A New Design Method for PI-like Fuzzy Logic Controllers for DC-to-DC Converters

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Abstract – **This paper proposes a novel design procedure of PI-like fuzzy logic controller (FLC) for DC-DC converters that integrates linear control techniques with fuzzy logic. The design procedure allows the small signal model of the converter and linear control design techniques to be used in the initial stages of FLC design. This simplifies the small signal design and the stability assessment of the FLC. By exploiting the fuzzy logic structure of the controller, heuristic knowledge is incorporated in the design, resulting in a non-linear controller with improved performance over linear PI controllers.**

I. INTRODUCTION

Fuzzy logic control (FLC) has been applied successfully to a wide variety of engineering problems, including DC-to-DC converters [1-3]. It has been shown that using fuzzy control can reduce development costs and provide good performance [4]. With advances in digital hardware and digital control techniques, it is becoming feasible to implement control schemes such as fuzzy logic for power converters [5]. Fuzzy control is an attractive control method because its structure, consisting of fuzzy sets that allow partial membership and "if… then…" rules, resembles the way human intuitively approaches a control problem. This makes it easy for a designer to incorporate heuristic knowledge of a system into the controller. Fuzzy control is obviously of great value for problems where the system is difficult to model due to complexity, non-linearity, and/or imprecision. DC-DC converters fall into this category because they have a time-varying structure and contain elements that are non-linear and have parasitic components.

Despite its advantages, there are some problems with fuzzy logic control. Design of fuzzy controllers is usually accomplished by trial and error [1-3]. Stability analysis can be difficult and usually involves the use of non-linear control techniques [6-7]. With fuzzy logic control, it can be harder to assess the performance of the controller than with linear control techniques where metrics such as bandwidth can be used. Using linear control techniques, we can know how changing control parameters (gains, poles and zeros) will affect performance (bandwidth) and stability (phase and gain margins), but there is no analogous approach for fuzzy logic control.

This paper proposes a design methodology of fuzzy logic controllers for DC-DC converters that addresses these issues. Models of DC-DC converters have been developed [8] and used to design suitable linear controllers [9]. In recent years, research shows that fuzzy control can be directly related to the linear control [10-12]. Using this knowledge, a method that integrates the advantages of linear control techniques and fuzzy logic control is developed in this paper. In this method, linear models and linear control techniques are used in the initial design of the fuzzy controller. This initial controller has exactly the same response as a linear PI controller. As a result, its stability and performance can be assessed using linear control techniques and small signal model of the converter. By capitalizing on the fuzzy logic implementation of the controller, heuristic knowledge can be incorporated. This can give an improved non-linear controller that outperforms its linear counterpart in the initial design. The improvement can be made so that it does not compromise the stability or performance of the controller for small signals. In addition, better large signal dynamic performance is achieved. This methodology is developed for PI controllers since these are simple two term controllers (compared to PID control which requires three terms) and give zero steady state error (compared to PD controllers which have steady state error).

The organization of the paper is as follows. Section II discusses a simple relationship between fuzzy logic control and linear PI control. Section III uses this relationship to develop a design procedure for fuzzy logic controllers that combines the benefits of linear control techniques and fuzzy logic control. Section IV will give a design example using this procedure and simulation/experimental results are given. Conclusions are summarized in Section V.

II. RELATIONSHIP BETWEEN THE PROPOSED FUZZY LOGIC CONTROL AND LINEAR PI CONTROL

This section will discuss the relationship between a PI-like FLC and a digital linear PI controller. The block diagram for a fuzzy logic controller (FLC) is given in Fig.1. In this paper, a PI-like FLC is applied. The inputs of fuzzy logic controller are the error and change of error. The output is the incremental change of the control signal. Usually, a FLC is implemented using digital hardware such as a digital signal processor (DSP) or field programmable gate arrays (FPGA) [1]. The block diagram for a digital implementation of a PI-like FLC is given in Fig.2. The error signal e is sampled with a sample period Ts. The change of error Δe is computed as:

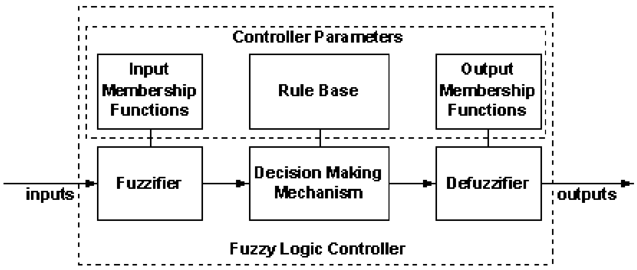

Fig. 1 Block diagram of fuzzy logic controller

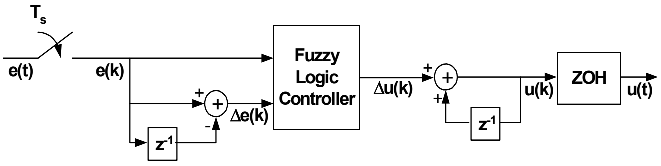

Fig. 2 Digital PI-like FLC

$$\Delta e(k) = e(k) - e(k-1) \tag{1}$$

where k is the sample number and z^{-1} represents the unit time delay. The error $e(k)$ and the change of error $\Delta e(k)$ are fed into the FLC depicted in Fig. 2. The output of the FLC is an incremental change of the control signal $\Delta u(k)$. Using a digital approximation for integration, the control signal $u(k)$ is obtained,

$$u(k) = \Delta u(k) + u(k-1) \tag{2}$$

A zero order hold (ZOH) is assumed between samples to obtain the continuous control output $u(t)$.

This controller will now be compared to a digital PI controller to obtain a relationship between the controllers. The transfer function for a continuous PI controller, C(s), with parameters a and G is given by

$$C(s) = \frac{U(s)}{E(s)} = G\frac{a \cdot s + 1}{s} \tag{3}$$

Various methods exist for finding the discrete equivalent of a continuous controller [5]. It should be noted that there is no exact digital equivalent for a continuous controller because a continuous controller has access to the complete time history of the error signal while a digital controller has access only to samples of this signal [13].

The bilinear transformation, given in (4), is one method to find a discrete equivalent of a continuous controller.

$$s = \frac{2}{T_s}\left(\frac{1-z^{-1}}{1+z^{-1}}\right) \tag{4}$$

Applying the bilinear transformation, a discrete equivalent $C(z)$ for $C(s)$ will be derived,

$$C(z) = \frac{U(z)}{E(z)} = \frac{m \cdot z + n}{z - 1} \tag{5}$$

where the parameters m and n are given by

$$m = G\left(a + \frac{T_s}{2}\right) \tag{6}$$

$$n = G\left(\frac{T_s}{2} - a\right) \tag{7}$$

The transfer function of (2) can be expressed as a difference equation

$$u(k) = (m+n)e(k) - n(e(k) - e(k-1)) + u(k-1) \tag{8}$$

A block diagram representation of this difference equation is illustrated in Fig.3.

The difference between Fig. 3 and Fig. 2 is that the dashed box of Fig. 3 is replaced by a two input, single output FLC in Fig. 2. It is noted that this dashed box has the relationship:

$$\Delta u(k) = (m+n)e(k) - n \cdot \Delta e(k) \tag{9}$$

Considering a fuzzy controller with the following constraints, the input membership functions are triangular except for the left most and right most membership function (shown in Fig. 4). The variable x in this figure is a generic variable; in the case of the PI-like FLC given in Fig. 2, x could represent the error e or the change in error Δe. The membership functions are not necessarily evenly distributed as illustrated in Fig. 4 and are arranged so that at most two have non-zero membership (are active) for any value of the input. Furthermore, the sum of the membership for all active fuzzy sets is exactly one.

With this description of the membership functions, if $x_1 < x < x_n$, membership can be calculated as:

$$\mu_{Ak+1}(x) = \frac{x - x_k}{x_{k+1} - x_k} \tag{10}$$

$$\mu_{Ak}(x) = 1 - \frac{x - x_k}{x_{k+1} - x_k} = 1 - \mu_{Ak+1}(x) \tag{11}$$

where μ_{Ak} is the membership of x to A_k, μ_{Ak+1} is the membership of x to A_{k+1}, x_k is the point where x has full membership to A_k, and x_{k+1} is the point where x has full membership to A_{k+1}. There are two exceptions where equations (10) and (11) cannot be used to calculate membership. If $x < x_1$, then $\mu_{A1}(x)$ = 1 and membership is zero for all other fuzzy sets. If $x > x_n$, then $\mu_{An}(x)$ = 1 and membership is zero for all other fuzzy sets.

The proposed fuzzy controller is defined to be a Sugeno-type fuzzy logic controller. This means that the output membership functions are singletons (crisp values). This fuzzy controller has rules of the form "If e is A_k and Δe is

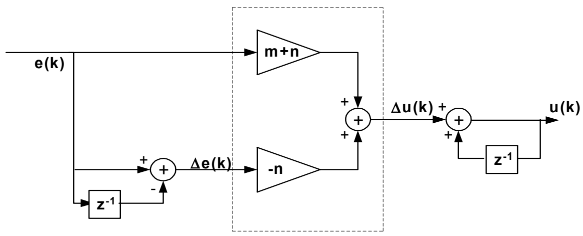

Fig. 3 Block diagram representation of equation (8)

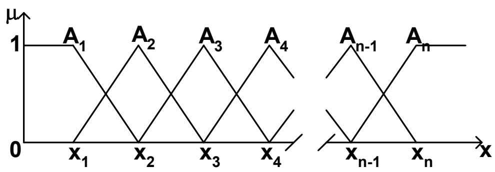

Fig. 4 Input membership functions of fuzzy logic controller

B_k, then $\Delta u = \Delta u_{AkBk}$", where A_k and B_k are fuzzy sets on the error and change of error inputs respectively. The "and" operation in the rule antecedent is performed by multiplication. Active rules are combined by the "or" operation, which is accomplished by addition. For example, ($e, \Delta e$) is the input to the controller, where e belongs to A_k and A_{k+1}, Δe belongs to B_k and B_{k+1}. Because for each input at most two fuzzy sets have non-zero membership, at most four rules are activated. These rules are:

(1) If e is A_k and Δe is B_k, then $\Delta u = \Delta u_{AkBk}$.

(2) If e is A_{k+1} and Δe is B_k, then $\Delta u = \Delta u_{Ak+1Bk}$;

(3) If e is A_k and Δe is B_{k+1} then $\Delta u = \Delta u_{AkBk+1}$;

(4) If e is A_{k+1} and Δe is B_{k+1} then $\Delta u = \Delta u_{Ak+1Bk+1}$.

The output of this FLC is the weighted sum of all the activated rules and is given by

$$\Delta u = (\mu_{Ak} \cdot \mu_{Bk}) \cdot \Delta u_{AkBk} + (\mu_{Ak+1} \cdot \mu_{Bk}) \cdot \Delta u_{Ak+1Bk} + (\mu_{Ak} \cdot \mu_{Bk+1}) \cdot \Delta u_{AkBk+1} + (\mu_{Ak+1} \cdot \mu_{Bk+1}) \cdot \Delta u_{Ak+1Bk+1} \quad (12)$$

In the case of a two input, single output fuzzy controller, the input-output relationship of the controller can be visualized as a control surface in three-dimensions. These constraints result in a FLC with two properties:

Property 1: Each rule gives the controller output when the inputs to the controller have full membership to the fuzzy sets in the antecedent of that rule. The controller output in this case is equal to the consequent of the rule. If the input-output relationship of the controller is visualized as a control surface, this means that each rule will define a specific point on the control surface.

Property 2: If the consequent of each of the four active rules lie in a plane on the control surface, then all points calculated by the controller using these rules will lie in that same plane.

Proof of Property 1: Consider the rule "If e is A_k and Δe is B_k then $\Delta u = \Delta u_{AkBk}$". At $e = e_k$, e has full membership to A_k, and at $\Delta e = \Delta e_k$, Δe has full membership to B_k. It can be seen from (12) that if the input is ($e_k, \Delta e_k$), μ_{Ak} =1, μ_{Bk} =1 and μ =0 for all other fuzzy sets. Then, the output is just $\Delta u = \Delta u_{AkBk}$, because all the other terms in (12) are zero. In terms of a control surface, this means that the point ($e_k, \Delta e_k, \Delta u = \Delta u_{AkBk}$) is a point on the surface. This is also true for all the other rules. This property arises from the restrictions placed on the membership functions that implied when membership is equal to 1 for one fuzzy set, it is zero for all others.

Proof of Property 2: Consider a plane defined by three points in a three-dimensional space defined by the variables e, Δe, and Δu. The points are called M($e_1, \Delta e_1, \Delta u_1$), N($e_2, \Delta e_1, \Delta u_2$), P($e_1, \Delta e_2, \Delta u_3$).

As illustrated in Fig. 5, using linear algebra, this plane can be described by the following equation:

$$\Delta u = \Delta u_1 + \frac{e - e_1}{e_2 - e_1}(\Delta u_2 - \Delta u_1) + \frac{\Delta e - \Delta e_1}{\Delta e_2 - \Delta e_1}(\Delta u_3 - \Delta u_1) \quad (13)$$

We now try to find a fourth point Q, which also lies in the plane described by (13). It is assumed that Q lies at $e = e_2$ and $\Delta e = \Delta e_2$ and has a Δu coordinate Δu_4. To make Q lie in the plane, by using (13), we can find that $\Delta u_4 = \Delta u_2 + \Delta u_3 - \Delta u_1$.

Now we consider an FLC with the constraints on its membership functions and inference mechanism as described above. The output of this FLC can be calculated by (10), (11) and (12). Assuming for each input x, $x_1 < x < x_n$, so that equations (10) and (11) can be used. Without loss of generality, we can assume that $e_1 < e < e_2$ and $\Delta e_1 < \Delta e < \Delta e_2$. In terms of notation in (10), (11) and (12), this means $e_k = e_1$, $e_{k+1} = e_2$, $\Delta e_k = \Delta e_1$, $\Delta e_{k+1} = \Delta e_2$, $A_k = A_1$, $A_{k+1} = A_2$, $B_k = B_1$, and $B_{k+1} = B_2$. Substituting this notation and (11) into (12), we can get

$$\Delta u = \Delta u_{A1B1} + \mu_{A2}(-\Delta u_{A1B1} + \Delta u_{A2B1}) + \mu_{B2}(-\Delta u_{A1B1} + \Delta u_{A1B2}) + \mu_{A2}\mu_{B2}(\Delta u_{A1B1} - \Delta u_{A2B1} - \Delta u_{A1B2} + \Delta u_{A2B2}) \quad (14)$$

From (10), the following can be obtained

$$\mu_{A2} = \frac{x - x_1}{x_2 - x_1} \quad (15)$$

$$\mu_{B2} = \frac{y - y_1}{y_2 - y_1} \quad (16)$$

Assuming the points M, N, P, and Q are defined by the active rules (this is possible according to property 1), in this case, $\Delta u_{A1B1} = \Delta u_1$, $\Delta u_{A2B1} = \Delta u_2$, $\Delta u_{A1B2} = \Delta u_3$, and $\Delta u_{A2B2} = \Delta u_4$. Substituting these values into (14), we can get

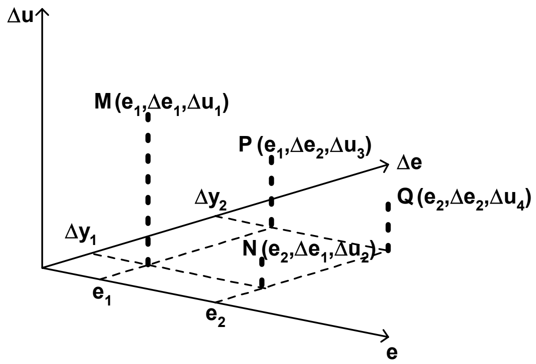

Fig. 5 Points in a three dimensional space

$$\Delta u = \Delta u_1 + \frac{e - e_1}{e_2 - e_1}(-\Delta u_1 + \Delta u_2) + \frac{\Delta e - \Delta e_1}{\Delta e_2 - \Delta e_1}(-\Delta u_1 + \Delta u_3) \tag{17}$$
$$+ \frac{e - e_1}{e_2 - e_1} \cdot \frac{\Delta e - \Delta e_1}{\Delta e_2 - \Delta e_1}(\Delta u_1 - \Delta u_2 - \Delta u_3 + [\Delta u_2 + \Delta u_3 - \Delta u_1])$$

Since the last term of (17) is zero, it is simplified to

$$\Delta u = \Delta u_1 + \frac{e - e_1}{e_2 - e_1}(\Delta u_2 - \Delta u_1) + \frac{\Delta e - \Delta e_1}{\Delta e_2 - \Delta e_1}(\Delta u_3 - \Delta u_1) \tag{18}$$

As we can see, equation (18) represents a plane. The input-output relationship of linear PI controller (shown in equation (9)) also represents a plane. Equation (18) is exactly the same as equation (13) for the plane. This means that if the consequent of each of the four active rules lie in a plane on the control surface, then all points calculated by the controller using these rules will lie in that plane.

We now note that the dashed box in the block diagram of Fig. 3 also describes a plane because (9) has the form of the equation for a plane. By using property 1, we can assign the rules of the fuzzy controller to have points that lie in the same plane as equation (9). This can be achieved by the following method: for the rule "If e is A_k and Δe is B_k, then $\Delta u = \Delta u_{AkBk}$", the value for Δu_{AkBk} is initialized as $\Delta u_{AkBk} = e_k(m+n) + \Delta e_k(-n)$. Thus, a FLC can be made to give the same control output as the digital PI controller of equation (5). Therefore, small signal model and linear control techniques for PI controller can be used to design a fuzzy logic controller. The significance of the proposed design method is that, linear control techniques and small signal model can be used to design a fuzzy logic controller. This avoids the use of trial and error and gives FLC with predictable small signal stability and performance. It can be proven that FLC have at least the same performance as a linear PI controller.

III. DESIGN METHODOLOGY

A flowchart of the design procedure is shown in Fig. 6. This procedure consists of three basic steps. In the first step, a conventional linear digital controller is designed. The second step transfers this controller to a fuzzy logic implementation. In the third step, this fuzzy logic implementation is exploited to incorporate heuristic knowledge resulting in a controller with improved performance.

Step 1 of Fig. 6 shows two possibilities for designing a digital controller. These two techniques include direct digital design and design by emulation. In direct digital design, design of compensation is done directly in the discrete time domain using a discrete model of the plant to be controlled. In design by emulation, compensation is first designed in the continuous time domain and then an equivalent digital controller is found by approximation [13]. Control of power supplies is usually implemented using analog electronics. As a result, many designers are accustomed to designing controllers in the continuous time domain. For this reason the design by emulation technique is adopted. In the case of design by emulation, the gain and zero of a continuous PI controller of equation (3) are chosen to provide the desired response. The bilinear transformation (equation (4)) is then used to find a digital equivalent, resulting in the digital compensator of equation (5). Considering frequency response, this digital compensator approximates its continuous counterpart very well for frequencies below 1/10th of the sampling frequency [5].

Once a digital controller has been designed, it can be transferred to the fuzzy controller as described in section II. This is the step 2 of the design procedure. The first property of fuzzy logic controller described in section II will be used. It should be noted that, the proof of the second property in section II makes the assumption that for each input x to the controller, $x_1 < x < x_n$. This means that the values of x_1 and x_n need to be chosen appropriately, so that property 2 will hold over the range of inputs expected by the controller. The number and distribution of the membership functions are chosen based on experience. More membership functions give more controller parameters, and thus more freedom to shape the control surface. Putting membership functions closer together means that there are more parameters to describe that region of control surface, and therefore more freedom to shape that region.

In step 3, heuristic knowledge of the system and trial and error are used to improve the performance of the controller. For example, for buck converter, the following heuristic knowledge rules can be used [1]:

1. If the error is far from zero, the change in duty cycle should be large.
2. If the error is near zero then, the change in duty cycle should be small.

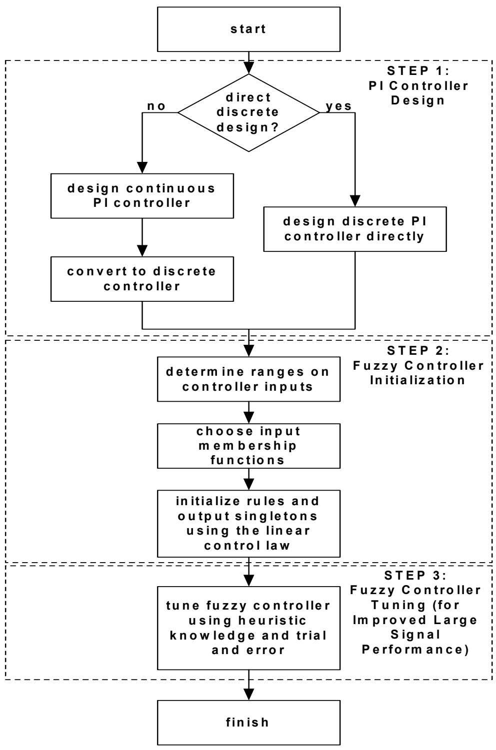

Fig. 6 Design procedure

3. If the error is near zero, but the change in error is large, the duty cycle should be changed to prevent overshoot.
4. If the change in error is in the direction such that the output is approaching the zero error, but the error is not close to zero, then the change in duty cycle need not be as large as if the change in error were in the opposite direction.

This knowledge can be included by altering the input membership functions or the consequents of the rules (output singletons). If the membership functions and rules are unaltered in a small region on the control surface near the zero error and zero change in error point, then the input-output relationship of the controller will remain unchanged in this region. This means the performance of the controller for inputs constrained in this region will be the same as for the initial controller and can be predicted using the small signal models and linear control techniques.

IV. SIMULATION AND EXPERIMENTAL RESULTS

The design procedure will be applied for a voltage mode controlled buck converter. The parameters of this converter are Vin=5V, Vo=2.5V, L=1μH, C=220μF, R_L=2mΩ, ESR=1mΩ. The switching frequency is 400kHz.

A continuous PI controller is designed with a transfer function $C(s)=\frac{2000(1+0.000125\cdot s)}{s}$ to achieve wide bandwidth and 50^0 phase margin.

Block diagrams of the digital PI-like fuzzy controllers are given in Fig. 7. The saturation blocks limit the duty cycle between 5% and 95%. For the error input e, nine membership functions were designated A_1 through A_9. For the change of error input Δe, nine input membership functions were designated B_1 through B_9. Note that e_i is the point where μ_{Ai} =1 and Δe_i is the point where μ_{Bi} =1. The values of e_1 through e_9 and Δe_1 through Δe_9 are given in Table 1 and Table 2 respectively. The membership functions are illustrated in Fig. 8-9.

The rule table for the fuzzy controller in this paper is given in Table 3. Each entry gives the change of duty cycle Δu , when membership is full to both the corresponding fuzzy sets in the rule antecedent. For instance, the entry in row 2, column 3 gives the normalized change of duty cycle if membership is full to the membership function A_3 on the error input and the membership function B_3 on the change of error input.

The rules were initialized as discussed in section III. For example for the rule "If e is A2 and Δe is B4 then $\Delta u = u_{A2B4}$", the value for u_{A2B4} is initialized to

$$\begin{aligned} u_{A2B4} &= e_2(m+n) + \Delta e_4(-n) \\ &= -1(0.2025 + (-0.1975)) + (-0.016)*(-(-0.1975)) \\ &= -0.081 \end{aligned}$$

where m and n can be obtained from equation (5)-(7).

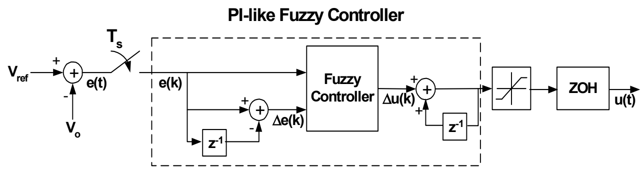

Fig. 7 PI-like fuzzy logic controller

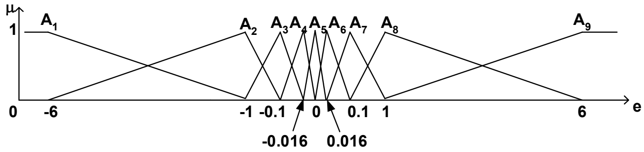

Fig. 8 Membership functions for the error

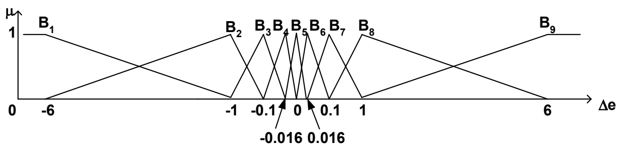

Fig. 9 Membership functions for the change of Error

Table 1. Values of e_1 through e_9

e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9
-6	-1	-0.1	-0.016	0	0.016	0.1	1	6

Table 2. Values of Δe_1 through Δe_9

Δe_1	Δe_2	Δe_3	Δe_4	Δe_5	Δe_6	Δe_7	Δe_8	Δe_9
-6	-1	-0.1	-0.016	0	0.016	0.1	1	6

Table 3 Rule table for fuzzy controller giving change in duty cycle

		Change in Error								
		B_1	B_2	B_3	B_4	B_5	B_6	B_7	B_8	B_9
Error	A_1	-1.2150	-0.2275	-0.0498	-0.0331	-0.0300	-0.0269	-0.0103	0.1675	1.1550
	A_2	-1.1900	-0.2025	-0.0248	-0.0081	-0.0050	-0.0019	0.0147	0.1925	1.1800
	A_3	-1.1855	-0.1980	-0.0203	-0.0036	-0.0005	0.0026	0.0193	0.1970	1.1845
	A_4	-1.1851	-0.1976	-0.0198	-0.0032	-0.0001	0.0030	0.0197	0.1974	1.1849
	A_5	-1.1850	-0.1975	-0.0198	-0.0031	0	0.0031	0.0198	0.1975	1.1850
	A_6	-1.1849	-0.1974	-0.0197	-0.0030	0.0001	0.0032	0.0198	0.1976	1.1851
	A_7	-1.1845	-0.1970	-0.0193	-0.0026	0.0005	0.0036	0.0203	0.1980	1.1855
	A_8	-1.1800	-0.1925	-0.0147	0.0019	0.0050	0.0081	0.0248	0.2025	1.1900
	A_9	-1.1550	-0.1675	0.0103	0.0269	0.0300	0.0331	0.0498	0.2275	1.2150

Table 4 Values of e_1 through e_9 for Improved Performance

e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9
-1	-0.3	-0.05	-0.01	0	0.01	0.05	0.3	1

Table 5 Values of Δe_1 through Δe_9 for Improved Performance

Δe_1	Δe_2	Δe_3	Δe_4	Δe_5	Δe_6	Δe_7	Δe_8	Δe_9
-1	-0.3	-0.05	-0.01	0	0.01	0.05	0.3	1

Rules 1 and 2 in section III state that the gain should be increased further from the zero error point. This knowledge was included into the design by changing the definitions of the input membership functions. Trial and error was used to pick appropriate values for input memberships (shown in Table 4-5).

In order to compare the small signal response of digital PI controller and the proposed fuzzy logic controller, simulation was done in frequency domain. From Fig.10, it can be seen that two controllers have the same small signal frequency response. For large signal response, simulations were done in terms of input voltage change, load current change and reference voltage change. It is shown in Fig. 11-13 that, the proposed fuzzy logic controller has better dynamic response than digital PI controller under large signal changes.

A comparison of the experimental results of the digital PI controller and the fuzzy logic controller is shown in Fig. 14-15. In Fig. 14, a small step reference change of 16mV (from 2.5V to 2.516V) was imposed. It is shown that the behaviour of the fuzzy controller and the original digital PI controller is the same for small signals and can be predicted by the small signal model. Fig. 15 gives the dynamic responses for large step reference change (from 2.5V to 3.0V). The results show that the improved fuzzy logic controller has better dynamic response than the original PI controller under large signal changes.

V. CONCLUSION

This paper presented a design procedure of fuzzy logic controllers for DC-DC converters. The proposed technique allows the small signal model of the converter and linear control techniques to be applied in the initial stages of fuzzy controller design. This makes assessing the performance and stability of the fuzzy controller easy and allows linear design techniques to be exploited. The FLC designed using linear techniques serves as a known starting point from which improved performance can be achieved by applying heuristic knowledge to obtain a non-linear controller. The performance and stability of the improved non-linear controller can still be assessed using linear control techniques for small signals if the control surface remains linear in the region in which these small signals fall. A design example was presented with simulation and experimental results to illustrate and verify this procedure.

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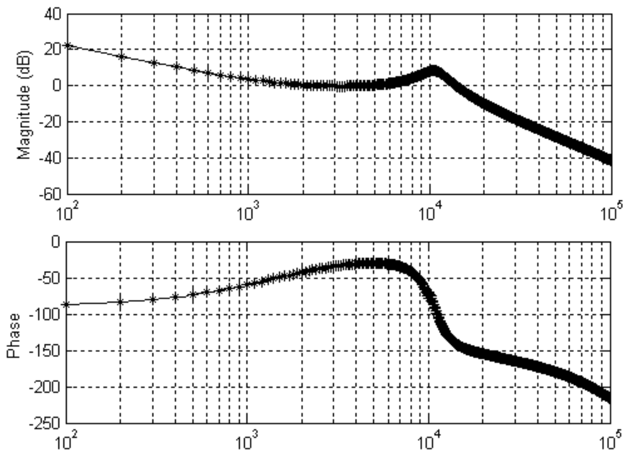


Fig. 10 Bode plot for fuzzy logic controller (solid line) and digital PI controller (star line)

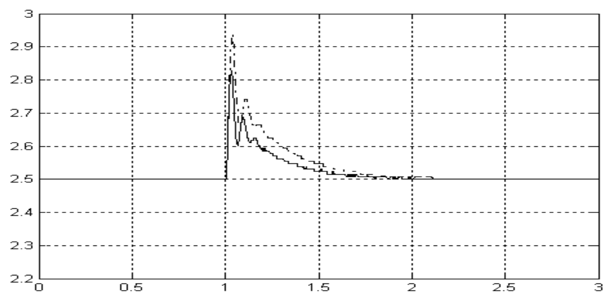


Fig. 11 Simulation results of output voltage response to input voltage change from 5V to 6V (solid line: FLC, dashed line: digital PI controller) X axis: 0.5ms/div, Y axis: 100mv/div

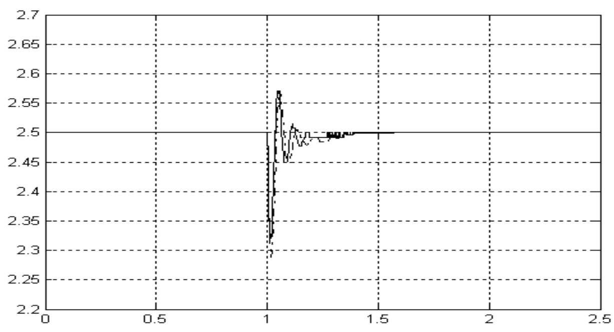


Fig. 12 Simulation results of output voltage response to load current change from 5A to 10A (solid line: FLC, dashed line: digital PI controller) (X axis: 0.5ms/div, Y axis: 50mv/div)

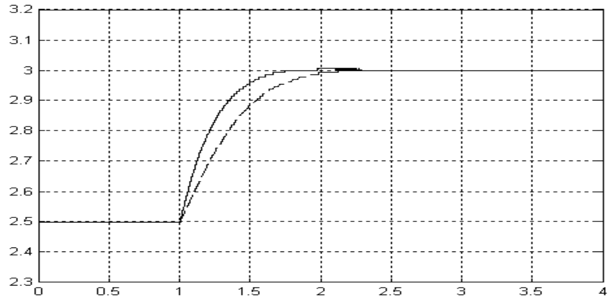
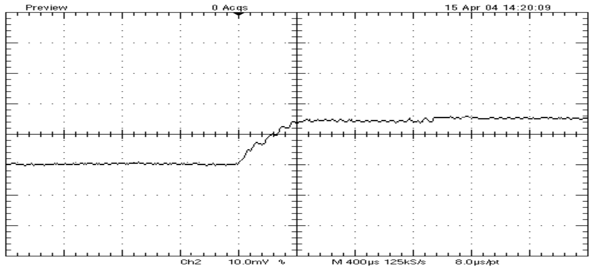
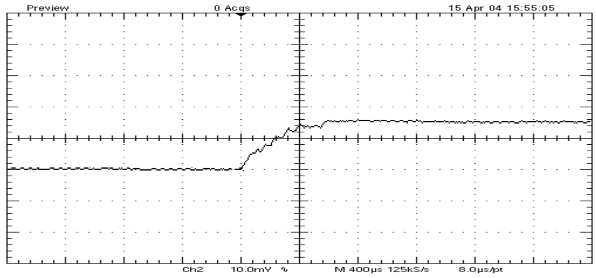


Fig. 13 Simulation results of output voltage response to reference voltage change from 2.5V to 3V (solid line: FLC, dashed line: digital PI controller) X axis: 0.5ms/div, Y axis: 100mv/div

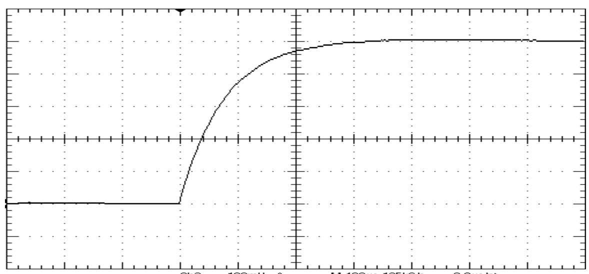


(a) Digital PI controller

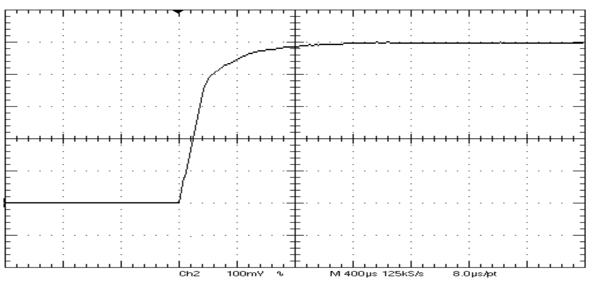


(b) Fuzzy logic controller

Fig. 14 Experimental results of output voltage response to small step reference change (X axis: 400us/div, Y axis: 10mv/div)



(a) Digital PI controller



(b) Fuzzy logic controller

Fig. 15 Experimental results of output voltage response to large step reference change (X axis: 400us/div, Y axis: 100mv/div)