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Regulating the Output Voltage of Buck-Boost Converters Using General Type2 Fuzzy Controller

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Abstract
Power electronic converters have been considered by many researchers and their control and robustness under various operating conditions has a great importance. The proposed type-2 fuzzy controller employs expert experience to control the power electronic converters, considering to their non-linear and time variant structure. Using type-2 fuzzy controller enhances the stability and robustness of system. This paper's attempt is to compare general and interval type-2 fuzzy controllers in terms of dealing with non-linear uncertain plants. It is shown that general type-2 fuzzy controller leads to more accuracy in comparison with interval type-2 and type-1 fuzzy controllers in regulating the output voltage, as it is shown in simulation part. To compare the performance of the controlling methods, the Euclidean norm of regulating error is calculated.

Keywords: Buck-Boost, Power Electronics Converters, Interval Fuzzy Type-2, General Fuzzy Type-2, Voltage Regulator.

1. INTRODUCTION

In the recent years, due to the use of renewable energy for power generation and the use of dc-dc converters in these industries, researchers have been drawing attention to these converters to improve their behavior [1]. One of the most important problems, caused by common plants of these converters is the uncertain variations of load and input voltage which leads to undesirable variations of output voltage. Importance of these variations is limited leads to development of different controlling methods which have been proposed in this field.

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These systems are combinations of semi-conductors which control the electrical power transition. The appearance of semi-conductors in 1950s was an important new stage in improvement of Switched Mode Power Systems (SMPS) such as boost converters. Since 1960s, DC-to-DC converters, which have been equipped by switchable semi-conductors, were introduced. The requirement of the industry to decrease the volume and weight and increasing the efficiency of these converters has led to their sharp advancement during recent years.

The achievement of a constant voltage in the output is possible by choosing a suitable power converter. DC-to-DC converters are used for increasing or decreasing the voltage. Typically, a Buck converter is used to decrease the input voltage in the output. A Boost converter is applicable for increasing the output voltage. Also, a Buck-Boost converter is considered as a linear converter in voltage setting for increasing or decreasing the voltage. Multi-level converters with one or two-direction power transition are another design feature [2]. Different studies have presented various type of topologies [3-6], controlling methods [7-13] and design features [14-15], depending on the voltage and power of converter. Proportional Integral Differential (PID) controllers are of the most common controllers in the industry. Despite their simplicity, these controllers have an acceptable performance in most cases. The introduction of artificial intelligence (AI) has brought a new era in industrial applications. Among different AI techniques, fuzzy logic control and neural network control are common. The fuzzy type-1 controllers which followed by type-2 fuzzy controllers have better behavior in contrast with non-conformity in the comparison with fuzzy type-1. One of the most important features of type-2 fuzzy sets is the ambition declaration. The fuzzy type-2 is used in cases where an exact membership function may not be found for a fuzzy set. Type-1 Fuzzy sets only solves the ambition, but they are not able to declare the ambition.

The fuzzy theory was executed on a power system firstly by Dr lotfi zade in 1965[17-18]. The proposed controller enhanced the results of linear controllers which have been applied to DC-to-DC converter previously [19]. In recent years, there have been growing attempts on the application of the fuzzy theory and neural/ neuro fuzzy networks on DC-to-DC converters [20-23]. The Pi-Like FLC fuzzy controller was introduced in [24-25]. The application of the Pi-Like FLC fuzzy controller on three DC-to-DC converter models including Buck, Boost and Buck-Boost converters was suggested in [26]. Fuzzy type-2 controller was introduced by Zadeh (1975) as an extension of fuzzy type-1 controllers [27]. The main components of the type-2 fuzzy sets introduced by Karnik and Mendelwere presented for practical applications [28-30]. The implementation of type-2 fuzzy controllers on power electronics systems was proposed in [31] for the first time.

In this paper a PI controller based on general fuzzy type-2 is proposed to adjust the power electronics converters' output voltage and the error index is introduced to define the efficiency of controllers. A new model, performed in this paper, shows that the recommended scheme is practical. The advantage of general type-2 fuzzy toward type-1 and interval type2, is evaluated by applying general type-2 fuzzy controller to three different topologies of nonlinear DC-DC converter.

This paper follows three main parts. The mathematical description of interval type2 fuzzy will be investigated in section 2. The application of the recommended controller to power electronics converters is presented in section 3. Section 4 presents the simulation results followed by the conclusion and summary in section 5.

2. GENERAL TYPE-2 FUZZY SET

The block diagram of the fuzzy type-2 controller is depicted in figure 1 for controlling a power electronics converter. As shown in figure1, a type-2 fuzzy controller consists of fuzzifier, defuzzifier, rules, data and the decision-making part. Before introducing the general fuzzy type-2 controller, we present some basic information as below.

There are various methods for defining type-2 fuzzy sets. It should be mentioned that the controlling methods that consider the third dimension in calculations, are known as the general type-2 fuzzy ones.

The vertical slice representation of the fuzzy type-2 is the extension of the representation of the fuzzy type-1. According to the Extension Principle, a fuzzy type-2 may be defined as below [30]:

$$\tilde{A} = \int_{x \in X} \mu_{\tilde{A}}(x.u) \,/x \qquad (1)$$

$$\mu_{\tilde{A}}(x) = \int_{u \epsilon J_x \in [0.1]} (f_x\,(u) = 1)/u \ , \quad J_x \epsilon [0.1] \qquad (2)$$

Tabel 1. ***Symbols.***

	Symbol	Meaning
1	$\mu_A(x)$	membership function of A Collection
2	$\mu_{\tilde{A}}(x)$	secondary or vertical membership function of A Collection
3	u	vertical slice domain
4	*	t -norm
5	v	t-conorm
6	$\overline{\mu}$, $\underline{\mu}$	upper/lower bonds
7	Δu_r	right hand points
8	Δu_l	Left hand points
9	Δu_s	highest part of the general fuzzy
10	α	Fuzzy type reducer

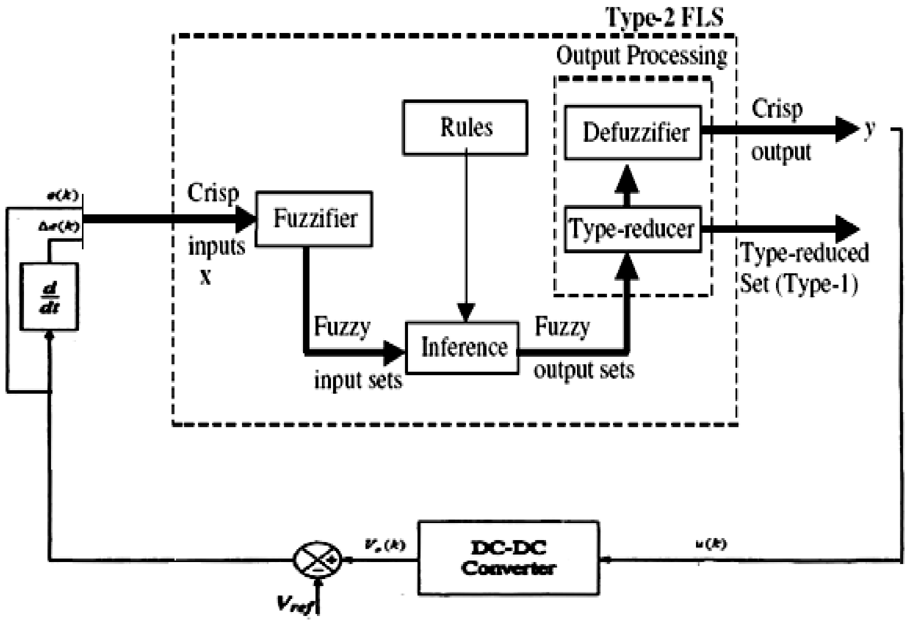


Fig.1. Block diagram of the type-2 fuzzy set.

where x is the input variable, $\mu_{\tilde{A}}(x)$ is the secondary membership function or the vertical slice that is indeed a fuzzy type-1 membership function. In addition, f_x (u) is the secondary membership function grade and u represents the vertical slice domain. Figure2 illustrates 2.5-D of the vertical slice show method.

Three operators used in fuzzy systems are union, intersection and complement. According to the Extension Principle [27], these relationships may be represented as below:

$$Union: \quad \bar{\tilde{A}} \cup \tilde{B} \leftrightarrow \mu_{\tilde{A}\cup\tilde{B}}(x) = \mu_{\tilde{A}}(x) \cup \mu_{\tilde{B}}(x) \int_u \int_w (f_x(u) * g_x(w))/(u \vee w) \qquad (3)$$

$$Inter\ section: \quad \bar{\tilde{A}} \cap \tilde{B} \leftrightarrow \mu_{\tilde{A}\cap\tilde{B}}(x) = \mu_{\tilde{A}}(x) \cap \mu_{\tilde{B}}(x) \int_u \int_w (f_x(u) * g_x(w))/(u * w) \qquad (4)$$

$$Compement: \quad \bar{\tilde{A}} \leftrightarrow \mu_{\tilde{A}}(x) = \int_u \frac{f_x(u)}{1-u} \qquad (5)$$

In general, the calculation of union and intersection using relations (3) and (4) is very difficult and there is not any proposed close formula for calculation of both relations so far. However, Karnik and Mendel [29] have presented an approximated relation for calculating the aggregation by using the multiplication operator when all of the membership functions are Gaussian, their result is also a Gaussian function.

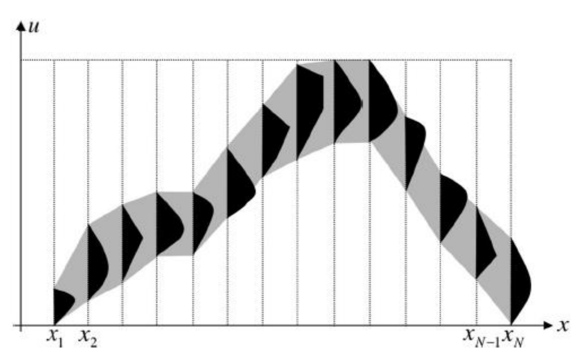


Fig. 2. 2.5-D representation of the vertical slice.

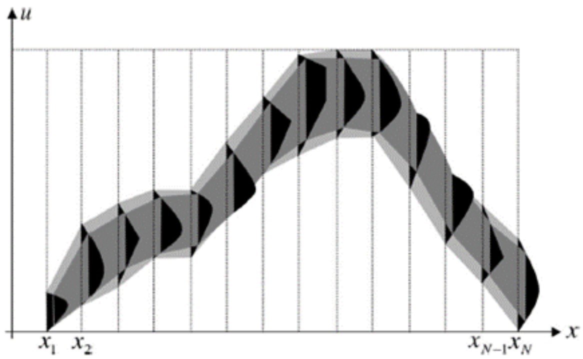


Fig. 3. The type-2 fuzzy membership function with an Å$_\alpha$ slice.

For the highest and the lowest membership function, the aggregation and sharing between two sets may be obtained as below [37]:

$$\tilde{A} \cup \tilde{B} = 1/[\mu_{-\tilde{A}}(x) \vee \mu_{-\tilde{B}}(x), \bar{\mu}_{\tilde{A}}(x) \vee \bar{\mu}_{\tilde{B}}(x)] \quad (6)$$

$$\tilde{A} \cap \tilde{B} = 1/[\mu_{-\tilde{A}}(x) \wedge \mu_{-\tilde{B}}(x), \bar{\mu}_{\tilde{A}}(x) \wedge \bar{\mu}_{\tilde{B}}(x)] \quad (7)$$

$$\tilde{A} = 1/[1 - \mu_{-\tilde{A}}(x), 1 - \bar{\mu}_{\tilde{A}}(x)] \quad (8)$$

As it is mentioned above, interval type-2 fuzzy contains simple relations. For example, for the aggregation of two type-2 fuzzy sets, the highest/lowest membership functions of both sets are aggregated separately. For this reason, the general type-2 fuzzy structure is usually represented by the interval type-2 fuzzy one. A method introduced for this purpose is the α-plane representation method that is the most prevalent representation presented for type-2 fuzzy sets which the gravity center of the fuzzy type-2 membership functions may be easily found with trivial calculations [33-35]. Liu proved it as the slice planes lemma for fuzzy type-2 sets [35] as below :

Lemma 1:

The α-plane $\tilde{A}_\alpha$ is the aggregation of all of the main membership functions whose secondary function membership degree is bigger than α, i.e.:

$$\widetilde{A_\alpha} = \cup_{x\in X}\ (x,u)|\mu_{\tilde{A}}(x,u) \geq \alpha = \cup_{x\in X}\ (\mu_{\tilde{A}}(x)))_\alpha \quad (9)$$

As a result, the fuzzy type-2 set may be obtained from the aggregation of $\tilde{A}_\alpha$s:

$$\tilde{A} = \cup_{\alpha\in[0,1]}\ FOU(\tilde{A}_\alpha) = \cup_{\alpha\in[0,1]}\ \alpha/(\tilde{A}_\alpha) \quad (10)$$

In fact. with this method, a vertical slice type-2 fuzzy set is transformed into the aggregation of several type-2 fuzzy sets. Figure 3 shows a fuzzy type-2 function on which there is an $\tilde{A}_\alpha$ slice to become an interval type-2 fuzzy.

Now aggregation and sharing may be presented as below [33]:

$$\tilde{A} \cup \tilde{B} = \frac{\cup_{\alpha\in[0,1]}\alpha}{(\widetilde{A\cup B})_\alpha} = \frac{\cup_{\alpha\in[0,1]}\alpha}{\tilde{A}_\alpha \cup \tilde{B}_\alpha} = \cup_{\alpha\in[0,1]}\ FOU(\tilde{A}_\alpha \cup \tilde{B}_\alpha) \quad (11)$$

$$\tilde{A} \cap \tilde{B} = \frac{\cup_{\alpha\in[0,1]}\alpha}{(\widetilde{A\cap B})_\alpha} = \frac{\cup_{\alpha\in[0,1]}\alpha}{\tilde{A}_\alpha \cap \tilde{B}_\alpha} = \cup_{\alpha\in[0,1]}\ FOU(\tilde{A}_\alpha \cap \tilde{B}_\alpha) \quad (12)$$

The above-mentioned relations transform the general type-2 fuzzy into several interval type-2 fuzzy so that the calculation of gravity center and other relations is rather easy. Figure 4 shows the block diagram of $\tilde{A}_\alpha$. As seen in figure 4, for α = 0, we have a fuzzy type-2 system.

In figure 5.a the fuzzy sets obtained by $\alpha = 0$ is considered, in such conditions, it converts to an interval type-2 fuzzy system. figure 5.b shows the conversion to type 1 fuzzy sets considering $\alpha = 1$.The output fuzzy sets used in center of gravity defuzzification are defined in figure 5.c.

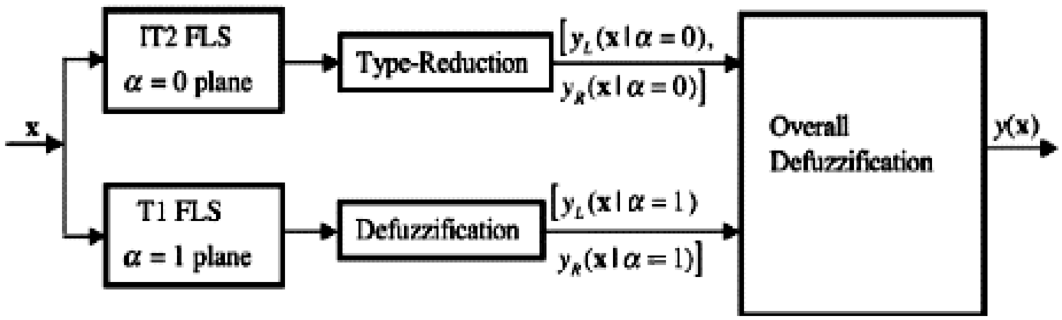
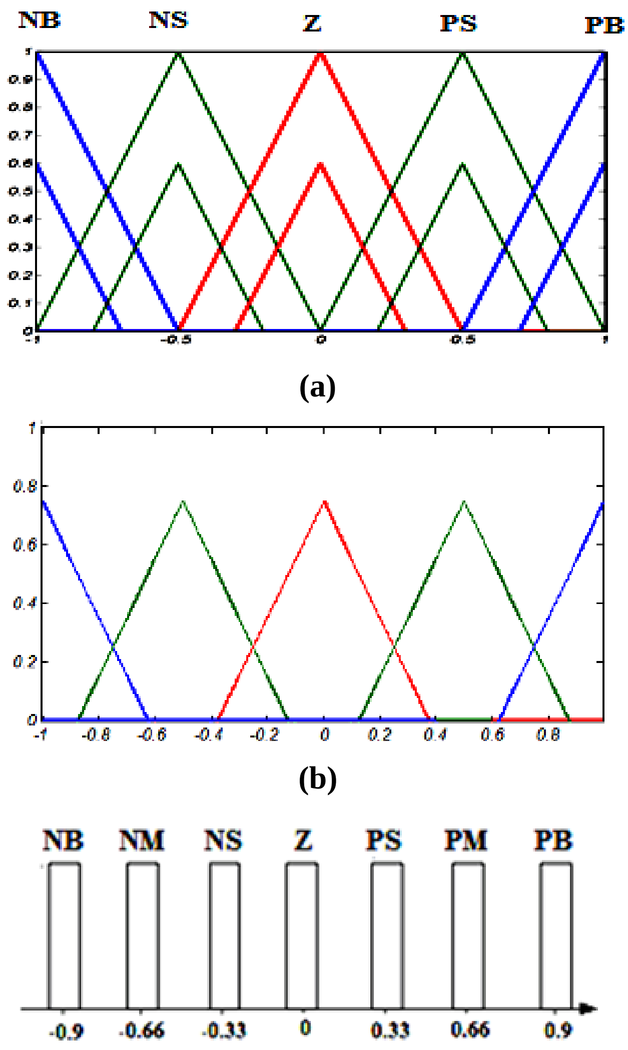


Fig.4. transformation of the general fuzzy type-2 into the fuzzy type-2 with $\tilde{A}_\alpha$ slices.



(c)

Fig. 5. Representation of t-norm calculation in range fuzzy type-2: (a) input functions α =0 (b)input functions α = 1. (c)output functions.

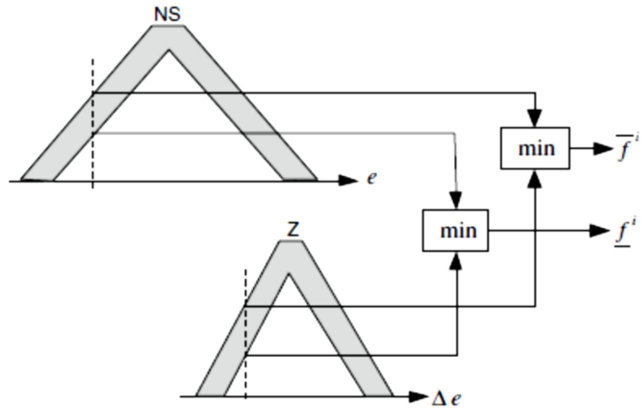


Fig. 6. calculation of t-norms in the range fuzzy type-2.

In the sequel the process of finding, the center of interval type 2 fuzzy sets will be explained.

According to the above-mentioned explanations, this paper uses the $\tilde{A}_\alpha$ representation method to demonstrate the fuzzy set.

The calculation of t-norms is explained as below:

$$\bar{f}^i = \mu_{A(e)^i} * \mu_{B(\Delta e)^i} \quad (13)$$

$$\underline{f}^i = \mu_{-A(e)^i} * \mu_{-B(\Delta e)^i} \quad (14)$$

As a result:

$$f^i = [\bar{f}^i \,.\, \underline{f}^i] \quad (15)$$

where $\bar{\mu}$ and $\underline{\mu}$ show the upper/lower bonds of the membership functions and * shows the t-norm operation.

Opposite to the fuzzy type-1, for the fuzzy type-2, in order that the defuzzifier can give a definite value, it needs a degree reducer. Different types of degree reducers include centroid, points centers, highest points, etc. This paper used the points centers method for fuzzy degree reduction. The degree reducer equations are given below:

$$\Delta u_{cos} = \int_{w^l \in [w_1^l, w_u^l]} \int \cdots \int_{w^M \in [w_1^M, w_u^M]} \int_{f^1 \in [f^{-1}, f_-^1]} = 1 \Big/ \frac{\sum_{i=1}^{M} f^i w^i}{\sum_{i=1}^{M} f^i} \quad (16)$$

In the above relation, Δu_c shows a fuzzy type-1 introduced with right (left)-hand points as Δu_r (Δu_l). So Δu_r and Δu_l must be found in order to calculate Δu_{cos}. There are two fuzzy type-1 logics whose secondary parts are c_r and c_l:

$$\triangle u_i = 1/\frac{\sum_{i=1}^{M} f_1^i w_1^i}{\sum_{i=1}^{M} f_1^i} \quad (17)$$

$$\triangle u_r = 1/\frac{\sum_{i=1}^{M} f_r^i w_r^i}{\sum_{i=1}^{M} f_r^i} \quad (18)$$

where the procedure of calculating Δu_r and $\Delta u_l$is defined by details in [36]. The calculation of a crisp value output is done by defuzzifier. For an interval type-reduced set, the defuzzified output can be obtained by following averaging:

$$\Delta_{u_{fc}} = \frac{\Delta u_1 + \Delta u_h}{2} \quad (19)$$

According to figure 4, the overall deffuzified output is the average of two crisp values that should finally be defuzzified. As a result:

$$\Delta u_{fc-overall} = \frac{(\Delta u_1 + \Delta u_h) + \Delta u_s}{3} \qquad (20)$$

where Δu_s is the highest part of the general fuzzy type-2 in the 3rd dimension. According to the fact that the membership function of the fuzzy 3rd dimension shows the importance of the internal functions of each range, it should be determined based on the experience of a plant's expert

$$\Delta u_{fc-overall} = \frac{(\Delta u_1 + \Delta u_h) + k\Delta u_s}{K+2} \qquad (21)$$

In this paper, after some examinations two determine that Δu_s with a big coefficient is very near to the upper bond of the range, and consequently k=8 has been chosen**.**

The recommended controller in this paper is a Pi-Like fuzzy controller which the related implementation is shown in figure 7.

3. CONTROLLER INFERENCE AND RULES

The recommended proportional controller, PI is defined as the general scheme below:

$$U = k_p e + k_i \int e\, dt \qquad (22)$$

where k_p and k_i are proportional and integral gains respectively. Differentiating (22) leads to:

$$\dot{U} = k_p \dot{e} + k_i e \qquad (23)$$

This relation is the basis of making a fuzzy system where fuzzy rules are presented as below:

If e(k) is A and ∆e(k) is B then ∆u(k) is C

where A and B are the conditions and C is the result. The fuzzy block inputs are the error and its differentiation, whereas the fuzzy output is the control signal that is transformed into u(k) with the help of a discrete integration.

This rule is observed in Table.2 for the model designed for the upper/lower bonds of the membership functions. For the fuzzy type-2 method, the conditions are the same, with the exception that the membership functions have upper/lower limits which is shown as below:

If e(k) is $\tilde{A}^i$ and $\tilde{B}^i$ is ∆e(k) then ∆u(k) is w_l^i and w_r^i

where the ∼ operator indicates the upper/lower bonds and i is the membership function used obtained for every range of α slices.

4. APPLING OF THE FUZZY LOGIC CONTROLLER ON BASIC POWER ELECTRONICS CONVERTER

The controller design steps were implemented so far. Now it should be applied to the plant. The equations of the status of converters are defined as the following linear relations.

Boost converter's governing equations are as follows:

$$\frac{di_L}{dt} = \frac{-r_L}{L} . i_L - \frac{(1-k)}{L} . v_C + \frac{1}{L} u(t)$$
$$\frac{dv_C}{dt} = \frac{(1-k)}{C} . i_L + \frac{1}{C.R_L} . v_C \qquad (24)$$

Buck converter's governing equations:

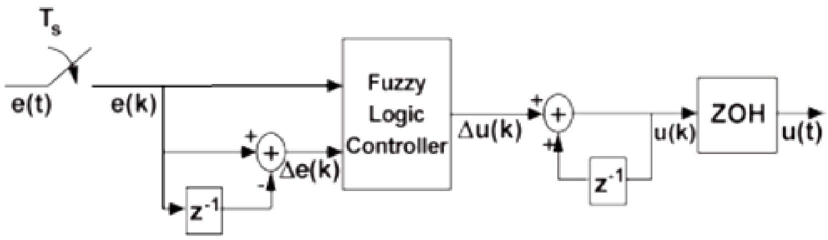


Fig.7. The Pi-Like FLC control digital model.

Table 2. ***Fuzzy if-then rules for the power converter control based on figure 5.***

e(k)/Δe(k)	**NB**	**NM**	**Z**	**PM**	**PB**
NB	NB	NB	NB	NB	**NM**
NM	NB	NM	NS	Z	**PS**
Z	NM	NS	Z	PS	**PM**
PM	NS	Z	PS	PM	**PB**
PB	PM	PB	PB	PB	**PB**

Table 3. Parameters considered for the three converters.

	boost	**Buck**	**Buck-boost**
Inductance L (µH)	250	200	100
Capacitance C (µF)	50	50	100
Inductance series resistance ($r_L\Omega$)	0.1	0.1	0.1
Capacitance series resistance ($r_c\Omega$)	0.1	0.1	0.1
Loud resistance ($R_L\Omega$)	25	10	10
Input voltage (v)	15	15	15
Reference voltage (Vref)	25	5	5
Switching frequency (Khz)	1	1	1

$$\frac{di_L}{dt} = \frac{-r_L}{L}.i_L - \frac{1}{L}.v_C + \frac{k}{L}u(t)$$
$$\frac{dv_C}{dt} = \frac{1}{C}.i_L + \frac{1}{C.R_L}.v_C \quad (25)$$

Buck-Boost converter's governing equations:

$$\frac{di_L}{dt} = \frac{-r_L}{L}.i_L - \frac{(1-k)}{L}.v_C + \frac{k}{L}u(t) \quad (26)$$

$$\frac{dv_C}{dt} = \frac{(1-k)}{C} . i_L + \frac{1}{C.R_L} . v_C$$

The software that used to simulate the proposed controller on the mentioned converters is "matlab" software. Dynamic relationships (24-26) are implemented in this software. Table 3 presents the values for the inductor, capacitor, resistor, and input and reference voltage values.

To apply the proposed controller on plant we follow these steps:

1. Consider converter's output voltage error and its differential as fuzzy controller crisp inputs (fig 7).
2. Consider input fuzzy sets as defined in figure 5 to fuzzify the crisp inputs for $\alpha = 0$ which lead to interval fuzzy sets.
3. Implement fuzzy rules according to Table 1.
4. Calculation of output for interval fuzzy sets using center of gravity method.
5. Consider input fuzzy sets as defined in figure 5 to fuzzify the crisp inputs for $\alpha = 1$ which leads to type1 fuzzy sets.
6. Use relations (19) and (20) to find the center of gravity of output fuzzy sets. It is clear that for type 1 fuzzy sets of step '5' the output sets will be similar to figure 5.c.
7. Calculate the controller output using a weighted average of outputs obtained from steps 4 and 6 using equation (20) or (21).
8. The output is implemented to converter in the form of an amplified voltage from 0v to 5v.

This paper used the error index parameter in order to investigate the effect of the recommended controller. In case that a system improves a parameter such as the error index at a specific time, the system is expected to have a better performance at all times.

We know that error refers to the difference of a variable trying to reach its set point. The sooner the voltage reaches the point, the better error index would be achieved. The error index relation may be shown as one of the following relations:

$$error\ index(IAE) = \int_0^t |e(t)| . dt \qquad (27)$$

$$error\ index(ISE) = \int_0^t (e(t))^2 . dt \qquad (28)$$

where $e(t) = v_o - v_{ref}$. The above relations are done in order to collect all of the error values including positive and negative ones. When a system takes a long time to reach the final value, it would have a large error index. As a result, this parameter is a good measure for the comparison of different systems in terms of the response rate and permanent state error.

Figures 8 to 10 show the output voltage of three converters obtained with the help of the designed fuzzy controller. Figures 11, 12 and 13 show the calculated error index for type-1 fuzzy controller [29], interval type-2 fuzzy controller [30] and general fuzzy type-2 defined in this paper.

It should be mentioned that due to the lack of effect of setting the controlling parameters, for the progressive steps from the fuzzy type-1 to the general fuzzy type-2, the parameters, rules and the conclusion model do not change relative to the previous state.

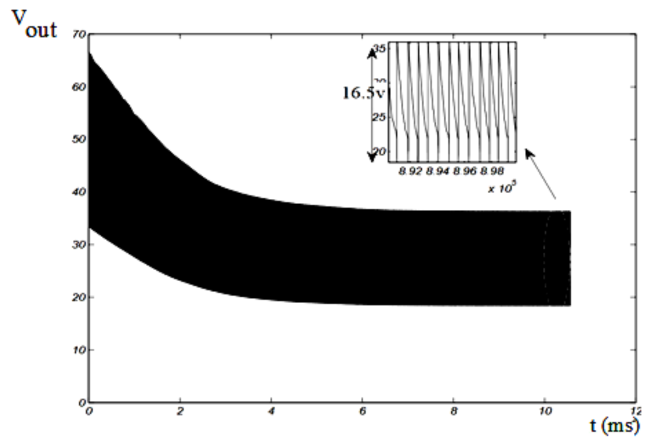


Fig. 8. The output voltage of the Boost converter with the general fuzzy type-2 controller.

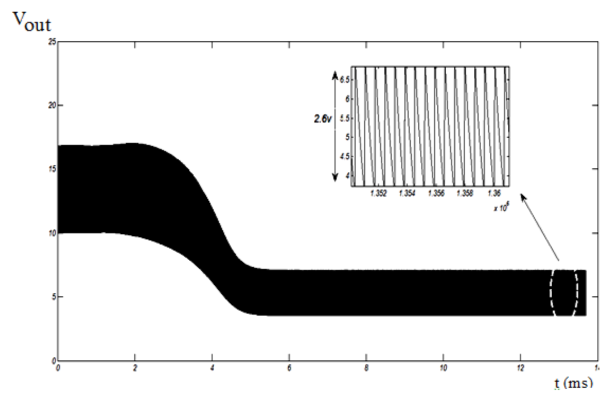


Fig. 9. The output voltage of the Buck converter with the general fuzzy type-2 controller.

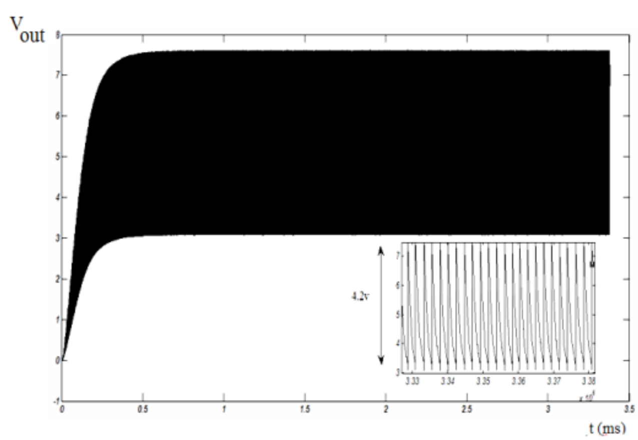


Fig. 10. The output voltage of the Boost converter with the general fuzzy type-2 controller.

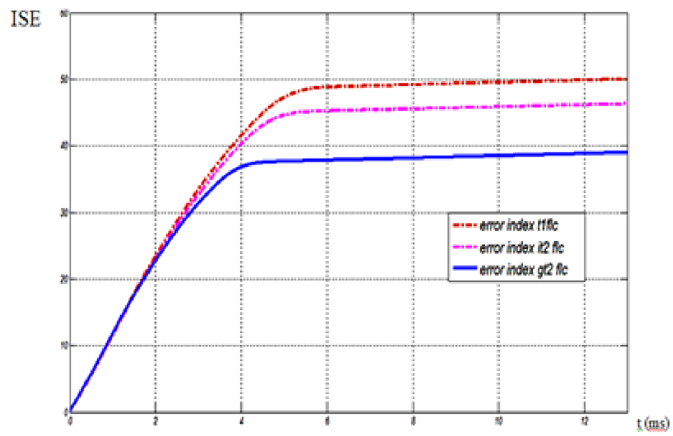


Fig. 11. Comparison of the error obtained from the application of the fuzzy type-1 controllers, the interval type-2 fuzzy and the general fuzzy type-2 on the Boost converter.

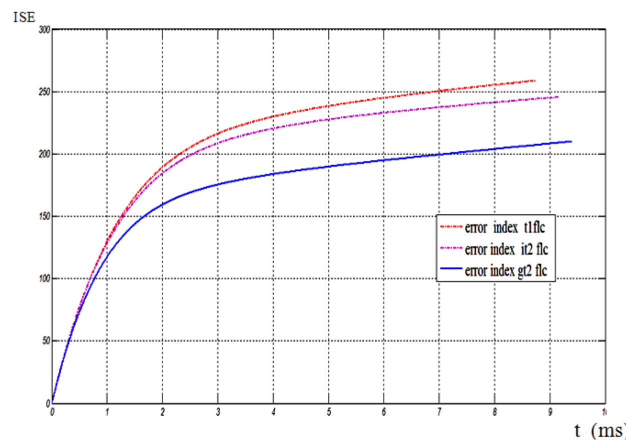


Fig. 12. Comparison of the error obtained from the application of the fuzzy type-1 controllers, the range fuzzy type-2 and the general fuzzy type-2 on the Buck-Boost converter.

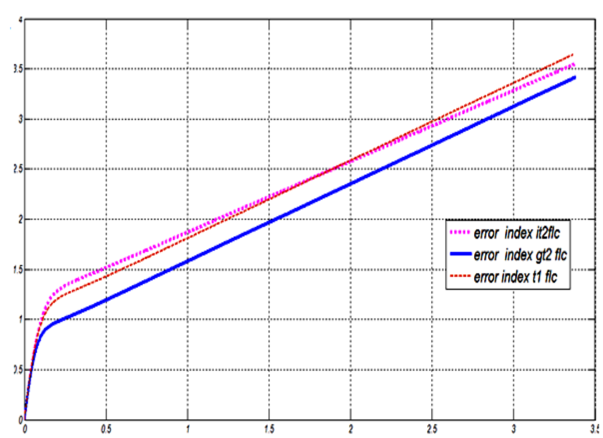


Fig. 13. Comparison of the error obtained from the application of the fuzzy type-1 controllers, the interval fuzzy type-2 and the general fuzzy type-2 on the Buck converter.

As expected, in terms of the response rate and the permanent state error, the general fuzzy type-2controller had a better performance than the fuzzy type-1 and the interval fuzzy type-2 controllers. This is shown with the help of the error index which is a good measure for the investigation of the performance of a controller.

5. CONCLUSION

In this paper the general typ2 fuzzy controller is applied to three different DC-DC converters. The simulation results show that for the same number of rules and membership functions, the recommended controller has better performance considering to its error index. The general type-2 fuzzy controller may be used due to its desirable performance in other power electronics systems such as multi-stage converters, power coefficient modifiers and resonance converters that include more non-linear structures than the plant used in this paper.

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