Application of Fuzzy Logic to Control the DC-DC Converter

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Abstract: - In this paper controlled DC-DC converter using several fuzzy logic control law algorithms are studied. These controllers are designed to eliminate the overshoot and reduce the settling time response. In order to improve this property several control algorithms were investigated. The first one was the state controller with decomposed fuzzy PI controller and the second one was fuzzy PD state space controller and the other one was fuzzy PID state space controller. All the analysis and simulations to duplicate on the above converter by MATLAB software were performed. The results confirm the capability of the control methods in the improvement of the above-mentioned converter functioning.

Key-Words: Buck Converter –fuzzy logic Controller

1 Introduction

DC-DC converters are nonlinear system in nature due to their switching property. Static and dynamic characteristics of these converters have been widely discussed in the literature. In many industrial applications there is a need for the transformation of a constant dc voltage source to a variable dc voltage source, and like a transformer, the converter can be employed for stepwise increase or reduction of dc source voltage. In this way Buck converter has a wide application in electrical industry and power systems and specifically it can supply the voltage for a direct current consumer. Buck is a one-input and multiple-output in structure with a non-linear property due to its switching behavior, but at the same time when the switch is on and off its behavior is linear. Therefore, by employing the averaging method, it is possible to exchange a non-linear system with a linear one. Many of the methods are centered on the isolation of the system variables and PI controller design [1]. Some control methods have defined the subject of control based on pole placement. One of the other control methods is the use of feedback stage in dc converter control [2]. Other control method is the feedback loop control [3]. Another one is the use of LQR method in the control of Buck converter [4] , [5]. To administer different control methods, varied models of dc-dc converters are presented which have satisfactory responses [6].

In general, most control systems must track inputs. One solution to this problem is to introduce integral control, just as with PI controller, together with the constant- gain state feedback. In this article fuzzy and PID control is designed that can improve the Buck converter response.

In this paper, several control structures based on the fuzzy-set approach are presented. The fuzzy-set theory has evolved as a powerful modeling tool that can cope with the uncertainties and non-linearity of the control systems [7], [8]. The first algorithm considered in this paper is based on decomposed fuzzy PI controller in order to eliminate the static error and to improve the converter dynamics. The second one is a PD fuzzy state controller, where a nonlinear fuzzy approach, and the third one is a PID fuzzy state controller that they are used for adaptive state controller gain adjustment in order to minimize the steady state error and improve dynamics.

2 DC-DC Converter Circuit Model

The Buck converter circuit model is depicted in Fig.1.

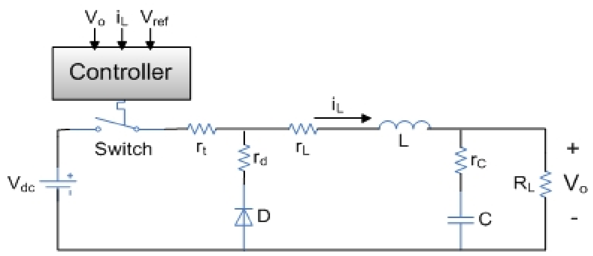

Fig.1 Buck converter

The function of the circuit is divided into two parts. The first part starts when the switch is turned on at *t=0*. The input current which is rising passes through

L filter inductor, C filter capacitor, and R_L load resistance. The second part starts when the switch is turned off at $t=t_1$. Due to the presence of stored energy in the inductor, and the inductor current continues passing from L, C, load and D. The inductor current declines until the second switch switching in the next cycle. In this model, Vo is the system output voltage and V_{ref} is the converter voltage. The converter state equations in low-frequency state, is presented.

Switch ON:

$$V_{dc} - (v_C + r_c * C * dv_C / dt) = (r_t + r_L) * i_L + L(di_L / dt)$$

$$i_L = C(dv_c / dt) + (v_c + r_c * dv_C / dt) / R_L$$

$$x_1 = i_L \ , \quad x_2 = V_c \ , \quad X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$\dot{X} = A_1 * X + B_1 * V_{dc}$$

$$A_1 = \begin{bmatrix} a_{11} & a_{12} \\ a_{13} & a_{14} \end{bmatrix}, B_1 = \begin{bmatrix} b_{11} \\ b_{12} \end{bmatrix} \qquad (1)$$

$$a_{11} = -\left[r_L + r_t + (r_c * R_L)/(R_L + r_c)\right]/L$$

$$a_{12} = -R_L / [L * (R_L + r_c)]$$

$$a_{13} = R_L / [C * (R_L + r_c)]$$

$$a_{14} = -1 / [C * (R_L + r_c)]$$

$$b_{11} = 1/L \ , \ b_{12} = 0$$

Switch OFF:

$$(r_d + r_L) * i_L + L(di_L / dt) + v_c + r_c * C * dv_c / dt = 0$$

$$i_L = C(dv_C / dt) + (v_c + r_c * C * dv_C / dt) / R_L$$

$$\dot{X} = A_2 * X + B_2 * V_{dc} \qquad (2)$$

$$A_2 = \begin{bmatrix} a_{21} & a_{22} \\ a_{23} & a_{24} \end{bmatrix} \ , \quad B_2 = \begin{bmatrix} b_{21} \\ b_{22} \end{bmatrix}$$

$$a_{21} = -\left[r_L + r_d + (r_c * R_L)/(R_L + r_c)\right]/L$$

$$a_{22} = -R_L / [L * (R_L + r_C)]$$

$$a_{23} = R_L / [C * (R_L + r_C)]$$

$$a_{24} = -1 / [C * (R_L + r_c)]$$

$$b_{21} = 0 \ , \quad b_{22} = 0$$

Now it is required to show the effect of on and off durations of switch in (1) and (2) to obtain the mean values of state equations.

$$\dot{X} = A * X + B * V_{dc}$$

$$A = d * A_1 + (1 - d) * A_2 \qquad (3)$$

$$B = d * B_1 + (1 - d) * B_2$$

$$d = \frac{t_{on}}{T}$$

3 FUZZY LOGIC

In 1965, Zadeh proposed Fuzzy logic; it has been effectively utilized in many field of knowledge to solve such control and optimization problems [9]. Fuzzy logic has been available as a control methodology for over three decades and its application to engineering control systems is well proven. In a sense fuzzy logic is a logical system that is an extension of multi-valued logic although in character it is quite different. It has become popular due to the fact that human reasoning and thought formation is linked very strongly with the ways fuzzy logic is implemented. In power system area, it has been used to stability studies, load frequency control, unit commitment, and to reactive compensation in distribution network and other areas.

The most important specifications of fuzzy control method are their fuzzy logical ability in the quality perception of system dynamics and the application of these quality ideas simultaneously for power systems [10]. A simple block diagram of a fuzzy system is shown in Fig.2.

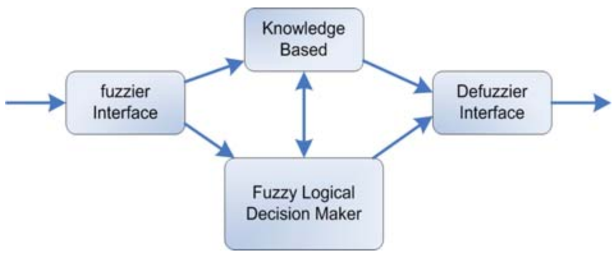

Fig.2 Details of a fuzzy controller.

Four major units are fuzzification block, a fuzzy knowledge-base block, a fuzzy inference engine and a defuzzification block. The functions of the blocks and working principles of the fuzzy system are briefly summarized [11].

A. Fuzzification

The fuzzification block performs the following tasks:

- Measures the value of input variables.
- Performs a scale mapping that transfers the range of values of input variables into the corresponding universes of discourse.
- Performs the function of fuzzification, which converts input data into suitable linguistic values that may be viewed as labels of fuzzy sets.

The input signals to FLC are scaled using appropriate scaling factors. These scaled input data are then converted into linguistic variables, which may be viewed as labels of fuzzy sets. Fuzzy sets can be characterized by membership functions. There are many types of membership functions e.g., the bell-shaped, linear function, triangular function, trapezoidal function and exponential function.

B. Knowledge-base

The knowledge base is comprised of two components namely called fuzzy sets (data base) and fuzzy control rule base. The concepts associated with fuzzy sets are used to characterize fuzzy control rules and fuzzy data manipulation in an FLC. These concepts are subjectively defined and based on experience. So, it should be noted that the correct choice of the membership functions of a term set plays an essential role in the success of an application [11].

The fuzzy rule base consists of a set of linguistic control rules written in the form:

IF a set of conditions are satisfied (premise), THEN a set of consequences are inferred The collection of fuzzy control rules that are expressed as fuzzy conditional statements forms the rule base or the rule set of an FLC.

In particular, the choice of linguistic variables and their membership function have a strong influence on the linguistic structure of an FLC. Typically, the linguistic variables in an FLC are the state, state error, state error derivative, state error integral, etc.

One of the key problems is to find the appropriate fuzzy control rules. In general, there are four models of derivation of fuzzy control rules [11]:

- Using the experience and knowledge of an expert.
- Modeling the control actions of the operator.
- Using a fuzzy model of a process.
- Using self-organized fuzzy controllers.

C. Fuzzy inference engine

The fuzzy engine is the kernel of a fuzzy logic controller, which has capability of simulating human decision-making based on fuzzy concepts and of inferring fuzzy control actions using fuzzy implication (fuzzy relation) and the rules of inference in fuzzy logic. This means that the fuzzy inference engine handles rule inference where human experience can easily be injected through linguistic rules.

D. Defuzzification

The defuzzification block performs the following functions:

- Scale mapping, which converts the range of values of output variables into corresponding universes of discourse.
- Transforms the fuzzy control actions to continuous (crisp) signals, which can be applied to the physical plant.

4 Fuzzy controller on DC-DC converter and Result of Simulation

With regard to the state equations for the converter and taking into consideration Table I the Buck converter equations are.

$$\frac{dx(t)}{dt} = Ax(t) + Bu(t)$$

$$y(t)=Cx(t)+Du(t)$$

$$X = \begin{bmatrix} i_L \\ V_c \end{bmatrix} \quad , \quad U = \begin{bmatrix} V_{dc} \end{bmatrix}$$

and

$$A=\begin{bmatrix} -4805.5 & -2357.4 \\ 68200.83 & -150.79 \end{bmatrix} \quad , \quad B= \begin{bmatrix} 59523.75 \\ 0 \end{bmatrix}$$

$$C= \begin{bmatrix} 0 & 1 \end{bmatrix} \quad , \quad D= \begin{bmatrix} 0 \end{bmatrix}$$

TABLE I
BUCK CONVERTER PARAMETERS

Symbol	Value
r_L	0.7 Ω
r_d	0.7 Ω
r_c	1.18 Ω
r_t	0.2 Ω
C	1450 μF
L	0.42 mH
R_L	118 Ω
V_{dc}	50 V
d	0.5

Open loop response will be in the form of Fig.3. To optimize the V_o several fuzzy control methods are used.

The overshoot of the output voltage in open loop response was 23% peak-to-peak (Vpp) and the settling time of the step response was 3.6 ms.

As it is evident from the study of outputs, the open loop system cannot hold the output in constant and ideal conditions. Of course, the outputs will eventually approximate the ideal rate with regard to the stability of the system.

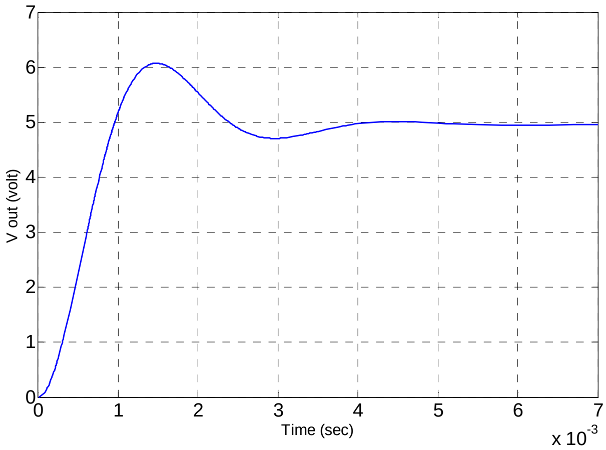

Fig. 3. Open Loop response of Buck converter

Better dynamic response and lower steady state error of the converter can be reached by introducing the decomposed fuzzy PI, PD, PID controllers that are shown in Fig. 4. Due to this the decomposed fuzzy PI, PD, PID controllers can be used. The linguistic description of the knowledge base is given by three RB's. The output signal is the sum of the defuzzified outputs of proportional FIS, differential FIS and integral FIS.

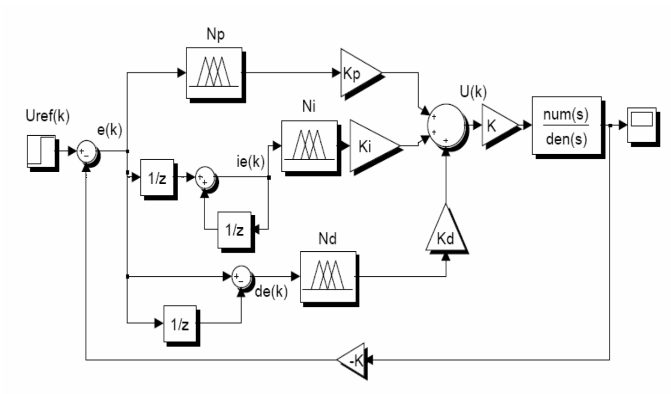

Fig.4 Structure of fuzzy controller in exciter system

The membership functions are shown in Fig.5. The fuzzy rules were designed that for each input membership function the output membership function was assigned. In Table II, 3 fuzzy rules for linguistic variable Np are shown. Similar fuzzy rules were assigned to the integral and differential part, that they are shown in Table III, and Table IV.

In the simulation by using the gain parameters, the effect of the fuzzy controllers are defined. The result of this procedure for Np, Ni, Nd are shown in Fig. 6. Where Np, Nd and Ni are the non-linear functions determined by a Fuzzy Rule-Based System (FRBS).

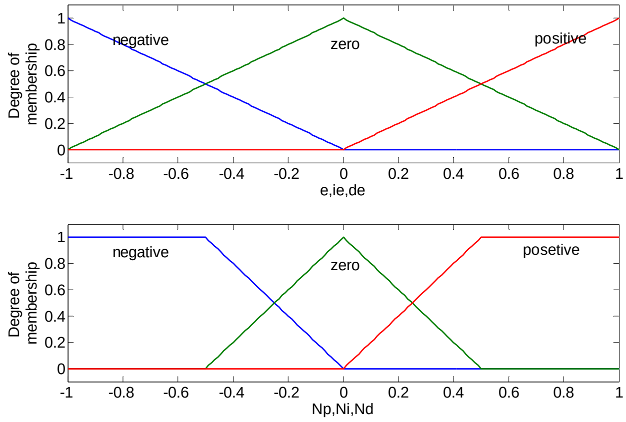

Fig.5 Membership functions of a fuzzy PID controller (Input membership function: e, ie, de) and (Output membership function: Np, Ni, Nd)

Table II
Np fuzzy rules

Kp (Np)
if e(k)=negative then y=negative
if e(k)=zero then y=zero
if e(k)=positive then y=positive

Table III
Ni fuzzy rules

Ki (Ni)
if ie(k)=negative then y=negative
if ie(k)=zero then y=zero
if ie(k)=positive then y=positive

Table IV
Nd fuzzy rules

Kd (Nd)
if de(k)=negative then y=negative
if de(k)=zero then y=zero
if de(k)=positive then y=positive

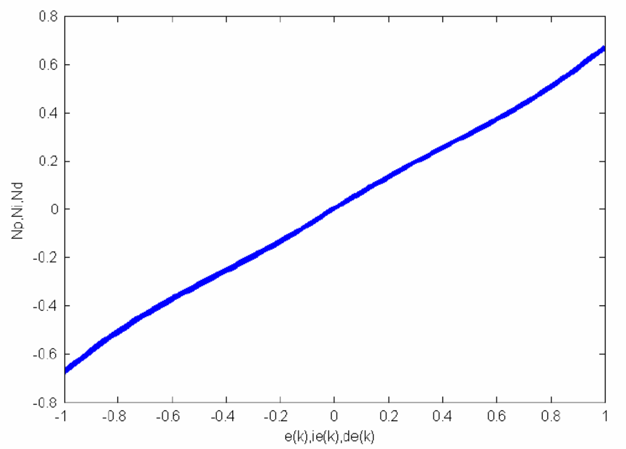

Fig.6 The Np, Ni, and Nd non-lineary

The output of the fuzzy PI controller is denoted by (4), and the gains are Kp=1.5, and Ki=1.2. The response of DC-DC converter with PI fuzzy controller is shown in Fig. 7.

$$u(k) = Np(e(k)) + Ni(ie(k)) \quad (4)$$

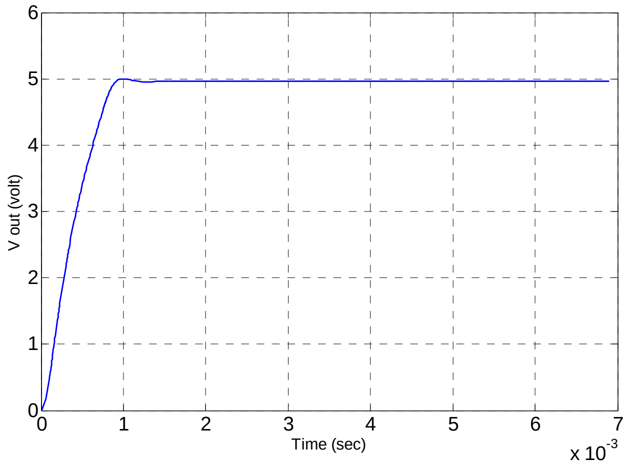

Fig. 7. Step response of a decomposed fuzzy PI controller

The output of the fuzzy PD controller is denoted by (5),and the gains are Kp=1.5, and Kd=0.1. The response of DC-DC converter with PD fuzzy controller is shown in Fig. 8.

$$u(k) = Np(e(k)) + Nd(de(k)) \quad (5)$$

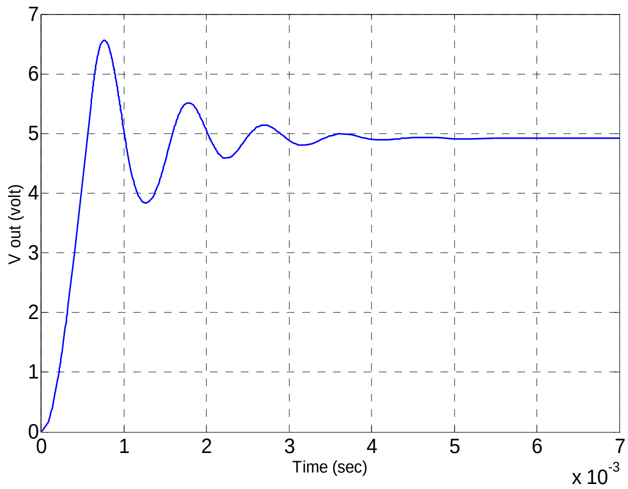

Fig. 8. Step response of a decomposed fuzzy PD controller

The output of the fuzzy PID controller is denoted by (6),and the gains are Kp=1.5, Kd=0.1, and Ki=1.2. The response of DC-DC converter with PID fuzzy controller is shown in Fig. 9.

$$u(k) = Np(e(k)) + Nd(de(k)) + Ni(ie(k)) \quad (6)$$

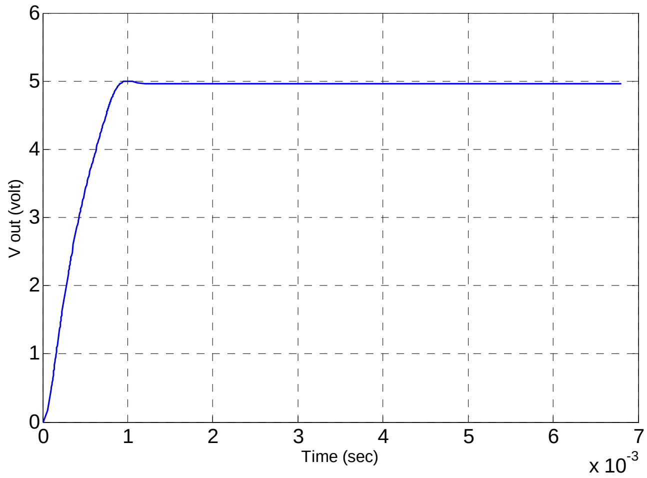

Fig. 9. Step response of a decomposed fuzzy PID controller

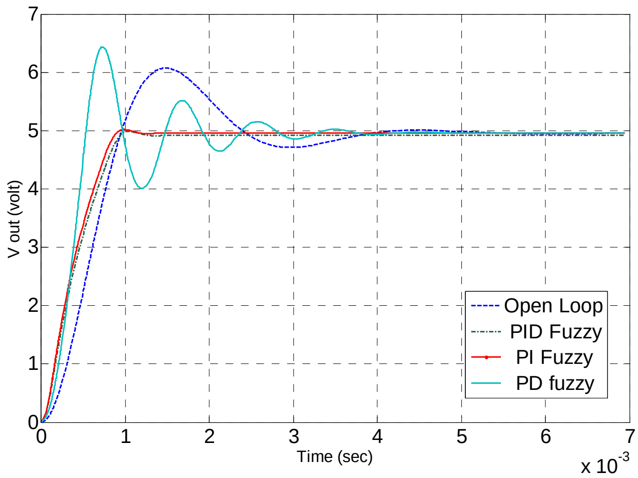

Fig. 10. Step response of a decomposed fuzzy PI, PD, PID controller and open loop

The results of this procedure are shown in Fig. 10 where the fuzzy PID controller is compare with open loop, fuzzy PI and fuzzy PD controllers that there is no overshoot at this response.

6 Conclusion

The dc-de conversion principle is a part of many electronics devices and is a subject of many research projects which are looking for the best control. Fuzzy control therefore simplifies the design of optimal compensation for DC-DC converters. These controllers are designed to eliminate the overshoot and reduce the settling time response. This paper demonstrated the effectiveness of the fuzzy controller applied to the state space averaging DC-DC converter using MATLAB

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