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Comparative Analysis of Conventional and Fuzzy Pd Controller for Dc-Dc Buck Converter Using Simulink

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Abstract
This paper deals with the design and comparison of tracking performance of fuzzy PD controller with conventional PD controller to control DC-DC Buck Converter which employs five and seven membership functions in each input variable and output variable. The computer simulations are presented to demonstrate the effectiveness of fuzzy PD controller for DC-DC Buck converter. The basic steps that needed for tracking performance of the fuzzy PD controller are discussed. In conventional PD, the controller is a simple linear controller with two fixed gain parameters; in contrast the fuzzy PD controller is a nonlinear controller. It was observed that even though it has the same linear structure as the conventional PD controller, its gain parameters are no longer constant.

Index terms: Buck converter, Fuzzy controller, Membership functions, Triangular and trapezoidal membership functions

I. INTRODUCTION

The dc-dc converter inputs an unregulated dc voltage input and outputs a constant or regulated voltage [1-6]. The regulators can be mainly classified into linear and switching regulators. All regulators have a power transfer stage and a control circuitry to sense the output voltage and adjust the power transfer stage to maintain the constant output voltage. Dynamic behavior of switching power converter depends on performance and design of the digital controller which in turn depends on the accuracy of the discrete-time mathematical model. Thus accurate modeling of switching dc-dc converters is needed for predicting stability and then designing a suitable controller with enhanced stability and performance. There are two widely used approaches for modeling of dc-dc converters namely digital redesign approach and direct digital design approach [2]. The controller in digital redesign approach is designed in *s*-domain and then discretised using transformation techniques. Compensator design in this case does not take into account computational delays and delays incurred in the control loop, also controller are not an optimized one. Discrete-time models, for both trailing-edge and leading-edge modulation, are developed for two-state dc-dc converters and their accuracy was compared by considering basic buck converter [3]. The result is an exact small-signal discrete-time model applicable to any constant-frequency PWM converter. It is necessary to convert a fixed-voltage DC source into a variable-voltage DC source. A DC–DC converter converts

directly from DC to DC and is simply known as a DC converter. In recent years, there has been growing interest in using fuzzy logic for control systems. Fuzzy controllers, in general, are suitable for many nontraditionally modeled industrial processes such as linguistically controlled devices and systems that cannot precisely described by mathematical formulations, have significant un modeled effects and uncertainties, or even contain a contradictory conditions. In recent years there has growing trend of using the fuzzy PD controller instead of conventional fuzzy PD controller, because it has been reported that the fuzzy PD controller can give better performance than conventional ones. In conventional PD case the controller is a simple linear controller with two fixed gain parameters, in contrast the fuzzy PD controller is a nonlinear controller. Even though it has the same linear structure as the conventional PD controller, its gain parameters are no longer constant.

II. Operation of Buck Converter

The operation of the buck converter is fairly simple, with an inductor and two switches (usually a transistor and a diode) that control the inductor. It alternates between connecting the inductor to source voltage to store energy in the inductor and discharging the inductor into the load. The buck converter operates in two modes viz. continuous mode and discontinuous mode.

Continuous mode

A buck converter operates in continuous mode if the current through the inductor (I_L) never falls to zero during the commutation cycle. In this mode, the operating principle is described by the chronogram in figure 3.

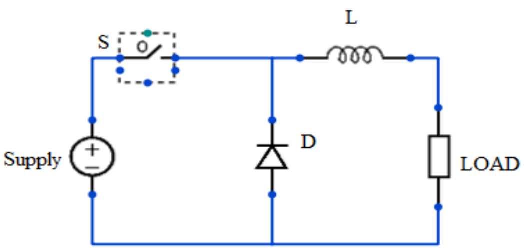


Fig.1. Buck converter circuit diagram

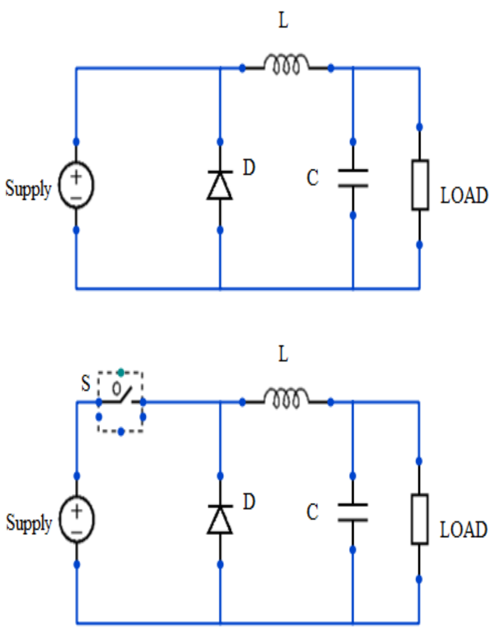


Fig.2: The two circuit configurations of a buck converter: On-state, when the switch is closed, and Off-state, when the switch is open

Discontinuous mode:

In some cases, the amount of energy required by the load is small enough to be transferred in a time lower than the whole commutation period. In this case, the current through the inductor falls to zero during part of the period. The only difference in the principle described above is that the inductor is completely discharged at the end of the commutation cycle (figure 4).

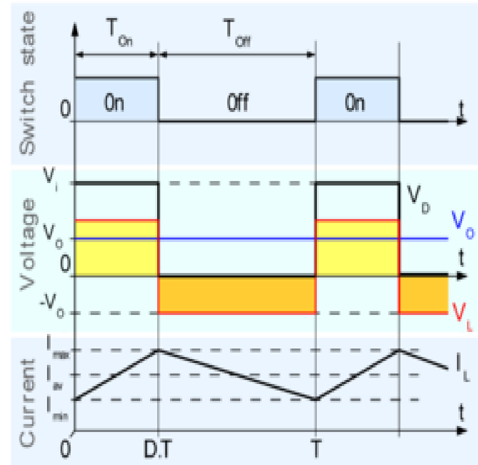


Fig.3: Evolution of the voltages and currents with time in an ideal buck converter operating in continuous mode.

This has, however, some effect on the continuous- time mathematical model equations. We still consider that the converter operates in steady state. Therefore, the energy in the inductor is the same at the beginning and at the end of the cycle (in the case of discontinuous mode, it is zero).

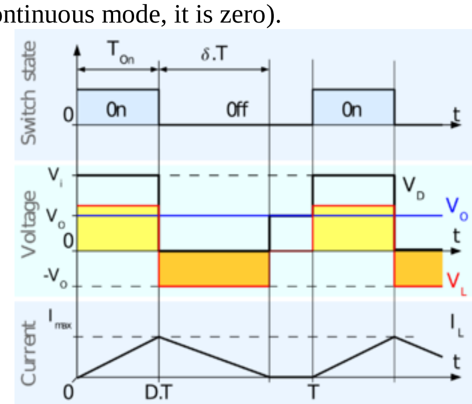


Fig.4: Evolution of the voltages and currents with time in an ideal buck converter operating in discontinuous mode.

III. FUZZY CONTROLLER

Fuzzy control is based on fuzzy logic, a logical system which is much closer in spirit to human thinking and natural language than traditional logical systems. The fuzzy logic controller (FLC) based on fuzzy logic provides a means of converting a linguistic control strategy based on expert knowledge into an automatic control strategy.

Membership functions: Every element in the universe of discourse is a member of a fuzzy set to some grade, may be even zero. The grade of membership for all its members describes a fuzzy set. The most popular choices for the shape of the membership functions are triangular, trapezoidal and bell shaped functions.

(i) Triangular Membership function: It is one of the most popular among the scientists in this field. The triangular membership function can be generally defined using a left point, center point and right point. Overlap and sensitivity are the two parameters that can be used to adjust the shape of the triangles for better performance. The triangular curve is a function of a vector, x, and depends on three scalar parameters a, b and c as given by

$$f(x{:}a,b,c) = \begin{cases} 0, x \le a \text{ and } c \le x \\ \frac{x-a}{b-a}, a \le x \le b \\ \frac{c-x}{c-b}, b \le x \le c \end{cases}$$

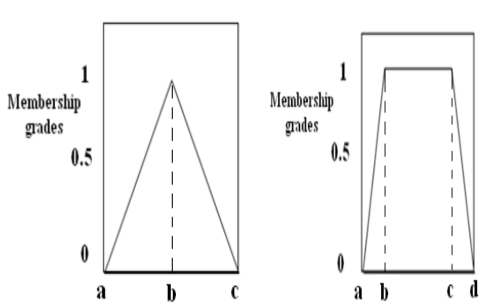
(ii) Trapezoidal Membership function: As the name suggests of this class of membership function is that of a trapezoid as shown in Fig.5 (b). The maximum membership value 1.0 occurs over a small range about the central point of the function. The trapezoidal curve is a function of a vector, x, and depends on four scalar parameters a, b , c and d as given by

$$f(x{:}a,b,c,d) = \begin{cases} 0, x \le a \\ \frac{x-a}{b-a}, a \le x \le b \\ 1, b \le x \le c \\ \frac{d-x}{d-c}, c \le x \le d \\ 0, d \le x \end{cases}$$

(iii) Bell shaped membership function: As the name suggests of this class of membership function is that of Bell Shaped shown in Fig 5(c) .The maximum membership value for Bell Shaped is 1 at x=c, and the membership 'x' decreases as its derivative from this central value of '0'. In the case of Bell-Shaped functions the oscillations are the minimum and the rise time is also greatly reduced.

$$f(x{:}a,b,c,d5) = \begin{cases} \dfrac{1}{1+(x-c)^2} & a \le x \le b \\ 1 & x = c \end{cases}$$

(iv) Singleton: A fuzzy set whose support is a single point in Universe of Discourse U with μ_F = 1.0 is referred to as fuzzy singleton.



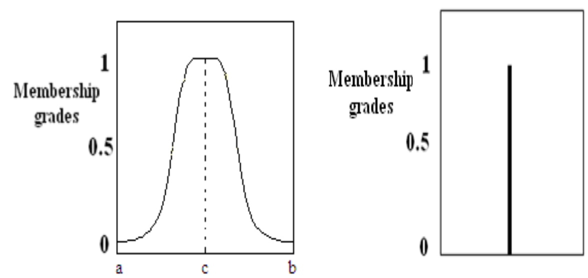


Fig.5. Membership functions: (a) Triangular (b) Trapezoidal (c) Bell-Shape (d) Singleton

Structure of a fuzzy logic controller

The general configuration of a fuzzy logic controller is composed of four specific components:

1) Fuzzification
2) Knowledge Base
   a) Data base
   b) Rule base
3) Inference Engine
4) Defuzzification

Fuzzification

Fuzzification can be defined as a mapping from an observed input space to fuzzy sets in certain input universe of discourse. The fuzzifier (Fuzzification module) converts the real (crisp) input values to degrees of membership of fuzzy sets. These conversions are carried out by lookup using the membership functions.

Knowledge Base

The knowledge base consists of two components: a database and a rule base. The basic function of the database is to provide the necessary information to the rule base and, the Fuzzification and defuzzification modules.

(a) DATA BASE

The main function of the database is to provide the required necessary information to the other modules in order to allow their proper functionality.

(b) RULE BASE

The rule base consists of N rules of the form IF-THEN which gives transparency to the system. Each rule consists of two parts: rule antecedent (IF) and the consequent (THEN). The antecedent defines imprecisely the system states while the consequent represents actions to be taken by the system to remedy the state condition.

Inference Engine

It has four main tasks: rule firing, strength calculation, fuzzy implication and rule aggregation. The result of the inference engine is one or several output fuzzy sets, whose membership functions are defuzzified to obtain the control action. The output represents the degree of relationship between the input and each output fuzzy set.

Defuzzification

Mathematically, the Defuzzification module is the mapping of the value of the fuzzy linguistic variable to a crisp variable. The Defuzzification module performs the following functions:

- It converts the set of modified control output value into a single point wise value.
- It performs an output denormalization which maps the point wise value of the control output onto its physical domain.

There are more than 30 defuzzification methods. Center of Area and Mean of Maxima are the most used defuzzification techniques.

IV. FUZZY PD CONTROLLER

The conventional continuous-time PD controller is described by

$$u(t) = K_p{}^c e(t) + K_d{}^c \dot{e}(t)$$

Where $K_p{}^c$ and $K_d{}^c$ are the proportional and derivative gains of the controller, respectively, and e(t) is the error signal.

The corresponding digital PD controller can be obtained as follows. Let T be the sampling period of the continuous time signal in the digital control system. By applying the standard conformal mapping

$$s = \frac{2}{T}\left(\frac{z-1}{z+1}\right).$$

We can convert the continuous-time system to its discrete-time setting in the complex Z-frequency domain.

Under this mapping

$$U(s) = \left(K_p{}^c + sK_d{}^c\right)E(s)$$

$$\Rightarrow U(z) = \left(K_p + K_D \frac{1-z^{-1}}{1+z^{-1}}\right)E(z)$$

Where K_P and K_D denoted by $K_P = K_p{}^c$ and $K_D = \frac{2}{T}K_d{}^c$ respectively are the discrete time proportional and derivative gains of the digital PD controller.

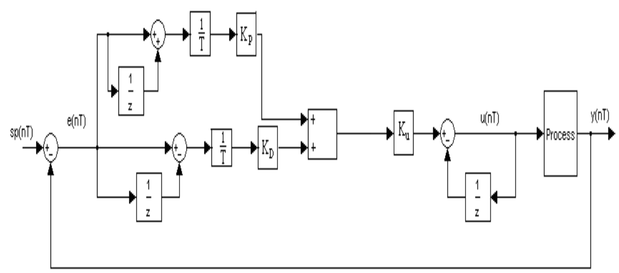


Fig.6 shows the conventional digital PD controller.

Implementation of the conventional digital PD controller is shown in fig.6.

Compared with the conventional PD controller, the fuzzy PD [12] controller has the same linear structure, except that the two gains (K_P and K_D) are not constant.

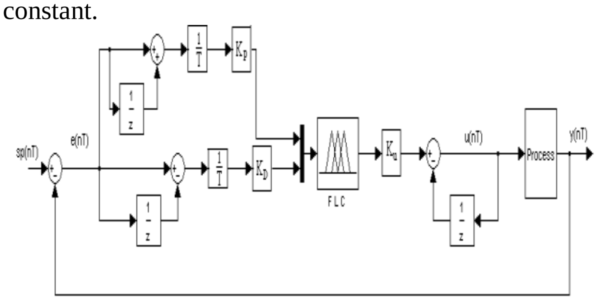
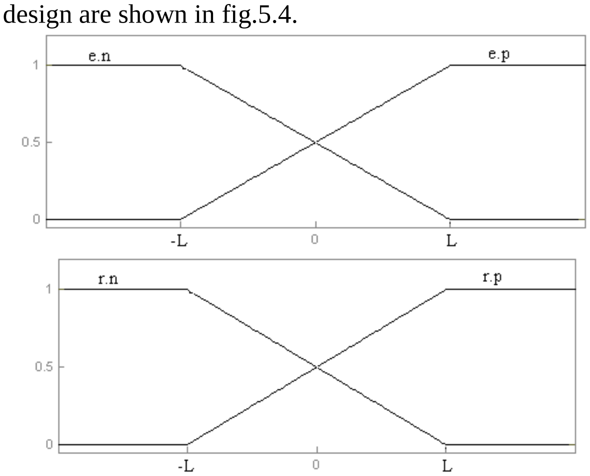


Fig.7 Fuzzy PD controller

Fuzzy controller design consists of three main components fuzzification, fuzzy logic rule base and defuzzification.

In the fuzzification step we employ two inputs: the error signal e(nT) and the rate of change of error signal r(nT) with only one control output u(nT) (to fed to the process under). The inputs to the fuzzy PD controller namely the "error" and the "rate" signals have to be fuzzified before being fed into the controller. The membership functions for the two inputs (error and rate) and the output of the controller that used in our design are shown in fig.5.4.



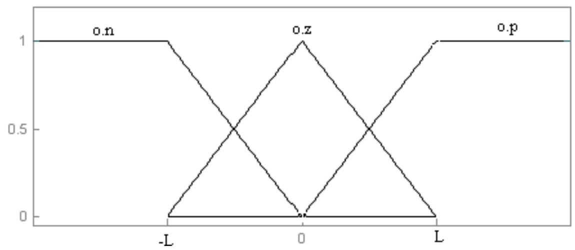


Fig.8 The membership functions of e(nT), r(nT) and u(nT).

Based on these membership functions the fuzzy control rules that we used are the following:

R1.If Error is e.p AND rate is r.p THEN output is o.z
R2.If Error is e.p AND rate is r.n THEN output is o.p
R3.If Error is e.n AND rate is r.p THEN output is o.n
R4.If Error is e.n AND rate is r.n THEN output is o.z
Here AND is Zadeh's logical "AND" [1] defined by

$$\mu_A \text{ AND } \mu_B = \min\{\mu_A,\ \mu_B\}$$

For any two membership values μ_A and μ_B on the fuzzy subsets A and B respectively.
The commonly used "centre of mass" formula employed in the defuzzification.

$$\Delta u(nT) = \frac{\Sigma\{\text{membership value of input} \times \text{membership value of output}\}}{\Sigma\{\text{membership value of input}\}}$$

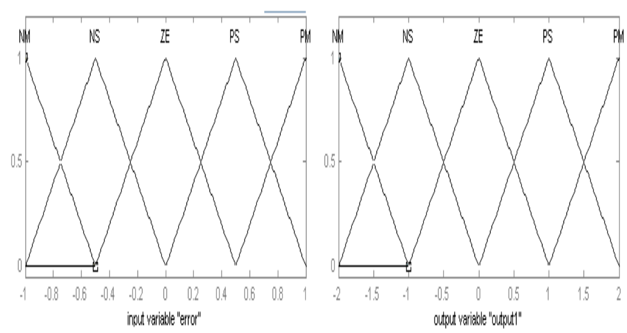


Fig.9 Triangular 5 membership functions of the error, input

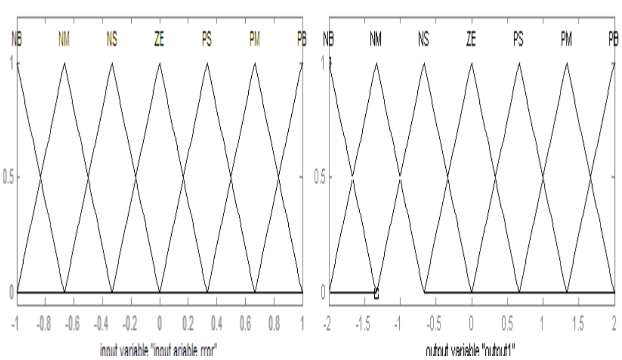


Fig.10 Triangular 7 membership functions of the error, output

V. V.SIMULATION RESULTS OF BUCK CONVERTER

As an example, consider the buck converter with trailing edge PWM and L= 5μ H, R_L =25 m Ω, C= 5 μF,R_C=16 m Ω ,R= 1 Ω, V_g =10 V, V_{ref} =1V, D=0.2, $f_s = 1$ MHz.
From the state space averaged model of a buck converter Considering $A_1 = A_2 = A$; $b_1 = b$; $b_2 = 0$; $C_1 = C_2 = C$

$$A = \begin{bmatrix} \frac{-1}{(R+R_c)} & \frac{R}{(R+R_c)\,C} \\ \frac{-R}{(R+R_c)\,L} & -\left((R_L + (R//R_c))\frac{1}{L}\right) \end{bmatrix}$$

$$b = \begin{bmatrix} 0 \\ 1/L \end{bmatrix} \quad X = \begin{bmatrix} V \\ i \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{R}{(R+R_c)} & (R//R_c) \end{bmatrix}$$

$$y = v_{out}\ ;$$

In order to simplify the analysis, losses are neglected except for the dominant effect of a capacitor C; Resulting simplified equations for A and C (neglect R_C)

$$A \approx \begin{bmatrix} \frac{-1}{RC} & \frac{1}{C} \\ \frac{-1}{L} & 0 \end{bmatrix} \quad c \approx [1 \quad 0]$$

The transfer function is given by

$$G_{vd}(Z) = \frac{N(Z)}{D(Z)}$$

$$= \frac{\frac{V_g T_s}{LC}(T_s - t_d)\left(Z + \frac{t_d}{T_s - t_d}\right)}{Z^2 - Z\left(2 - \frac{T_s}{RC}\right) + \left(1 - \frac{T_s}{RC} + \frac{T_s^{\ 2}}{LC}\right)}$$

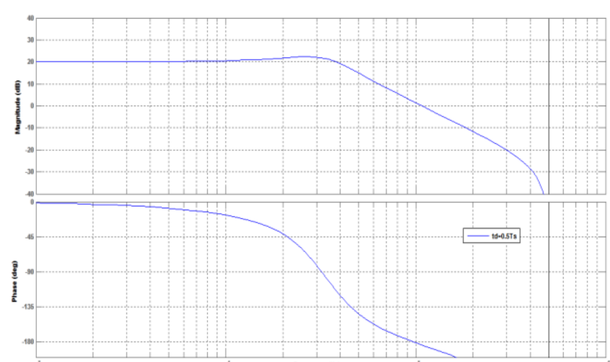


Fig 11 Magnitude and phase response of G_{vd}(Z) for digitally controlled buck converter with no losses

Considering $A_1 = A_2 = A$; $b_1 = b$; $b_2 = 0$; $C_1 = C_2 = C$

$$A = \begin{bmatrix} \frac{-1}{(R+R_c)} & \frac{R}{(R+R_c)\,C} \\ \frac{-R}{(R+R_c)\,L} & -\left((R_L + (R//R_c))\frac{1}{L}\right) \end{bmatrix}$$

$$b = \begin{bmatrix} 0 \\ 1/L \end{bmatrix} \quad X = \begin{bmatrix} V \\ i \end{bmatrix}$$

$$C = \begin{bmatrix} \frac{R}{(R+R_c)} & (R//R_c) \end{bmatrix}$$

$y = v_{out}$;

In order to simplify the analysis, losses are not neglected resulting simplified equations for A and C

$$A \approx \begin{bmatrix} \frac{-1}{RC} & \frac{1}{C} \\ \frac{-1}{L} & 0 \end{bmatrix}$$

$$C \approx \begin{bmatrix} 1 & R_c \end{bmatrix}$$

The transfer function is given by

$$G_{vd}(Z) = \frac{N(Z)}{D(Z)} = \frac{\frac{V_g T_s}{LC}(T_s - t_d + CR_c)\left(Z + \frac{T_s}{T_s - t_d + CR_c}\left(\frac{R_c}{R} - C\frac{R_c}{T_s} - \frac{(T_s - t_d)R_c}{L} + \frac{t_d}{T_s}\right)\right)}{Z^2 - \left(Z - \frac{T_s}{RC}\right)Z + \left(1 - \frac{T_s}{RC} + \frac{T_s^{\,2}}{LC}\right)}$$

$G_{vd}(Z)$ is the control to output transfer function. By considering this transfer function with various values of t_d , the bode plot is given in the figure 11

Fuzzy PD controller for digitally controlled buck converter:

The Simulink results of Fuzzy PD Controller Buck Converter that is the proposed scheme is shown in Figure 12 and 13. The chosen range of output variable for Fuzzy Buck Converter is [-2 2] then output of Fuzzy Buck Converter is 2.5, means 50% duty cycle. The Simulink results are done for trapezoidal and triangular with 5 and 7 membership functions in each input

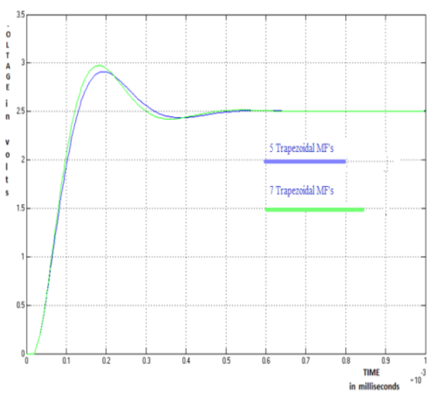


Fig. 12 Simulation of Buck Converter using Trapezoidal five and seven membership functions.

OBSERVATIONS: It is observed from the graph that fuzzy logic controller with 7 trapezoidal membership functions in each input is slightly exhibiting more overshoot and slightly less settling time.

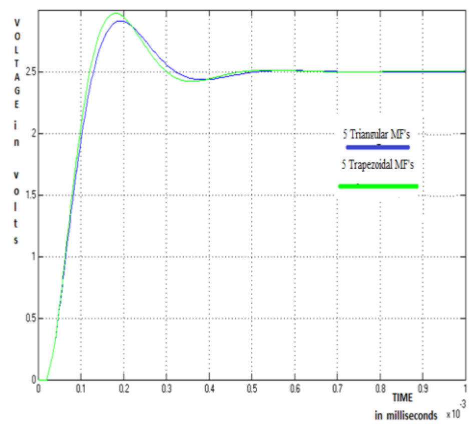


Fig. 13 Simulation of Buck Converter using triangular and trapezoidal five membership functions.

OBSERVATIONS: It is observed from the graph that fuzzy logic controller with 5 trapezoidal membership functions in each input is slightly exhibiting more overshoot and slightly less settling time.

VI. CONCLUSION

We observe the settling time is less for Fuzzy PD buck converter using Trapezoidal 7 membership functions when compared with the other fuzzy controller and conventional PD controller. Some computer simulation results, for different membership functions of the buck converter which demonstrate the advantage of the fuzzy PD controller over the conventional PD controller are shown.

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