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Design, simulation and comparative evaluation of both a classic and a fuzzy logic PI controller applied to a DC-DC converter

***Abstract**. This paper presents the design, simulation and comparative evaluation of both a classic proportional-integral (PI) controller and a fuzzy logic PI controller applied to the output voltage control of a DC-DC buck converter. The performance comparison was done in terms of overshoot and settling time simulated in Matlab-Simulink. Results demonstrated that the fuzzy logic PI controller has a superior performance compared to the classic PI controller, furthermore the design becomes simpler, since it is not necessary to find the mathematical model of the system to be controlled.*

Streszczenie:** W pracy przedstawiono projektowanie i badania symulacyjne układów sterowania przekształtnika DC-DC opartych na klasycznym regulatorze typu PI i regulatorze PI, zrealizowanym z wykorzystaniem logiki rozmytej. Zarówno projektowanie jak i badania symulacyjne zostały przeprowadzone przy użyciu programu Matlab – Simulink. Uzyskane wyniki wskazuję na lepsze właściwości układu sterowania zrealizowanego w logice rozmytej. **Projektowanie, symulacja i badania porównawcze właściwości układów sterowania z klasycznym regulatorem typu PI i regulatorem PI zrealizowanym z wykorzystaniem logiki rozmytej

Keywords: fuzzy controller, buck converter, PI controller.
Słowa kluczowe: regulator PI, logika rozmyta, przekształtnik DC-DC obniżający napięcie – typu buck.

Introduction

The proportional integral differential (PID) controller is widely used in industry due to its simple structure, easy implementation and low cost [1].

In the 40s, advances of analysis and modelling techniques in frequency domain allowed engineers to develop closed loop linear systems meeting desired performance requirements. Thereafter, in the following decades PID controllers started being used to control processes of physical quantities such as temperature, pressure among others [1].

On the other hand, fuzzy logic controllers (FLC) succeed well in solving problems where traditional mathematical modelling fails due to a lack of the complete knowledge of a particular system, or when the mathematical model of the system is known [2,3].

Some typical applications where FLC may be encountered are: liquid tank level control [4,5,6,7], torque and speed control of AC motors [8,9], speed control of DC motors [10,11,12], position control using a hybrid stepper motors [13], position control using a DC motor [14], single-axis solar tracking system [15], and power converters DC-DC [16,17,18,19,20] and DC-AC [21,22], among others.

The main idea behind the fuzzy logic control design is to extract the expert knowledge about the process to be controlled and apply that knowledge in developing a simpler solution using fuzzy logic tools, instead of developing the whole mathematical modelling of the process [23,24].

Differently from binary logic, which deals only with true and false variables, fuzzy logic may deal with a multitude of values and uncertain values within 0 and 1, allowing theirs variables to assume a larger range of values. Thus, the fuzzy reasoning methods may deal with linguistic variables associated with those numeric values using a degree of membership between 0 and 1 instead of the number. Typical linguistic variables may be: *absolute true*, *partially true*, *neutral*, *partially false* and *absolute false*, or any other ones which represent levels of uncertainty.

One of the main advantages for applying a fuzzy controller over a classic PID one is the similarity with human natural thinking and language [24]. From this point of view, in this paper we propose the design and simulation of both classic and fuzzy PI controllers applied to a buck converter. Using the simulation data we proceed to the comparison of both controllers in respect to their main performance parameters, that is, settling time and overshoot.

The Buck Converter

DC-DC converters are electronic systems comprised of power semiconductors operating as switches along with passive elements like inductors and capacitors as energy storing devices. Those switching converters are usually operated in high frequencies by using semiconductors devices that work in two states, *ON* and *OFF*, which results in smaller capacitors and inductors. These structures are able to deliver high power and assure low losses [25].

The buck converter is an example of a DC-DC converter that delivers at the output a voltage which is a fraction of the input voltage, by modulating the amount of time a switch stays opened and closed [26]. In Fig. 1 it is shown the standard diagram of a buck converter in its constituent parts: an input power source - V_{in}, a controlled switch, a diode - D, an inductor - L, a filter capacitor – C, and a resistive load RL. When the inductor's current is different from zero this particular state is called mode of continuous current.

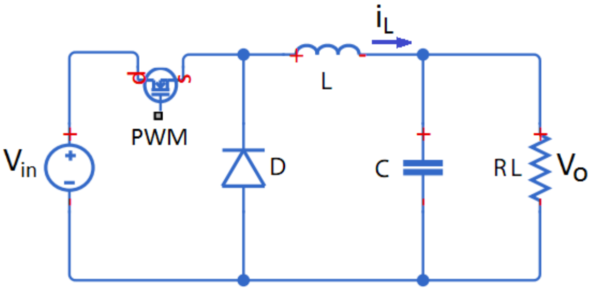

Fig.1. Buck converter topology

Design Parameters

The design parameters chosen for the buck converter are listed below:

- Output Voltage: V_o = 15 V
- Input Voltage: V_{in} = 25 V
- Output Power: P_o = 20 W
- PWM Switching Frequency: f_s = 20 kHz
- Maximum Inductor's Current Deviation: Δi_L = 5 %
- Maximum Load Voltage Deviation: ΔV_L = 1 %

By replacing the parameters above into Eq. 1 and Eq. 2, the values of the inductor and capacitor are obtained [26].

(1) $$L=\frac{(V_{in}-V_o).G}{\Delta i_L . f_s}=2.99mH$$

(2) $$C=\frac{1}{8}\frac{\Delta i_L}{\Delta V_L . f_s}=1.85\mu F$$

Where: G is the duty cycle, given by: V_o / V_L

Mathematical Model

The transfer function which relates the converter output voltage to the PWM duty cycle is presented in Eq. 3.

(3) $$H(s)=\frac{V_{in}}{(LC).s^2+(\frac{L}{R}).s+1}$$

In Eq. 4, the transfer function is presented with its design parameters replaced, which will be used later in the development of the classic PI controller.

(4) $$H(s)=\frac{4.5x10^9}{s^2+4.8x10^4 s+1.8x10^8}$$

The Classic Controller

The proportional integral derivative (PID) classic controller, as its name implies, is comprised of three adjustable parameters: a proportional gain (K_p), an integration gain (K_i) and a derivative gain (K_d), being the performance of the controller directly dependent of the suitable adjust of those three parameters. In today's industrial environment most of the controllers are PID [1].

The unitary step response of the system represented by Equation 4 in open loop can be seen in Fig. 2.

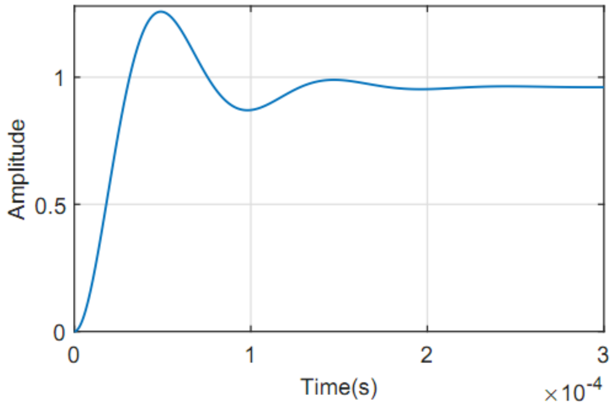

Fig.2. System's unitary step response without any controller

Using the **rltool()** tool in Matlab, it was possible to obtain a proportional integral (PI) controller whose mathematical model is shown in Equation 5, producing an overshoot less than 20 %.

(5) $$C=\frac{0.2064(s+8620)}{s}$$

A better unitary step response of the system can be achieved using the PI controller from Eq. 5 in a closed loop with the system's transfer function from Eq. 4, as can be seen in Fig. 3.

It is possible to note from Fig. 2 that the resulted overshoot for the system without any controller is over 20 % and the voltage reference is not achieved, implying a steady state error.

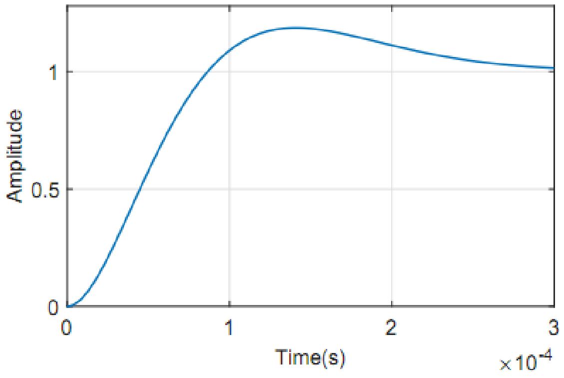

Fig.3. System's unitary step response with the classic PI controller

On the other hand, the system with the classic PI controller presented an overshoot less than 20 %, and in steady state the reference was asymptotically reached, as shown in Fig. 3.

The Fuzzy Controller

In functional terms a fuzzy control system is composed of the following constituent parts [27]:

- Fuzzification interface - whose functions is to convert the controller discrete input variables into linguistic fuzzy variables that the inference mechanism can easily use to activate and apply rules;
- Rule-base (knowledge base) - which contains the expert's knowledge using linguistic description in terms of If-Then rules, describing how to control the system properly;
- Inference engine or inference mechanism - emulates the expert's decision making in interpreting and adapting knowledge about how to control the system;
- Defuzzification interface - whose functions is to convert the conclusion of the inference mechanism into actual output of the controller.

For the implementation of a fuzzy controller some basic design steps must be accomplished [28]:

1. Choosing the type of fuzzy controller implementation model (PID, PI, ...) and type of inference system (Mamdani, Sugeno);
2. Choosing the input and output variables, based on the implementation model, theirs universe of discourse and creating the linguistic context of those variables, which constitutes the semantics associated to each variable;
3. Choosing format and number of membership functions for the input and output variables in order to create the fuzzy variables used in the fuzzification process;
4. Creating the inference rules based on an human expertise in order to associate input and output fuzzy variables;
5. Choosing and creating the defuzzification process in order to provide the controller's output value.

A fuzzy logic PI controller is expressed by Equation 6.

(5) $$dU = K_P.E + K_I.dE$$

Where: the two inputs are: the error - *E*, and the error variation - *dE*; and the output: the output variation - *dU*.

In order to implement the fuzzification interface, some typical linguistic variables appropriate for defining a quality instead of a quantity must be chosen, such as: "Negative Big" (NB), "Negative Mean" (NM), "Negative Small" (NS), "Neutral" (ZE), "Positive Small" (PS), "Positive Mean" (PM) and "Positive Big" (PB), or any other suitable terms.

In Fig. 4 it is shown the designed membership functions for the controller's input variable Error - E, represented by the linguistic fuzzy variables: NB, NM, ZE, PM and PB, being the input ranging from -30 to 30 considering that the desired output is 15 V.

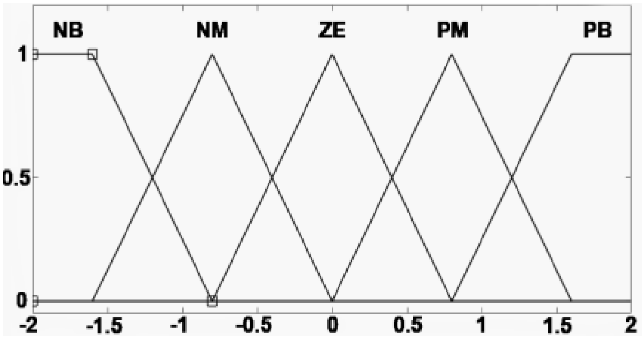

Fig.4. Membership functions for the input variable Error: *E*.

In Fig. 5 it is presented the designed membership functions for the controller's input variable Error Derivative - *dE*, being their shapes and displacements similar to the Fig. 4, except that the limits are from -2 to 2, since it represents a differential error.

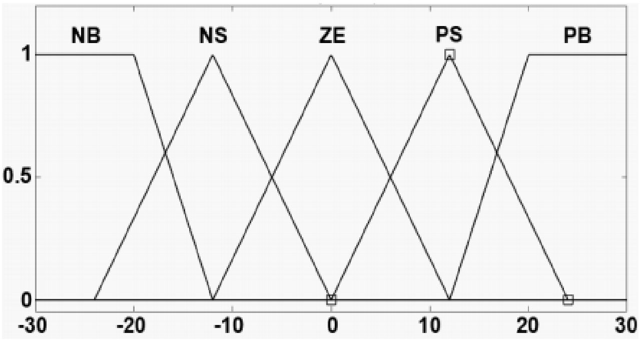

Fig.5. Membership functions for the input variable Error Derivative: *dE*.

Finally, in Fig. 6 it is presented the designed membership functions for the output variable Output Derivative - *dU*. Note that for the output variable it is ranging from -25 to 25 and there are 7 membership functions instead of 5, since a fine adjust for the control law is needed. The output membership functions are those 5 present in the input variables (NB, NM, ZE, PM and PB), plus the Positive and Negative Small (PS and NS).

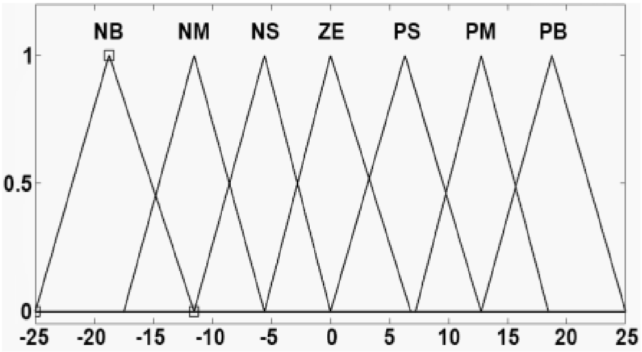

Fig.6. Membership functions for the output variable Output Derivative: *dU*

The inference rules used for the implementation of the control rule are presented in Table 1. The inference engine used is the Mamdani fuzzy inference system.

The format of each rule for the PI fuzzy logic controller is as shown below:

IF *error* = E_i ***AND*** *error variation* = dE_i ***THEN*** *control variation* = dU_i

Where: E_i and U_i are the sets of membership functions for the *e* and *u* variables.

Table 1. The inference rules presented as a rule table.

E/ΔE	**NB**	**NM**	**ZE**	**PM**	**PB**
NB	NB	NB	NB	NB	NM
NM	NB	NM	NS	ZE	PS
ZE	NM	NS	ZE	PS	PM
PM	NS	ZE	PS	PM	PB
PB	PM	PB	PB	PB	PB

In this case the fuzzy controller has two input variables: the error and its first derivative.

Note that the controller's output must be integrated, since it is in fact a derivative output.

The defuzzification process, which is the final process toward to the control action, will demand the composition of the resulted recommendations of the activated rules by the inference engine, resulting in a single discrete output value. In fact, the composition of the rules will be fuzzy operations over fuzzy sets.

Using the **fuzzyLogicDesigner** tool of Matlab the membership functions for the input and output variables and the inference rules were implemented based on a Mamdani fuzzy inference system. For the defuzzyfication process the chosen method was the centroid.

In order to evaluate the FLC, a step function was applied to the buck converter (represented by Eq. 4 having the controller in the closed loop as seen in Fig. 7.

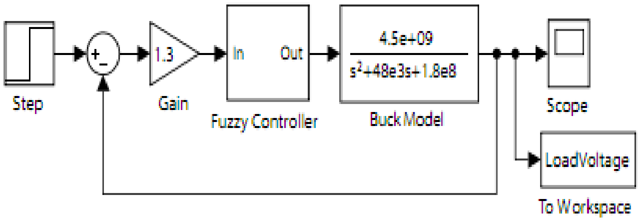

Fig.7. Simulink model for the complete system using the FLC

In Fig. 8 the Fuzzy Controller block of Fig. 7 can be seen in details. Notice that, at the input, the resulting error which is the subtraction of the reference and the output is delayed of one sample *E(k-1)* and then this result subtracted from the actual error *E(k)*. Therefore, the fuzzy logic controller receives at its two input variables: *E(k)* and *dE(k) = E(k) - E(k-1)*.

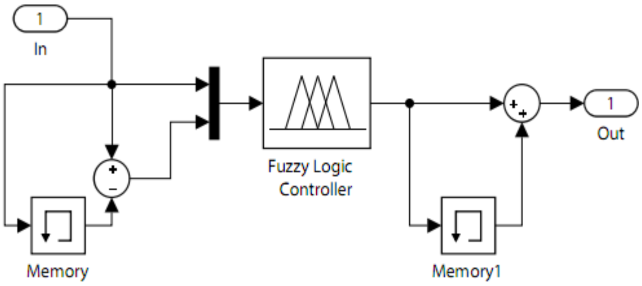

Fig.8. Detailed Fuzzy Controller block of Figure 7.

The resulted control law at the fuzzy controller's output is evaluated as the sum of the actual result plus the previous result, that is: $U(k) = U(k) + U(k-1)$.

Another simulation made in Simulink used the electronic circuit of the buck converter as shown in Fig. 1 instead of its mathematical model. In this alternative simulation the block 'Buck Converter' inside the Simulink block diagram was already shown in Fig. 9. In this block diagram notice the presence of the PWM Generator block (frequency set to 20 kHz) receiving the control output of the FLC, the Buck Converter block following the PWM Generator block and the same 15 V step function applied as the reference input. In this simulation a load step at 1.5 ms from 50 to 100% load power (20 W) was provided to the buck converter and the same scenario applied to the classic PI controller.

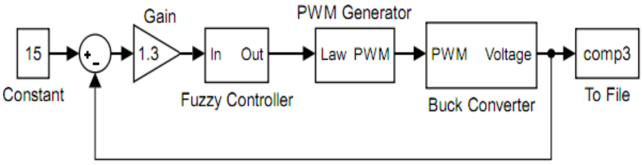

Fig.9. Detailed Fuzzy Controller block of Figure 7.

The Classic Controller

The output signal showed at the Scope block of Fig. 7, which is the response to a 15 V step applied at the system model of Equation 4, can be seen in Fig.10. Notice that the overshoot is less than 20 %, in fact the overshoot is zero. Also, notice that the steady state error is less than 2 %, therefore less than the system requirement given by the design parameters.

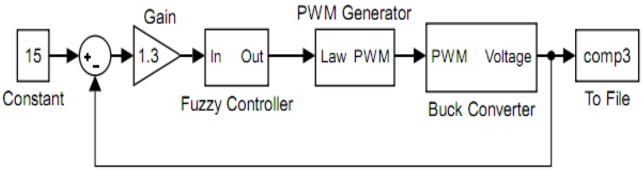

Fig.10. Step response for a 15 V step using the fuzzy controller

In Fig. 11 it is shown a comparison between the simulated step response for the classical PI controller and the fuzzy controller when a 15 V step is applied. As the Fig. 11 shows the fuzzy controller presents a much better performance in terms of settling time and overshoot.

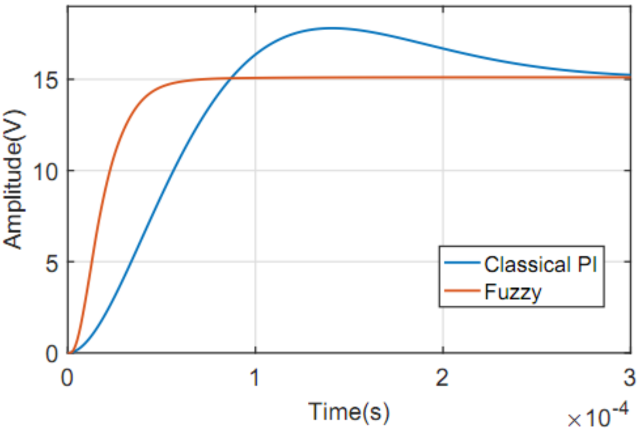

Fig.11. Classic and fuzzy logic PI controllers step response comparison without any disturbance.

For the alternative simulation using the electronic circuit of the buck converter instead of its mathematical model, the Fig. 12 shows the step response with the load disturbance at 1.5 ms from both classic and fuzzy PI controllers, and once again the fuzzy approach presented a much better performance in terms of overshoot and settling time. In terms of maximum voltage and current variation in both controllers the response was in accordance with the design parameters.

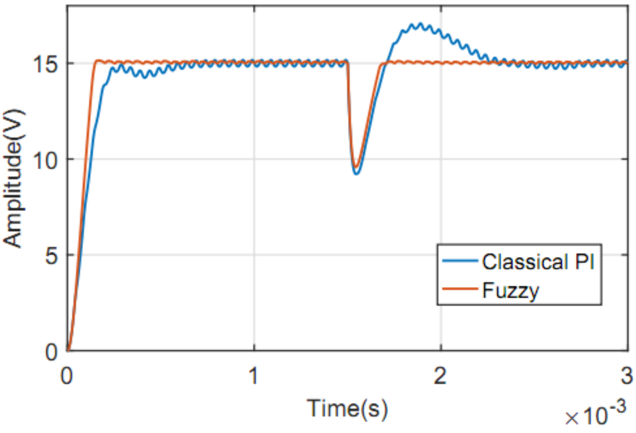

Fig.12. Classic and fuzzy logic PI controllers step response comparison without any disturbance.

Conclusions

As seen in reference [12] where a comparative study was done between both a PID and a fuzzy logic controller when applied to DC motor speed control, revealing a superior performance of the FLC over the PID, in this paper we have shown that the use of a FLC to control the output voltage of a buck converter also demonstrated the same superior performance as compared to a classic PI Controller. The superior performance was noticeable in terms of overshoot and settling time, therefore having also a superior stability. Notice however, that in both controllers the maximum current and voltage variation specified as design parameters were observed.

Another great advantage in applying the fuzzy approach is the fact that no mathematical model knowledge of the system is required, only the expert knowledge about the system working in order to build the inference rules and membership functions.

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