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Design and Real Hardware Implementation of Fuzzy Logic Controller for DC-DC Boost Converter

Abstract. *This research focuses on the practical and low-cost implementation of a fuzzy logic controller (FLC) for controlling the output voltage of a DC-DC boost converter. It is carried out using an ATmega2560-based Microcontroller of the Arduino Mega board under Matlab/Simulink environment. The developed FLC controller aims at driving the output voltage to follow the desired reference voltage signal whatever load or input voltage changes. The obtained results demonstrate the excellent performance of the proposed prototype in terms of dependability and precision in following the desired reference voltage. A comparative study with the PI conventional baseline controller shows that the developed FLC offers rapid dynamic response and better performance.*

Streszczenie. *Niniejsze badania koncentrują się na praktycznym i tanim wdrożeniu kontrolera z logiką rozmytą (FLC) do sterowania napięciem wyjściowym przetwornicy podwyższającej napięcie DC-DC. Odbywa się to za pomocą mikrokontrolera opartego na ATmega2560 płytki Arduino Mega w środowisku Matlab/Simulink. Opracowany kontroler FLC ma na celu sterowanie napięciem wyjściowym zgodnie z pożądanym sygnałem napięcia odniesienia niezależnie od zmian obciążenia lub napięcia wejściowego. Uzyskane wyniki pokazują doskonałe osiągi proponowanego prototypu pod względem niezawodności i precyzji w podążaniu za pożądanym napięciem odniesienia. Badanie porównawcze z konwencjonalnym kontrolerem bazowym PI pokazuje, że opracowany FLC zapewnia szybką reakcję dynamiczną i lepszą wydajność.* ***(Projekt i rzeczywista implementacja sprzętowa kontrolera Fuzzy Logic dla przetwornicy DC-DC Boost)***

Keywords: Boost converter, fuzzy logic controller, Arduino Mega
Słowa kluczowe: Przetwornica boost, kontroler logiki rozmytej, Arduino Mega

Introduction

A DC-DC boost converter is an electronic power circuit that takes a direct voltage and transforms it into another direct voltage of a greater value. It consists of an ultra-fast diode, a MOSFET transistor, and two energy storage devices (inductor and capacitor) [1],[2]. It is widely used in home and industrial applications. This kind of power electronic circuit has many advantages compared to the linear voltage regulator, such as reduced size and cost, low heat generation and increasingly high efficiency [3]–[6]. The DC-DC boost converter also performs an important role in connections for wind turbines, photovoltaic systems, hybrid systems and storage batteries [7]–[9]. However, its control is still a difficult mission due to its inherently nonlinear behaviour with the presence of disturbances and uncertainties. Therefore, the conventional control method cannot guarantee good results and satisfactory performances in terms of rapidity and tracking error minimization. Consequently, many works have been proposed based on nonlinear and advanced control techniques to resolve this issue.These include sliding mode [10]–[12], linearization control [13], backstepping control approach [14],[15], exact linearization methods and adaptive control [16], [17].

A sliding mode approach has been employed to control a boost converter in [10], [11] and [12]. Their works clearly show the proposed controller's simplicity and durability. Still, these advantages are nullified by practical disadvantages such as the presence of the undesirable chattering phenomenon (fluctuations having finite amplitude and frequency), which makes its hardware implementation a problematic task [14], [15]. Other controllers have been recently proposed in [16] and [17] based on the adaptive backstepping method. Their results show good performances of the proposed method. However, it also suffers from many limitations and obstacles in the implementation phase. In [13] a feedback linearization-based control technique has also been proposed for the DC-DC boost converter without considering the impacts of the different parasitic elements on electrical components, rendering it ineffective during varying operating conditions.

In general, most of these control methods share the same disadvantage: the design of the controllers is based mainly on a good knowledge of the mathematical model of the controlled system, which is not always provided due to different hypotheses taken into consideration during the modeling phase. Therefore, many difficulties and limitations appear, especially during the implementation stage [18]. To overcome this problem, a fuzzy logic-based control approach has proved its successful efficiency in many industrial processes due to its various advantages: it does not require a deep knowledge of the system's mathematical model. The fuzzy logic controller is quite different from the classical controller, as it is based only on expert knowledge of the controlled system [19], [20].

The primary goal of this search is the design and hardware implementation of a low-cost fuzzy logic controller based on Mamdani models for a DC-DC boost converter. The suggested controller control unit includes two inputs, error and change in error and one output, signal control. To enhance the performance of the controlled system, a scaling factor is assigned to each input and output. A practical implementation of the developed FLC controller is done using an Arduino Mega board and a spatial package installed in the Matlab/Simulink environment called the "Simulink Support Package for Arduino Hardware". The obtained results from simulation and experiment show that the proposed FLC control offers robust performance, fast response and guarantees less bypass compared to base-line proportional-integral (PI) control.

The remainder of this study is organized in the following structure: The second section is devoted to the mathematical model of the considered boost converter. The control structure based on fuzzy logic is designed in the third section. The fourth section is reserved for the simulation results in different operating conditions and for comparing the proposed control and the classical one. The practical implementation stages of the FLC control method are discussed in section five. Finally, a conclusion is given at this end of this work.

Proposed fuzzy logic based control

This work aims to develop a fuzzy logic controller that permits driving the output voltage of a DC-DC boost converter V_o to follow a reference voltage signal V_{ref}, as illustrated in Fig. 1. The following sections will discuss the boost converter and fuzzy controller in detail.

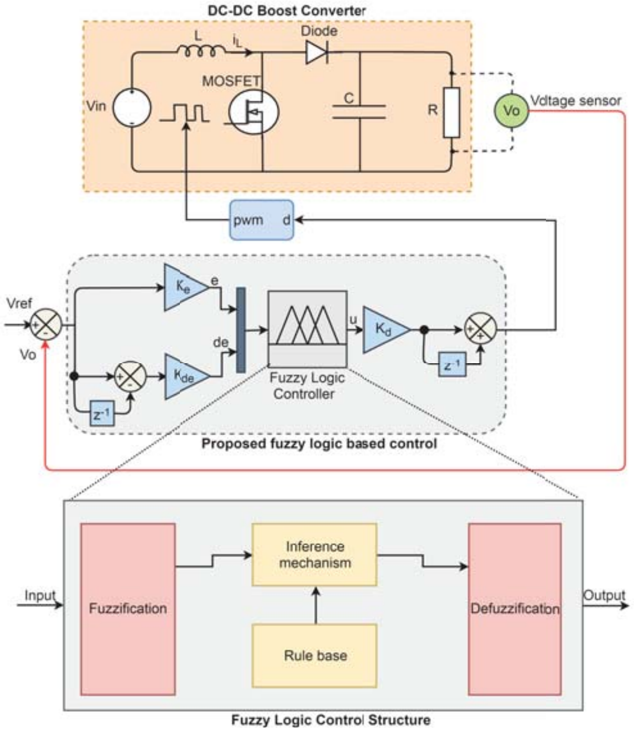

Fig. 1. Proposed FLC structure for boost converter.

DC–DC Boost converter modeling

In this research, the state-space averaging technique is used to describe the transfer function of the considered system as follows [21]:

$$(1)\qquad \frac{\hat{V}_o(s)}{\hat{d(s)}} = \frac{V_{in}}{RC(1-D)^2} \cdot \frac{\frac{(1-D)^2}{L} - s}{s^2 + \frac{s}{RC} + \frac{(1-D)^2}{LC}}$$

Where the circumflex accent represents a small variation around the operating point. V_o denotes the output voltage. L, C, and R designate inductance, capacitor, and resistive load, respectively. D represents the duty ratio and V_i represents the input voltage.

The realized prototype in this work consists of two potentiometers used as input and output voltage sensors and an input current sensor ($ACS712$), a MOSFET transistor, an ultra-fast diode, a capacitor used as an input voltage filter, an inductor, an output capacitor and a resistive load.

Fig.2 shows the circuit that includes the real electronic components of the considered boost converter, while the printed circuit board (PCB) created using OrCAD PCB Designer PRO is depicted in Fig. 3 .

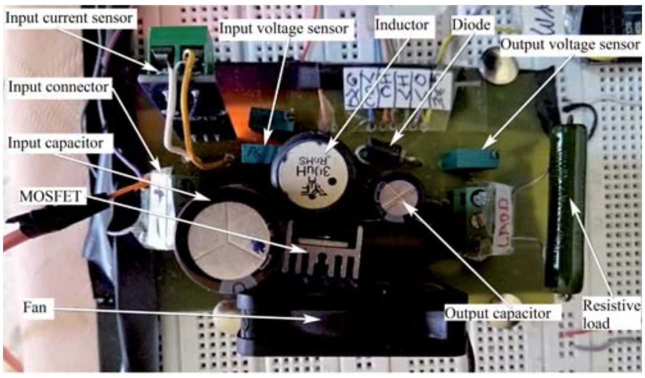

Fig. 2. Boost converter prototype.

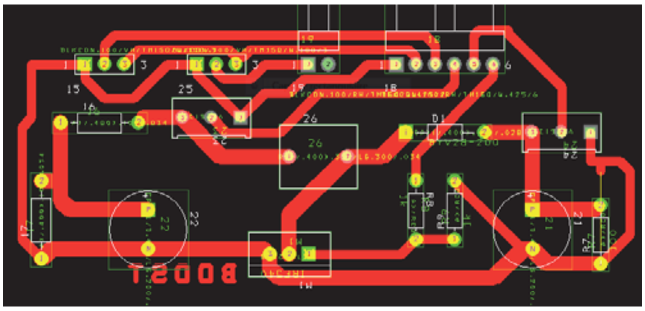

Fig. 3. Boost converter PCB.

The following formulas are used to determine the dimensions of the output capacitor (C) and inductance coil (L):

$$(2)\qquad L > \frac{V_{in}D_{max}(1-D_{max})}{f2i_0} > 14.6590\mu H$$

$$(3)\qquad C > \frac{i_o}{f \bigtriangleup V_o} > 424.9\mu F$$

where $D_{max} = 0.92$ is the maximal duty cycle, $\bigtriangleup V_o = 0.09V$ is the ripple output voltage, $f = 31.38Khz$ is the switching frequency and $i_o = 1.2A$ is the output current draw.

Table 1 lists the component values for the converter under consideration.

Table 1. Values of the components for considered boost converter.

MOSFET	$IRFZ44N$
Ultrafast diode	31DF4
Inductor	$30uH$
Input capacitor	$2200uF$
Output capacitor	$470uF$
Load resistor	56Ω
Switching frequency	$31,38KHz$

Fuzzy logic controller design

The proposed controller is designed based on the Mamdani style fuzzy inference system. It has two inputs error $e(k) = V_{ref}(k) - V_o(k)$ and change in error $de(k) = e(k) - e(k-1)$ and one output u. The inputs are scaled by factor gains K_e and K_{de} and the fuzzy controller output is scaled by a factor gain K_u. These scaling gains can be adjusted to get superior performances in terms of time response and tracking error minimization. The FLC controller is designed from the following four main parts:

- Fuzzification interface converts crisp data input to membership degree according to the shape of the membership function (MF). As shown in Fig. 4, seven fuzzy levels are selected and described by the following fuzzy-set values for the inputs and output, as follows: NS negative small, NM negative middle, NB negative big, Z zero, PB positive big , PM positive middle, PS positive small.
- The rule base includes the expert linguistic knowledge needed to achieve reasonable control. In this work 49 fuzzy rules are selected and implemented, as shown in Table 2. The following describes the typical structure of rules:

  IF input 1 is NS and input 2 is NS Then output is NS
- Fuzzy inference uses fuzzy logic to map an input to an output. The mapping then serves as a foundation for judgement calls and the identification of patterns. The

previously mentioned membership functions, fuzzy logic operators, and other components are used in the fuzzy inference process.

- Defuzzification is a technique that enables the transformation of a fuzzy value into a precise quantity.

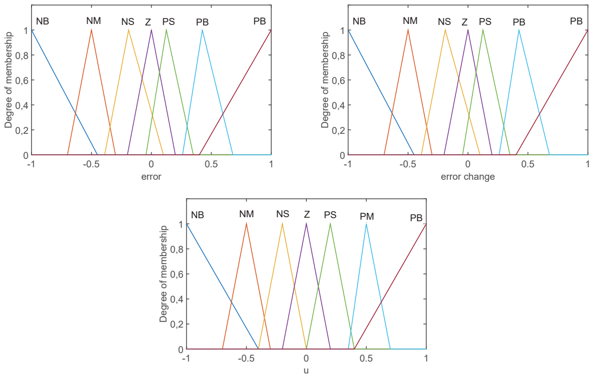

Fig. 4. Used membership functions.

Table 2. Fuzzy rule base of FLC.

de/e	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NM	NM	NS	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NS	NS	Z	PS	PS	PM
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PS	PM	PM	PB
PB	Z	PS	PM	PM	PB	PB	PB

Simulation results

Simulation tests using the Simulink model displayed in Fig. 5 have been performed to confirm the accuracy and efficacy of the proposed controller.

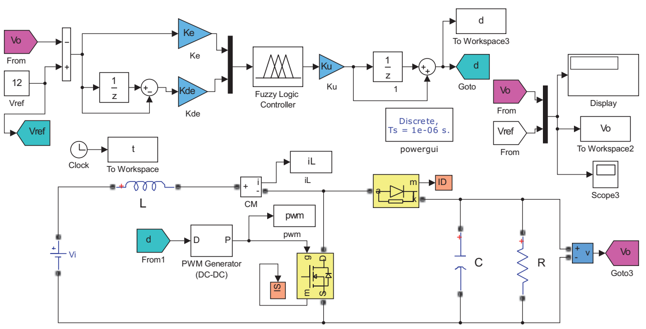

Fig. 5. DC-DC boost converter with FLC.

The first simulation test is carried out for the voltage reference $V_{ref} = 12V$. Fig.6 shows the responses of the output voltage, inductance current, error signal and duty ratio, respectively. These results demonstrate that the load voltage completely follows the desired trajectory. Additionally, it is proved that the time response needed to follow the reference model is very short ($0.05s$) and overshoot-free. It may be concluded that the suggested FLC performs effectively.

The second simulation test is carried out for an output voltage reference $V_{ref} = 10V$ and a variable resistive load ($R = 50\Omega \longrightarrow R = 60\Omega$) at $t = 0.5s$. The responses of the output voltage and inductance current are shown in Fig. 7. It is clear that despite the variation of the load, the output voltage follows, perfectly, its set point.

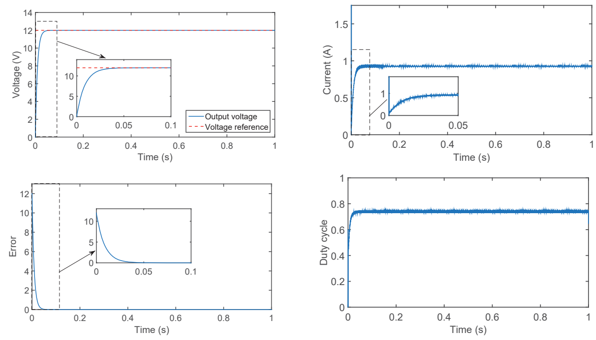

Fig. 6. Simulation results for a voltage reference $V_{ref} = 12V$.

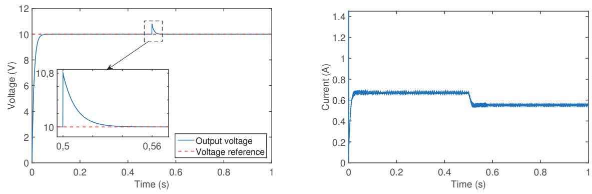

Fig. 7. Simulation results for a voltage reference $V_{ref} = 10V$ and variable load.

Experimental results

To connect Matlab/Simulink with the hardware setup, as shown in Fig. 8, a special package called "support package for Arduino hardware" was created by MathWorks, particularly for a microcontroller-based Arduino board. This package is used to validate the simulation results.

The considered hardware setup includes a DC power supply, a boost converter with voltage and current sensors, a USB oscilloscope, and a digital multimeter, as shown in Fig. 9.

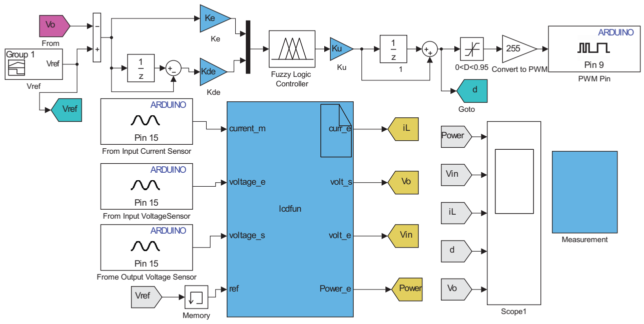

Fig. 8. Simulink model used to implement the FLC.

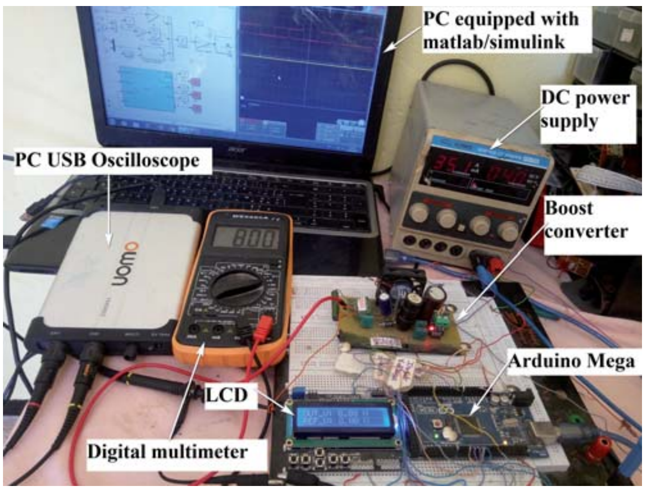

Fig. 9. FLC Hardware implementation using Arduino Mega and Matlab/Simulink environment.

The first experiment is carried out with an input voltage $V_{in} = 5V$ and a multi-step voltage reference. The experimental waveforms (recorded using MATLAB/Simulink environment) of output voltage, inductance current, error signal and duty ratio are displayed in Fig. 10. One can clearly see that the results from the simulation and the implementation are in good accord with one another.

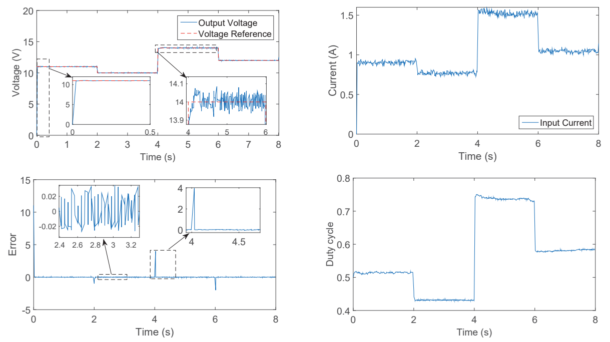

Fig. 10. Experimental results for multi-step voltage reference.

The second experiment is carried out using another multi-step voltage reference and input voltage $V_{in} = 5V$.

Fig. 11 illustrates the load voltage response obtained in by using MATLAB/Simulink environment, whereas Fig. 12 shows the load voltage waveform recorded on a PC USB oscilloscope. These figures make it obvious that they have the same shapes.

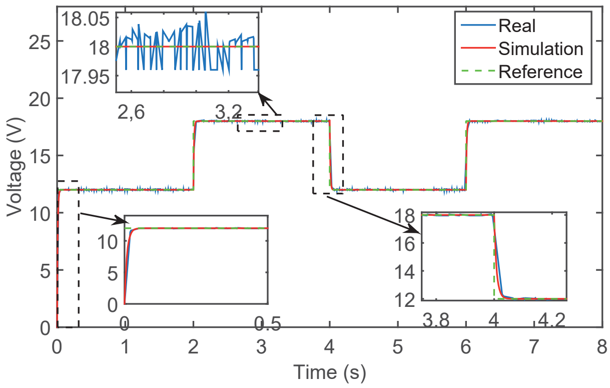

Fig. 11. Results recorded using Matlab/Simulink.

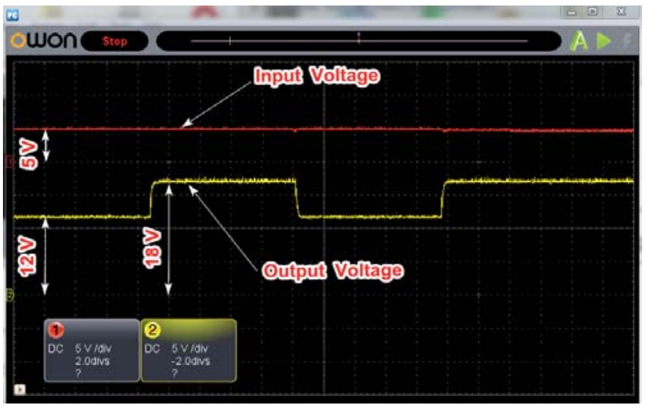

Fig. 12. Results recorded using PC USB oscilloscope.

Furthermore, the baseline PI controller and the suggested FLC are compared. Note that the transfer function given in (1) is used to calculate the PI gains using the known compensation method, as follows: $K_p = 0.0077$ and $K_i = 0.56$.

Fig. 13 shows the responses of the output voltage while Table 3 shows the performances comparison. It can be seen that the proposed FLC has high tracking speed and is also more efficient than PI.

It can be seen that the proposed FLC has a high tracking speed and is also more efficient than the PI as the output voltage responses with the proposed FLC tracks perfectly its reference voltage with much less oscillation, whereas the response of the load voltage with the compared controller exhibits a considerable amount of oscillation. It should be noted that the comparison PI controller can be adjusted to produce a faster time response, but in this case, an undesirable high peak overshoot will arise.

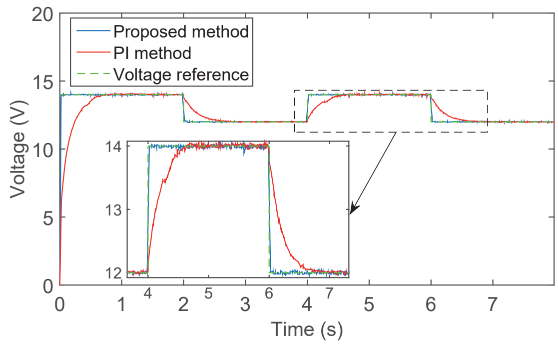

Fig. 13. Comparison between FLC and PI controllers.

Table 3. Performances comparison between FLC and PI controller

Method	PI controller	Fuzzy logic controller
Rise time (s)	0.1295	0.0192
Settling time (s)	0.2514	0.0235
Overshoot $(\%)$	0.3984	0.3799

These experimental tests show that independent of changes in input voltage or resistive load, the boost converter can be controlled by the proposed fuzzy logic controller to produce precisely the desired output voltage. They also show that it offers better performance than the conventional PI controller.

Conclusion

This work described the hardware implementation of a fuzzy logic controller for a DC-DC boost converter utilizing an Arduino-based microcontroller under Matlab/Simulink environment. The proposed controller has two inputs, which are the error and change in error and has one output which is the signal control. Each input and output is assigned a scaling factor to improve the performance of the controlled system. The developed prototype shows excellent performance in terms of dependability and precision in tracking the desired output voltage, according to the simulation and experimental results. A comparative study with the PI baseline controller shows that the proposed control structure gives a fast time response and superior performance.

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