dc-Dc Buck Converter

The buck converter is shown in Figure 2. When the switch is on the circuit is connected to the dc input source resulting an output voltage across the load resistor.

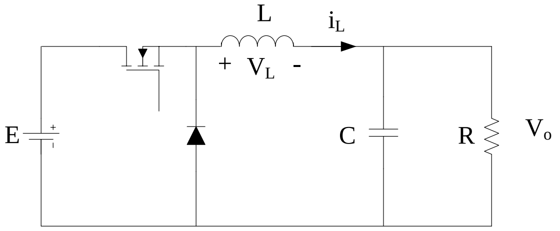


Figure 2. Buck converter

If the switch changes to off position, the capacitor voltage will discharge through the load. Controlling switch position the output voltage can be maintained at a desired level lower than the input source voltage. The buck converter can be described by the following set of equations

$$L\frac{di_L}{dt} = uE - V_o \tag{1}$$

$$C\frac{dV_o}{dt} = i_L - i_0 \tag{2}$$

Where i_L is the inductor current, Vo is the output capacitor voltage, E is the constant external input voltage source, L is the inductance, C is the capacitance of the output filter and R is the output load resistance. u is the control input taking discrete values of 0 and 1 which represents the switch position.

$$u = \begin{cases} 0\ if\ switch\ is\ off \\ 1\ if\ switch\ is\ on \end{cases} \tag{3}$$

It is assumed here that the inductor current will have a nonzero value due to load variations which is known as the continuous conduction mode (CCM). Figure 3 shows the current and voltage in continuous conduction mode.

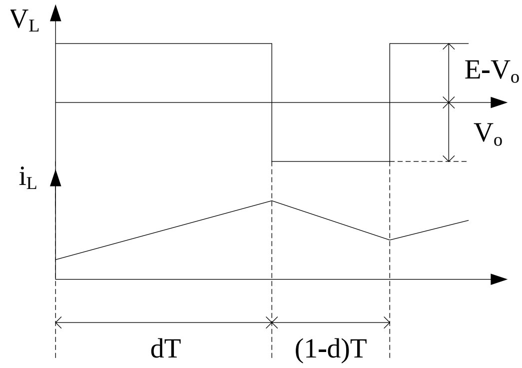


Figure 3. Current in buck converter

If taking the inductor current and capacitor voltage as the states of the system and rewriting equations (1) and (2) in the form of state equations, the following state equations in matrix form can be obtained.

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_0}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_0 \end{bmatrix} + \begin{bmatrix} \frac{E}{L} \\ 0 \end{bmatrix} u \tag{4}$$

where

$$i_0 = \frac{V_o}{R} \tag{5}$$

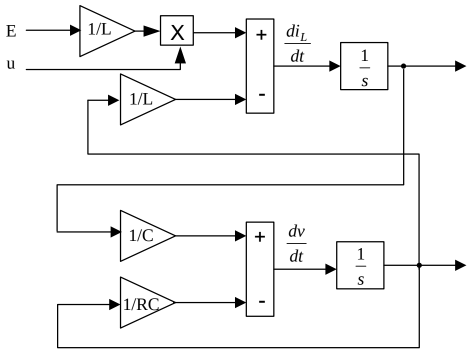


Figure 4. Simulink block diagram of a buck converter

Figure 4 shows the Simulink block diagram implementation of the buck converter using state equations (4).

3. Fuzzy Logic Control

The fuzzy logic control is an important application of the fuzzy set theory first introduced by L. A. Zadeh in 1965. The most important feature that distinguishes the concept of fuzzy set from the classical set concept is that fuzzy set uses linguistic variables rather than numerical variables [7].

Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and large), may be represented by fuzzy sets. The application of fuzzy logic does not require accurate mathematical formulations. A block diagram of a fuzzy logic controller is shown in Figure 5. and the implementation involves the processes of fuzzification, inference and defuzzification.

The fuzzification interface converts input data into suitable linguistic values using the membership functions. During the phase of inference, the fuzzy if-then rules are evaluated using an inference engine and the controller action is inferred from the knowledge of the fuzzy rules and the linguistic variables definition. The conversion of the inferred fuzzy result to a crisp control actionis performed through the defuzzification [8].

Because its control algorithm is described by if-then rules instead of intensive mathematical equations or large look-up tables, the design of fuzzy logic non-linear controller is easier. It reduces the development cost and time and needs less data storage in the form of membership functions and rules. It is also highly reliable and robust to change in circuit parameters and external disturbances [9].

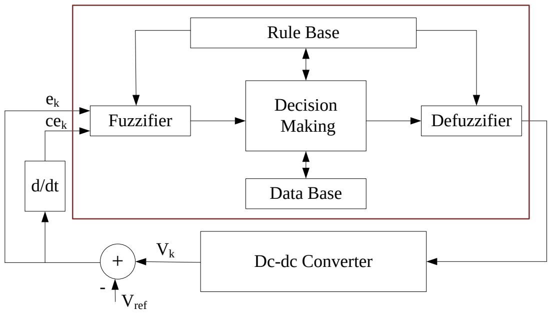


Figure 5. Basic configuration of fuzzy logic controller

4. Fuzzy Logic Controller Design

Fuzzy set is an extension of crisp set, where the element belongs or does not belong to the set with 0 or 100%. That is in a fuzzy set, the element may partially belong to the set, that is an element can belong to more than one set. This set is characterized by a membership function that applies a membership degree forthe set with a range of 0 to 1 to each element in a given class.

Design of fuzzy controllers is based on expert knowledge of the system to be controlled instead of accurate mathematical model. There are two inputs in the fuzzy controller. The first is the error e(k) between the output voltage V[k] and the reference value Vref and the second is the difference between successive errors i.e. change of error ce(k) and are given by

$$e(k) = Vref - V(k) \tag{6}$$

$$ce(k) = e(k) - e(k-1) \tag{7}$$

The output of the fuzzy controller is the change in duty cycle Δd[k], which is fed to PWM block and the PWM output is fed as switching signal to the converter [10]. In Figure 5, the voltage at the output of the buck converter is compared with reference voltage and the output of the comparator is the error signal which is the input of the Fuzzy controller together with the change in error signal. The output of the controller is duty cycle which is fed to PWM block and the PWM output is fed as switching signal to the converter.

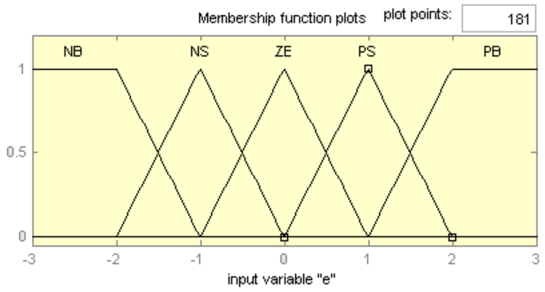
A Mamdani based control system architecture has been realized. Max–min composition techniques and center of gravity methods have been used in the inference engine and defuzzification. The max–min inference methodis used to obtain the control decision. It is based on the minimum function to describe the AND operator present in each control rule and the maximum function to describe the OR operator. The output of the fuzzy controller structure is crisp, and thus, a combined output fuzzy set must be defuzzified. The sum–product composition method has been used to express the qualitative action in a quantitative action. It calculates the crisp output as the weighted average of the centroids of all output membership functions.

Fuzzy logic controller consists of three components fuzzification, fuzzy inference system and defuzzification. In general a fuzzy set issued to express a fuzzy variable which is defined by a membership function. The values of membership function vary between 0 and 1. The fuzzy rule base are the IF-THEN rules.

4.1 Fuzzification

Fuzzification is the process of converting input data into suitable linguistic values. The first step in the design of a fuzzy logic controller is to define membership functions for the inputs. Five fuzzy levels are chosen and defined by the following fuzzy-set values for the error e and change in error ce:

NB negative big;
NS negative small;
ZE zero;
PS positive small;
PB positive big.



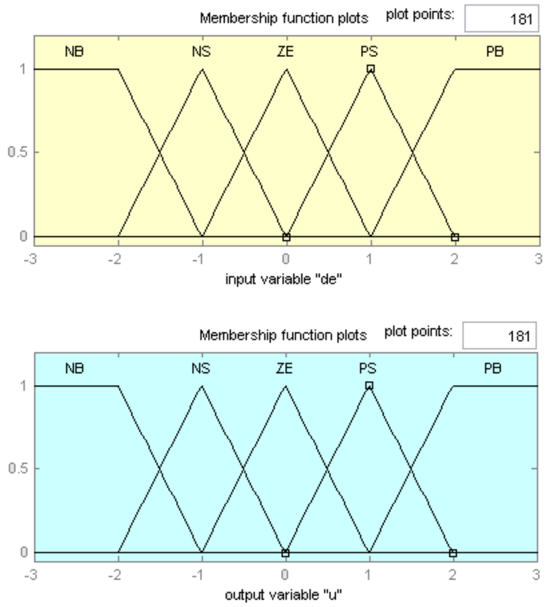


Figure 6. Membership functions for e, ce and u

The number of fuzzy levels depends on the input resolution. Increasing the number of fuzzy levels, increases the input resolution. Due to its simplicity, the triangular membership function is chosen for the controller input. Fuzzifier determines the degree of membership in every linguistic variable for given inputs. All linguistic variables other than two will have zero membership because there are only two overlapping memberships.

4.2 Rule base or decision-making

The heuristic control rules that correspond the fuzzy output to the fuzzy inputs are obtained from analysis of the system behavior. Sometimes the control actions in the rule table might also be developed using “trial and error” and from an “intuitive” feel of the system to be controlled. The control rules listed in Table 1 for the dc–dc converter are determined from converter behavior. A typical rule can be written as follows.

If e is NB and ce is PS then output is ZE
Error (e), change of error (ce) and output represent degree of membership.

Table 1. Rules

CE \ E	NB	NS	ZE	PS	PB
NB	NB	NB	NB	NS	ZE
NS	NB	NB	NS	ZE	PS
ZE	NB	NS	ZE	PS	PB
PS	ZE	ZE	PS	PB	PB
PB	NS	PS	PB	PB	PB

The fuzzy IF-THEN rule expresses a fuzzy implication relation between the fuzzy sets of the premise and the fuzzy sets of the conclusion. The rules IF part describes situation for which rules are designed and THEN part describes the response of fuzzy system. For example, IF the Error is NB and Change of Error is PS THEN Duty Cycle is ZE.

If the membership functions of the input variables provide a linear mapping between the inputs and the output of the controller, any control law can be directly implemented by choosing the output as the desired control law because the output is a function of the input variables.

The derivation of the fuzzy control rules is heuristic in nature and based on the following criteria [11-13]:

1) If the output of the converter is far from the reference point, the change of duty cycle must be large so as to bring the output to the reference point quickly.
2) If the output of the converter is approaching the reference point, a small change of duty cycle is necessary.
3) If the reference point is reached and the output is steady, the duty cycle remains unchanged.
4) If the output is above the reference point, the sign of the change of duty cycle must be negative.
5) If the output of the converter is far from the reference point, the sign of the change of duty cycle must be negative and large in order to bring the output to the reference point quickly.

Figure 7 represents the surface view of the rules for the proposed fuzzy logic control. The rules are represented as the combinations of the two inputs error and change in error for a function of output

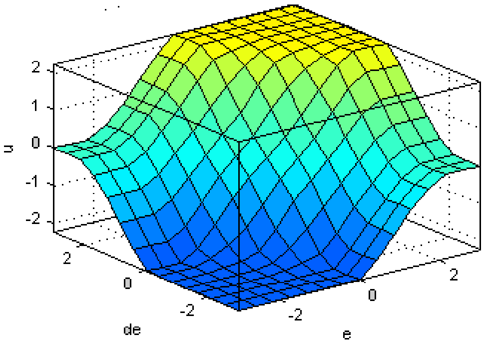


Figure 7. Rules in 3D surface

4.3 Inference mechanism

The max-min inference method is used to obtain the control decision. It is based on the minimum function to describe the AND operator present in each control rule and the maximum function to describe the OR operator.

4.4 Defuzzification

Convertion of the fuzzy to crisp or non-fuzzy output is defined as De-fuzzification. That is defuzzification unit transforms the fuzzy control actions to continuous (crisp) signals, which is applied to the physical plant.

5. Simulations

The steady-state output voltage of a dc-dc converter is controlled by the duty ratio. To account for changes in load current, input voltage, losses, and nonidealities in the converter, a closed loop control is required to obtain a desired output voltage and to maintain it. Figure 8 shows a block diagram of output voltage control for a buck converter.

The goal here is to implement a robust fuzzy controller that can achieve robustness around the operating point (e.g. in the case of a load change), good dynamic performance (i.e. rise time, overshoot, settling time and limited output ripple) in the presence of input voltage variations (and load changes); and invariant dynamic performance in presence of varying operating conditions. Therefore the system performance is checked under four different conditions namely start-up transient, line variation, load variation, and also circuit components variations.

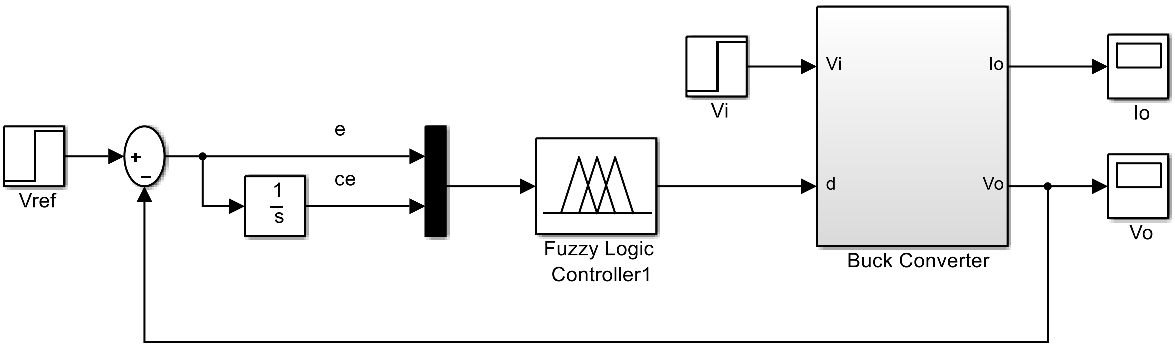


Figure 8. Simulink block of the fuzzy controlled buck converter

Simulations were performed on a typical ‘buck’ converter circuit, whose parameters are shown in Table 2.

Table 2. Buck converter parameters

E (V)	L (mH)	C (□F)	R (□)
20	40	4	40

Figure 9 shows the output voltage and current when a change in the reference voltage from 10V to 12V occurs at 5ms.

The robustness is tested against the load variation. Figure 10 shows the recovering features of the fuzzy controlled buck converter to the imposed load variation. The load resistance was subject to a sudden change from R = 40 Ω to R= 60 Ω at time t = 5ms. while the system was already stabilized to the desired voltage value of 10 V.

Figure 11 shows the waveforms, when the input voltage E is changed from 20 V to 18V at the time t=5 ms with a desired steady state output voltage of 10 V. Figure 10 and 11 proves the robustness of the fuzzy logic control against changes in the load and variations in the input voltage.

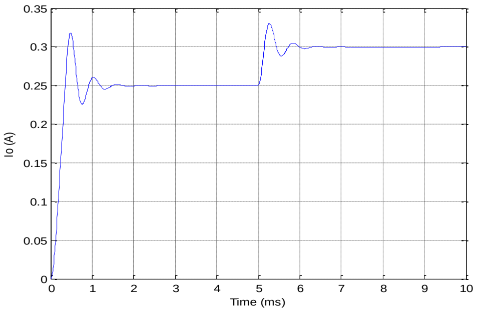


Figure 9. Output voltage and current waveforms for step change in reference voltage

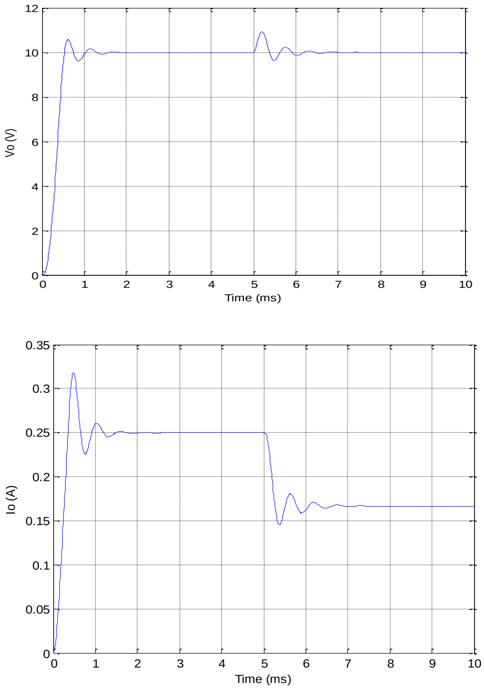


Figure 10. Output voltage and input current waveforms for 50% step load variations

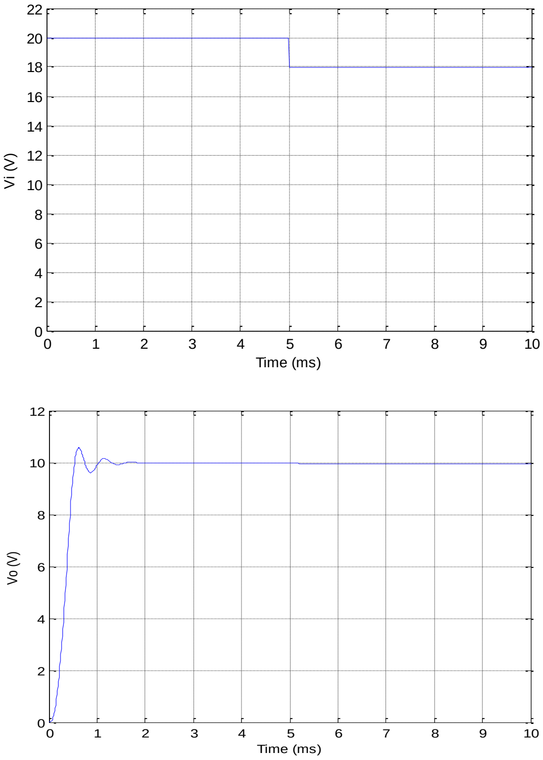


Figure 11. Input and output voltage waveforms for step changes in input voltage

6. Conclusions

A fuzzy logic controller designed and simulated for a dc-dc buck converter. The control feedback error computed as the difference between the output and the reference voltage, and its rate of change, are used as inputs for the fuzzy block which in turn determines the duty ratio of signal driving the switching element. The results of the simulations demonstrate that with the use of fuzzy logic controlller the robustness of the output voltage and good dynamic behavior is achieved even for large supply and load variations. The simulation results illustrate that the fuzzy logic control can be an alternative to conventional control techniques and can provide considerable control performances as tracking the desired output voltage.

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