Development of Fuzzy Logic Controller for DC – DC Buck Converters

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Abstract
This paper deals with the design of fuzzy logic controller for dc – dc controllers. Fuzzy systems can be considered as a type of nonlinear function interpolator. The design of fuzzy controllers does not require an exact mathematical model. Instead they are designed based on general knowledge of the plant. Fuzzy logic controller (FLC) is cheaper to develop, they cover a wider range of operating conditions, and they are more readily customizable in natural language terms.

Keywords: *Fuzzy Logic Controller, FLC, DC - DC converter, Buck converter, Boost converter.*

I. INTRODUCTION

In the past few years the dc-dc converters are controlled using analog integrated circuit technology and linear system design techniques. Conventional control techniques used for dc-dc converters are PID controllers which tend to provide linear characteristics [1]. But dc-dc converters exhibit non-linear characteristics. The causes of nonlinearity in the power converters include a variable structure within a single switching period, saturating inductances, voltage clamping, etc. So whenever there is any change in system, any parameter variations or even load disturbances PID controllers tend to be less [1-6]. To control non linear systems satisfactorily non linear controllers are often developed.

It is always desirable for buck converters with constant output voltage that the output voltage remains unchanged in both steady and transient operations whenever the supply voltage and/or load current is disturbed. This condition is known as zero-voltage regulation, which means that the output voltage is independent of the supply voltage and the load current. To achieve zero-voltage regulation, the choice of the control method plays a very critical role in the performance of converters. The most commonly used method in converters is the direct duty ratio control. This method is too complex to be practically executed. Another popular method is the current control mode control. But this method cannot eliminate the load current disturbances. Using human linguistic terms and common sense, several fuzzy logic based controllers have been developed. The main problem with fuzzy logic is that there is no systematic procedure for the design of fuzzy controllers [5,6].

Fuzzy logic, which is the logic on which fuzzy control is based, is much closer in spirit to human thinking and natural language than the traditional logical systems. Basically, it provides an effective means of capturing the approximate, inexact nature of the real world [2]. The essential part of the FLC is a set of linguistic control rules related by the dual concept of fuzzy implication and the compositional rule of inference. The FLC provides an algorithm which can convert the linguistic control strategy based on expert knowledge into an automatic control strategy. Experience shows that the FLC yields results superior to those obtained by conventional control algorithms. The FLC appears very useful when the processes are too complex for analysis by conventional quantitative techniques [3].In [1-13] various methods are discussed and used.

II. BASICS OF FUZZY LOGIC CONTROLLERS

Fuzzy logic control is a new addition to control theory. Its design philosophy deviates from all the previous methods by accommodating expert knowledge in controller design. FLC is one of the most successful applications of, fuzzy set theory. Its major features are the use of linguistic variables rather than numerical variables [5]. Linguistic variables, defined as variables whose values are sentences in a natural language (such as small and large), may be represented by fuzzy sets. FLC's are an attractive choice when precise mathematical formulations are not possible.

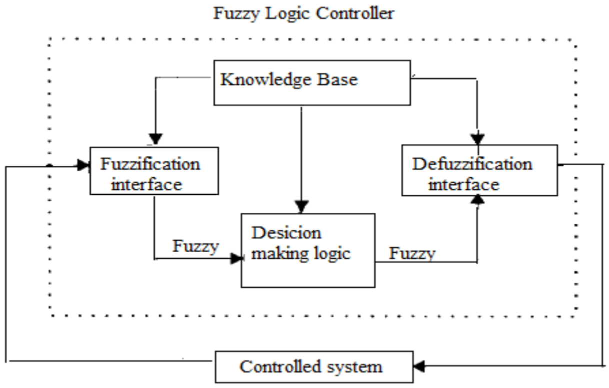

Fig. 1. Basic configuration of FLC

The general structure of an FLC is represented in Fig. 1 and comprises four principal components: 1) a fuzzification interface which converts input data into suitable linguistic values; 2) a knowledge base which consists of a data base with the necessary linguistic definitions and control rule set; 3) a decision making logic which, simulating a human decision process, infers the fuzzy control action from the knowledge of the control rules and the linguistic variable definitions; and 4) a defuzzification interface which yields a nonfuzzy control action from an inferred fuzzy control action. [2]

Design of fuzzy logic or rule based non-linear controller is easier since its control function is described by using fuzzy sets and if-then predefined rules rather than cumbersome mathematical equations or larger look-up tables; it will greatly reduce the development cost and time and needs less data storage in the form of membership functions and rules. It is adaptive in nature and can also exhibit increased reliability, robustness in the face of changing circuit parameters, saturation effects and external disturbances and so on.

III.DESIGN OF FUZZY CONTROLLER FOR DC-DC CONVERTERS

Design of fuzzy controllers is based on expert knowledge of the plant instead of a precise mathematical model. There are two inputs for the fuzzy controller for the buck and boost converters. The first input is the error in the output voltage given by (1), where $ADC[k]$ is the converted digital value of the kth sample of the output voltage and Ref is the digital value corresponding to the desired output voltage. The second input is the difference between successive errors and is given by

$$e[k] = Ref - ADC[k] \quad (1)$$

$$ce[k] = e[k] - e[k-1] \quad (2)$$

The two inputs are multiplied by the scaling factors $g0$ and $g1$, respectively, and then fed into the fuzzy controller. The output of the fuzzy controller is the change in duty cycle $\Delta d[k]$, which is scaled by a linear gain h [1]. The scaling factors $g0$, $g1$, and h can be tuned to obtain a satisfactory response.

A. Two Methods for Computing the Commanded Duty Cycle

There are two methods to calculate the new duty cycle from the fuzzy controller's output $\Delta d[k]$. A block diagram model of the first method is shown in Fig. 2(a).

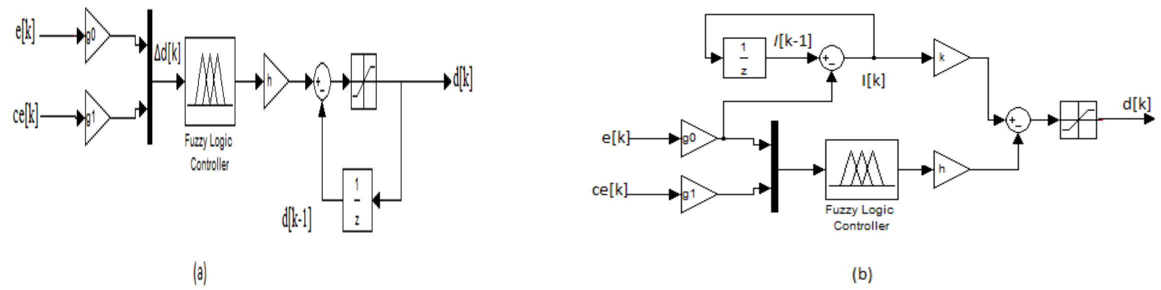

Fig. 2.(a) Method (3). (b) Method (4).

In this method, the fuzzy controller output $\Delta d[k]$ is scaled by the output gain *h*, and then added to the previous sampling period's duty cycle $d[k-1]$,

$$d[k] = d[k-1] + h\Delta d[k]. \qquad (3)$$

The first method (3) represents a discrete time integration of the fuzzy controller output. Integrating the fuzzy controller's output increases the system type and reduces steady-state error.
The second method of computing the new duty cycle is shown in Fig. 2(b). The fuzzy controller's output is scaled by *h*, and then added to the output of a parallel integrator

$$d[k] = KiI[k] + h\Delta d[k]. \qquad (4)$$

Here, $I[k]$ is the output of the discrete time integration of the error $e[k]$, and Ki is the gain of the integrator. The integrator is used to eliminate steady-state error. In the first structure of the fuzzy controller, an integrator is in series with the fuzzy logic controller, while in the second structure, the integrator is in parallel with the fuzzy logic controller. A disadvantage of the first structure is that the output gain *h* has to be tuned to very small values to avoid voltage oscillations in steady state. On the other hand, a very small output gain *h* tends to slow down the transient response time because more sampling periods are needed to arrive at the desired duty cycle. In the second structure, the change of duty cycle is not accumulated every sampling period, so the output gain *h* can be increased to reduce transient response time. The second structure is a combination of linear and nonlinear controllers.

B. Fuzzification

The first step in the design of a fuzzy logic controller is to define membership functions for the inputs. Seven fuzzy levels or sets are chosen and defined by the following library of fuzzy-set values for the error *e* and change in error *ce*:

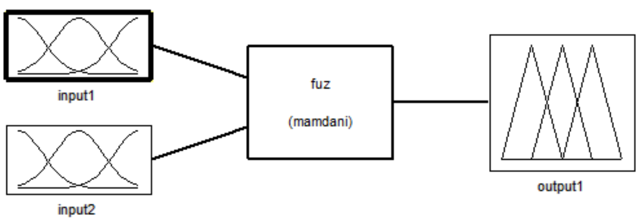

Fig. 3. Membership functions for e and ce.

They are as follows

NB negative big;
NM negative medium;
NS negative small;
ZE zero equal;
PS positive small;
PM positive medium;
PB positive big.

The number of fuzzy levels is not fixed and depends on the input resolution needed in an application. The larger the number of fuzzy levels, the higher is the input resolution. The fuzzy controller utilizes triangular membership functions on the controller input. The triangular membership function is chosen due to its simplicity. For a given crisp input, fuzzifier finds the degree of membership in every linguistic variable. Since there are only two overlapping memberships in this specific case, all linguistic variables except two will have zero membership.

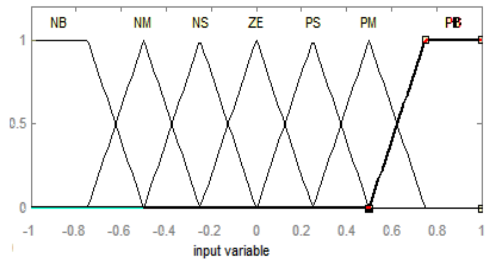

Fig. 4. Membership functions of the input linguistic variables

C. Rule Base or Decision-making

Fuzzy control rules are obtained from the analysis of the system behavior. In their formulation it must be considered that using different control laws depending on the operating conditions can greatly improve the converter performances in terms of dynamic response and robustness. The control rules that associate the fuzzy output to the fuzzy inputs are derived from general knowledge of the system behavior. However, some of the control actions in the rule table are also developed using "trial and error" and from an "intuitive" feel of the process being controlled. The control rules for the dc–dc converter in Table I resulted from an understanding of converter behavior. A typical rule can be written as follows.

If *e* is NB and *ce* is PS then output is ZE

Where are the labels of linguistic variables of error (*e*), change of error (*ce*) and output respectively. e, ce and output represent degree of membership. To obtain the control decision, the max-min inference method is used. It is based on the minimum function to describe the AND operator present in each control rule and the maximum function to describe the OR operator. Control rules are given below.

error(e)

change in error(ce)	NB	NM	NS	ZE	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	ZE
NM	NB	NB	NB	NM	NS	ZE	PS
NS	NB	NB	NM	NS	ZE	PS	PM
ZE	NB	NM	NS	ZE	PS	PM	PB
PS	NM	NS	ZE	PS	PM	PB	PB
PM	NS	ZE	PS	PM	PB	PB	PB
PB	ZE	PS	PM	PB	PB	PB	PB

The derivation of the fuzzy control rules is heuristic in nature and based on the following criteria [5]:

1) When the output of the converter is far from the set point, the change of duty cycle must be large so as to bring the output to the set point quickly.
2) When the output of the converter is approaching the set point, a small change of duty cycle is necessary.
3) When the output of the converter is near the set point and is approaching it rapidly, the duty cycle must be kept constant so as to prevent overshoot.
4) When the set point is reached and the output is still changing, the duty cycle must be changed a little bit to prevent the output from moving away.
5) When the set point is reached and the output is steady, the duty cycle remains unchanged.
6) When the output is above the set point, the sign of the change of duty cycle must be negative, and vice versa

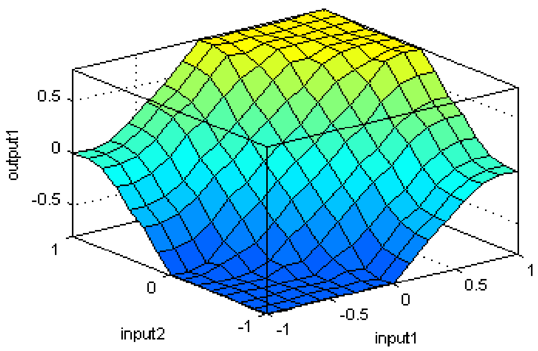

Fig. 5. Rules in 3D surface

D. Inference Mechanism

The results of the inference mechanism include the weight Factor wi and the change in duty cycle ci of the individual rule. The weight factor wi is obtained by Mamdani's min fuzzy implication of μe(e[k]) and μce(ce[k]), where wi = min{μe(e[k]), μce(ce[k])} and μe(e[k]), μce(ce[k]) are the membership degrees. The change in duty cycle inferred by the *i*th rule zi = wi × ci is given by

$$z_i = \min \{\mu e(e[k]), \mu ce(ce[k])\} \times c_i. \quad (5)$$

E. Defuzzification

Conservation of the fuzzy to crisp or non-fuzzy output is defined as De-fuzzification. In the defuzzification operation a logical sum of the inference result from each of the four rules is performed. This logical sum is the fuzzy representation of the change in duty cycle (output). A crisp value for the change in duty cycle is calculated using the center of gravity method.

$$\delta d(K) = \frac{\sum_{i=1}^{4} w_i m_i}{\sum_{i=1}^{4} w_i} \quad (6)$$

The product of centroid *mi* of *Ci* (obtained from control rules) and the weighting factor *wi* gives the contribution of the inference result to the crisp value of the change in duty cycle. The resultant change of duty cycle can therefore be represented by

IV.SIMULATION RESULTS

The input voltage of the prototype buck converter is 12V, and the output voltage Vo is 5V. The load resistance R is 10Ω, L is 150μH and C is 1000μF. The input voltage of the boost converter is 5V, the output voltage Vo is 12V, and the nominal duty cycle D is 58%. C is 1056μF, L is 250μH, and the load resistance R is 25 Ω. The equivalent series resistance of the capacitor C and the inductor L are represented by Rc and Rl, respectively. For buck converter when the input voltage increased from 17 to 23 V, the settling time remained at about 1 ms, and the maximum transient error remained at about 60 mV. However, the gain factor η, the normalization factor, βe of the error *e,* and the normalization factor βce of the change of error ce in the experiments have been adjusted slightly to give better transient performance.

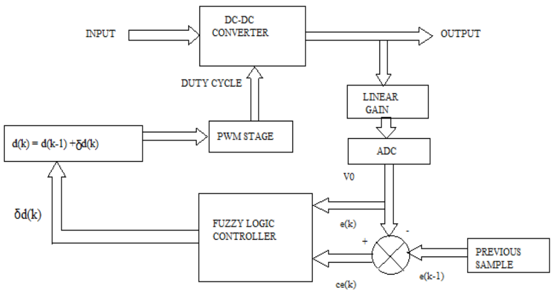

Fig.6 Output voltage for Buck converter without fuzzy controller

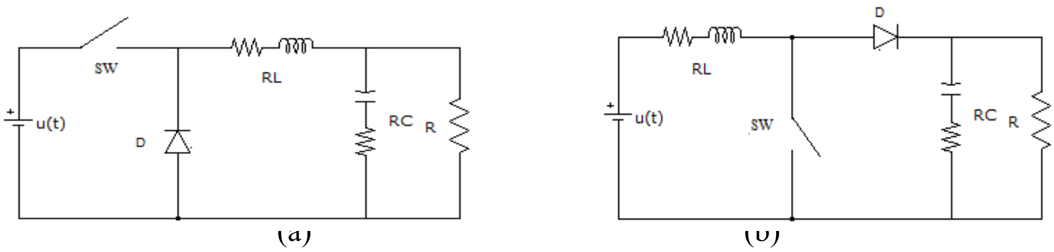

Fig.7 .Basic dc-dc converters. (a) Buck converter. (b) Boost converter.

For the experiment, the prototype boost converter's input voltage is 5 V, the output voltage is 12 V, and the nominal duty cycle is 58%. The scaling factors g0, g1 and h of the fuzzy controller for the boost converter are tuned to be 1.5, 1, and 1, respectively.

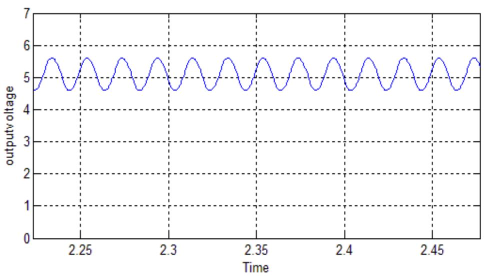

Fig.8 Output voltage for Buck converter without fuzzy controller

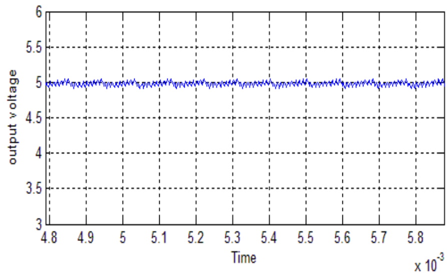

Fig.9 Output voltage for Buck converter with fuzzy controller.

The settling time is about 1ms with a little overshoot. When the load current changes from 1.364A to 0.16A. The settling time is about 2ms. The maximum transient error is 140mV.

V. CONCLUSION

Fuzzy controllers were designed the buck and boost converters. The fuzzy controllers were designed based on the in-depth knowledge of the plant, simulation by Simulink and experimental results. The fuzzy controller for the boost converter uses two different controller configurations for the start up transient and for steady state to obtain a fast and stable response, while only one configuration is used for the buck converter. Fuzzy logic appears to be a valid element for generalization to many control applications. Since both buck and boost converters are controlled using the same fuzzy control algorithm (without any modifications to the program), this shows that the fuzzy controller is developed based on the linguistic description of the system and not its mathematical model.

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