Hybrid Fuzzy Logic Controllers for Buck Converter

Behrouz Safarinejadian and Farzaneh Jafartabar

Abstract- In order to control the output voltage of a Buck converter, hybrid fuzzy logic controllers are investigated in this paper. A fuzzy proportional-integral (PI) controller is proposed to improve the performance of the converter instead of a conventional digital PI controller too. The model of the power system is developed using SimPowerSystem toolbox and the control part is realized using Fuzzy Logic Toolbox in MATLAB. Simulation results show the better performance for buck with a fuzzy PI in comparison with conventional PI, also less settling time and less steady state error with two-level hybrid and fuzzy PD+I respectively.

Keywords--- Buck converter, PI controller, fuzzy PI controller, two-level hybrid fuzzy logic controller, fuzzy PD+I controller

I. Introduction

IN many industrial applications, it is required to convert an unregulated DC input voltage into a regulated DC output voltage. Switch mode DC-DC converters are used for this purpose [1]. There are many types of switching DC-DC converters. Buck is a step down one which converts a higher DC voltage to a lower DC voltage and the output polarity is same to that of the input voltage. Buck inherent behavior is non-linear, because of the presence of parasiti elements [2], [3].Thus the important item to the performance of the converter is the choice of control method. Sliding mode method, linear-based method and nonlinear-based method are the commonly used control methodology for DC-DC converters [4]. A system model is required for sliding mode. Linear-based method has a simple structure to design bus is not proper for systems with strong nonlinearity. But a nonlinear-based controller has ability to overcome problems associated with linear-based controllers [5].

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A Fuzzy Logic Controller (FLC) does not require thesystem model and it can be used as a nonlinear controller [4]. Thus a fuzzy logic control is a proper method for buck converter. In this study a fuzzy PI is proposed to control the output voltage of buck. In order to decrease the settling time, it is useful to add the derive term to the controller. Since the design of fuzzy PID is complex, other types of controllers are used such as hybrid fuzzy logic. Fuzzy P+ID, two-level hybrid fuzzy logic controller and fuzzy PD+I are some useful methods of fuzzy hybrid[6], [7]. In this study, two-level hybrid fuzzy logic controller is used to decrease the settling time. In order to minimize the steady state error, fuzzy PD+I is proposed. Figure 1 shows the buck converter system. Q is a power MOSFET as a component, LC filter is used to minimize the voltage ripple, R_L is used as a load, r_C and r_L are the parasitic elements in the LC filter and D is a diode. V_i and V_O are input and output voltage of buck converter respectively.The paper is organized as follows. In section 2, control schemes for buck converter are presented. Simulation results are shown in section 3. Finally conclusions are given in section 4.

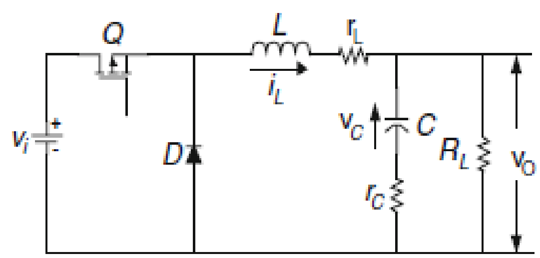

Fig.1 Circuit diagram of a Buck converter

II. Control schemes for Buck converter

Since it is considered to control the output voltage of the buck converter, the change of the duty cycle should be controlled. Thus error in the output voltage and the change of error in the output voltage are given to controller. The output of the controller is the reference signal which compare to the carrier signal. The output signal is the switching signal given to the gate of the MOSFET. The control loop block diagram is shown in figure 2.

Design of conventional PI controller

A classical analog PI controller is described by equation (1).

$$u(t) = K_p e(t) + K_i \int_o^T e(\tau)\, d\tau \qquad (1)$$

Where, $u(t)$ is the output from controller, $e(t)$ is the error signal, given by *m(t)-y(t)*, *m(t)* is the desired value, *y(t)* is the output from process and K_p and K_i are the proportional and integral gain of the controller respectively. The corresponding equation in the frequency domain is as follow.

$$U(s) = \left[K_p + \frac{K_i}{s}\right] E(s) \qquad (2)$$

In the recent years, technology advances has led to use of digital control because of its advantages instead of analog control [1].Therefor equation (1) needs to be expressed in digital domain. There are several methods are used to obtain to discrete-time equivalent of an analog PI controller, such as forward difference method, backward difference method, impulse invariant and step invariant methods, bilinear transformation method and matched pole-zero method [8].

Applying the bilinear transformation:

$$s = \frac{2}{T}\left(\frac{Z-1}{Z+1}\right) \qquad (3)$$

Where T is the sampling time.

Substituting the expression (3) into equation (2) gives,

$$U(Z) = \left[K_p - \frac{K_i T}{2} + \frac{K_i T}{1 - Z^{-1}}\right] E(Z) \qquad (4)$$

Consequently, the discrete-time domain equation is obtained as

$$u(k) = u(k-1) + k_1(e(k) - e(k-1)) + k_2 e(k) \qquad (5)$$

Where the coefficients k_1 and k_2 are

$$k_1 = K_p - \frac{K_i T}{2} \quad , \quad k_2 = K_i T \qquad (6)$$

Design of fuzzy PI controller

Structure of a FLC consist of: fuzzifire which converts each piece of input data to degrees of membership, rule base, inference engine which infer a fuzzy control action from knowledge of the rule base and the linguistic variable definition, defuzzifier which convert the inferred fuzzy control action into a crisp control action [7], [9]. The inputs of the fuzzy controller are the error *e(k)* and the change of the error $\Delta e(k)$ which are given as follow

$$e(k) = v_{ref} - v_o(k) \qquad (7)$$

$$\Delta e(k) = e(k) - e(k-1) \qquad (8)$$

Where v_{ref} is the reference output voltage and $v_o(k)$ is the measured output voltage in the k_{th} sample. The output of the fuzzy controller is the change of the reference signal $\Delta u(k)$. The reference signal is determined by

$$u(k) = u(k-1) + \Delta u(k) \qquad (9)$$

Where $u(k-1)$ is the previous reference signal.

$u(k)$ is sent to the PWM generator. PWM generator generates the necessary switching signal for the gate of the MOSFET in the converter. For ease the computation the fuzziffication method is fuzzy singleton. Fuzzy rules are in the form:

R_i: If e is A_i and Δe is B_i, then Δu is C_i

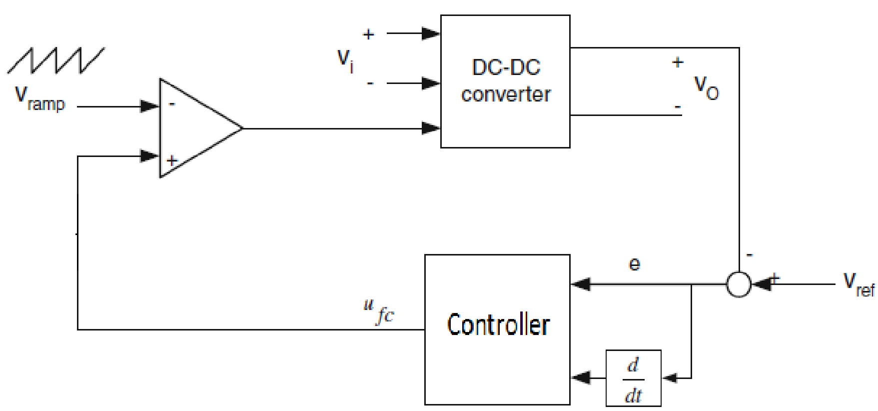

Fig. 2 Block diagram of the control loop for a buck converter

Where A_i and B_i are fuzzy subsets in their universe of discourse and C_i is a fuzzy singleton. Each universe of discourse is divided into five fuzzy subsets: PB(Positive Big), PS(Positive Small), ZE(Zero), NS(Negative Small), NB(Negative Big).The partition of fuzzy subsets is shown in figure 3 and 4. For simpler design, universe ranges for inputs and outputs are normalized in [-1,1]. Fuzzy control rules are derived from the analysis of the converter behavior:

1) When the output of the converter is far from the set point (e and Δe are PB or NB), the duty cycle should be close to zero or one so as to bring to the set point quickly.

2) When the output of the converter is approaching to the set point (e and Δe are NS or PS), a small change of the duty cycle is necessary.

3) When the output of the converter is approaching very close to the set point, duty cycle must be kept constant in order to prevent the overshoot.

There are twenty five rules according to these benchmarks. They are shown in table 1. A maximum of four rules are obtained for each combination of e and Δe.

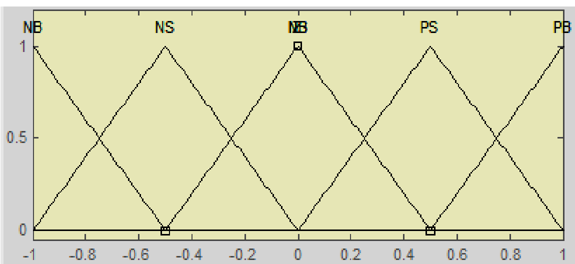

Fig.3 Inputs membership functions of fuzzy PI controller (error and the change of error)

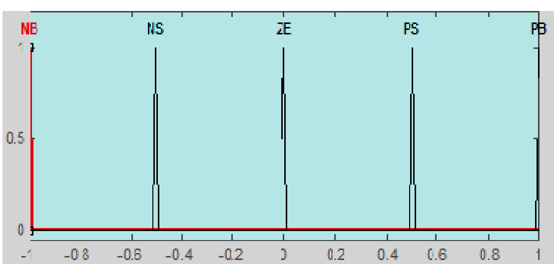

Fig.4 Output membership functions of fuzzy PI controller

Among the various fuzzy inference method, Mamdani's min implication is used in this part. With this method, the inference result of each rule consists of two parts: the weighting factor, w_i and the singleton value of the fuzzy output which are in table 1, C_i. The inferred singleton output of each rule, z_i is given by

$$z_i = min\{\mu_{A_i}(e), \mu_{B_i}(\Delta e)\}. C_i = w_i C_i \qquad (10)$$

The center of gravity (centroid) defuzzification method is preferred in this study. According to this method, the inferred value, Δu is as follow

$$\Delta u = \frac{\sum_{i=1}^{4} w_i C_i}{\sum_{i=1}^{4} w_i} \qquad (11)$$

Table I. Fuzzy control rules

The change of error (Δe)	Error (e)				
	NB	**NS**	**Z**	**PS**	**PB**
NB	NB	NB	NB	NS	Z
NS	NB	NB	NS	Z	PS
Z	NB	NS	Z	PS	PB
PS	NS	Z	PS	PB	PB
PB	Z	PS	PB	PB	PB

Design of two-level hybrid fuzzy logic controller

Figure 5 shows the structure of a fuzzy hybrid with two levels. As figure shows, controller I and controller II belong to the first level. Usually one of these two controllers is a PI and another one is a PD controller. In this study, these are fuzzy logic controllers. Fuzzy supervisory controller belongs to the second level. According to the system condition, fuzzy supervisory controller chooses PD or PI as a switch. At first, supervisory controller switch to the fuzzy PD (FPD) so as to increase the settling time, then controller switch to the fuzzy PI (FPI) in order to minimize steady state error. FPD and FPI should be designed at first. FPI is designed at section 2-3. The output of this controller is one of the inputs of fuzzy supervisory controller. The inputs of FPD controller are error and the change of error which are given by (7), (8). Inputs membership functions are as figure 3 and output membership functions are as figure 4. Fuzzifire, defuzzifire, inference engine and rule base are as FPI controller part. The output of PD controller is another input of the fuzzy supervisory controller. Error and the change of error are other inputs of it. To fuzzy supervisory controller design, singleton fuzzifire and sugeno implication method are used. In switching structure, sugeno's linear type is preferred. Fuzzy rules are in form:R_i: If e is A_i and Δe is B_i, then $z_i = f_i(x, y)$

When z_i is the fuzzy output. The partition of inputs fuzzy subsets (PI and PD) are shown in figure 6. The partition of error and the change of error fuzzy subsets are shown in figure 3.

When supervisory controller switch to PI, the output is shown by P_i and when switch to PD, the output is shown by P_d. Fuzzy rules are derived according to these criteria:

When error and the change of error are around zero, system response approaching to steady state and supervisory controller should switch to PI, otherwise system is in transient state and controller should switch to PD.According to these criteria, four rules are derived, given as follow:

1- If e is ZE & $\Delta e$is ZE then U is P_i

2- If e is not ZE & Δe is ZE then U is P_d

3- If e is ZE & Δe is not ZE then U is P_d

4- If e is not ZE & Δe is not ZE then U is P_d

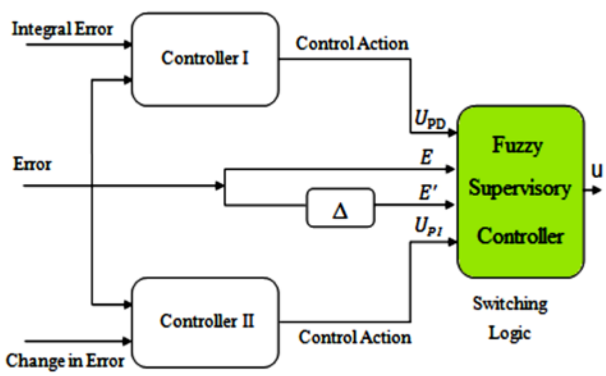

Fig.5 Structure of fuzzy hybrid with two levels

When the fuzzy implication method is sugeno, fuzzy output is as follow

$$\alpha[U_{PD}] + \beta[U_{PI}] + \gamma[e] + \xi[\Delta e] = z_i \qquad (12)$$

$$\equiv [\alpha \quad \beta \quad \gamma \quad \xi \quad 1]$$

Where $\alpha, \beta, \gamma, \xi$ are constant coefficients, U_{PD} is output of FPD and U_{PI} is output of FPI. Since error and the change of error do not appear in the output, $\gamma = \xi = 0$. βandα are appointed according to system condition. So

Output is PI $\rightarrow \beta U_{PI}$=P_i , *Output is PD* $\rightarrow \alpha U_{PD}$=$P_d$

So output membership functions (P_i ,P_d) are shown by the vectors $[0 \;\; \beta \;\; 0 \;\; 0 \;\; 1]$ and $[\alpha \;\; 0 \;\; 0 \;\; 0 \;\; 1]$ respectively. The weighted average (wtaver) deffuzification method is selected for this fuzzy controller.

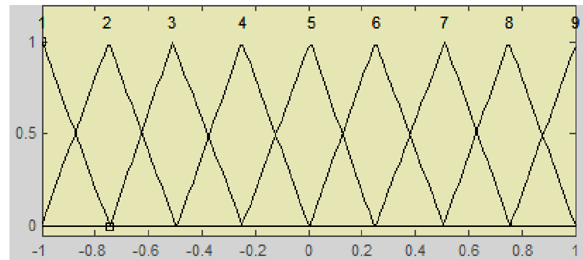

Fig.6 Input membership functions of fuzzy supervisory controller(PI and PD)

Design of fuzzy PD+I

The block diagram of fuzzy PD+I controller is given in figure 7. According to this figure E is error, CE is the change of error and IE is the integral of error. Error and the change of error are the inputs of fuzzy PD which are given by (7) and (8), the output of it, is added with integral of error. The total output of the controller, U is the reference signal given to the PWM generator. Fuzzy PD is designed in section 3-2.

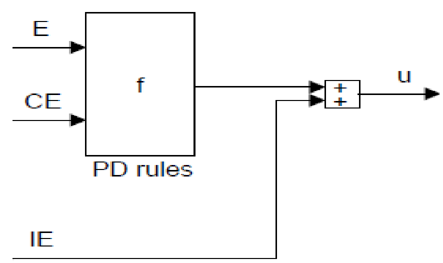

Fig.7 structure of fuzzy PD+I controller

III. Simulation Results

The model of the entire system has been developed using SimPowerSystem toolbox and Fuzzy Logic Toolbox in MATLAB. Table 2 shows the simulation parameters.

Figure 9 shows a comparison between the simulation results obtained using two different techniques for controller design for buck converter: one uses of conventional digital PI and the other uses fuzzy PI controller, Where k_1=0.3, k_2=0.015 in equation (5). As it can be seen, the steady state error and the settling time of the system with conventional PI are 4.5V and 8.3ms and of the system with fuzzy PI are 0.9V and 8ms respectively. The overshoot in the output voltage of conventional PI is 0.65% and the output voltage of fuzzy PI does not have any overshoot.

TABLE II. CIRCUIT PARAMETERS FOR THE BUCK CONVERTER

Parameters	Values
$V_i(v)$	100
Vo(v)	80
$L(\mu H)$	500
$r_L(m\Omega)$	10
$C(\mu F)$	440
$r_C(m\Omega)$	5
$F_s(kHz)$	20

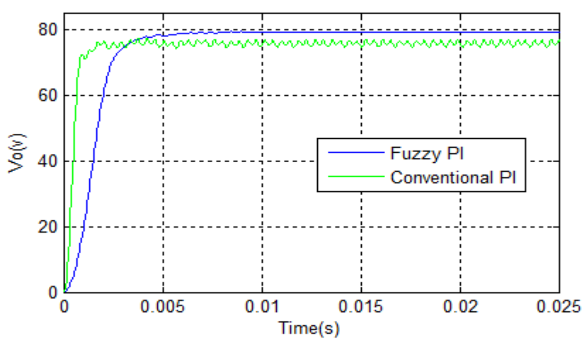

Fig.8 Output voltage of buck converter with fuzzy PI and conventional PI controller

The output voltage of buck converter depicted in figure 9, has been studied using two-level hybrid and fuzzy PI controller, in order to compare the settling time in two cases. The settling time of the output voltage of fuzzy hybrid is 6.6ms. The steady state error in two cases is the same. It can be observed in figure 10, that the buck output voltage with fuzzy PD+I controller had less steady state error compared with fuzzy PI controller. Steady state error in first case is 0.3V and the settling time is 7.7ms, that is less than fuzzy PI.

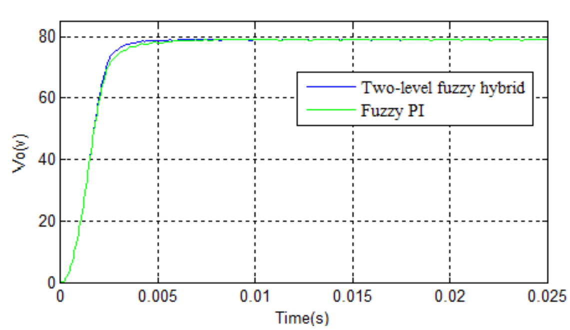

Fig.9 Output voltage of buck converter with fuzzy PI and Two-level fuzzy hybrid

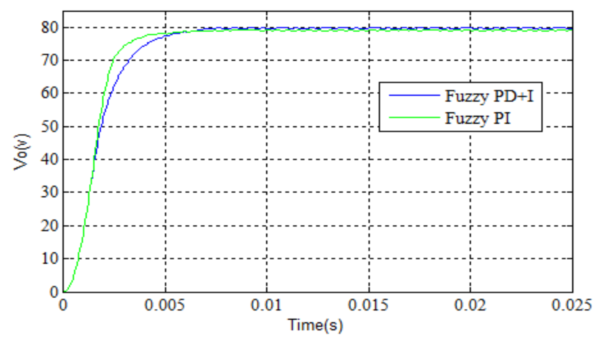

Fig. 10 Output voltage of buck converter with fuzzy PI and fuzzy PD+I

IV. CONCLUSIONS

This paper has investigated fuzzy logic controllers for a buck converter. The system performance has been investigated in relation to the voltage regulation. First a classical PI controller is designed. Then in order to have the better performance three fuzzy logic controllers are proposed: fuzzy PI, two-level fuzzy hybrid, fuzzy PD+I. These results show that fuzzy PD+I is a proper controller when minimizing the steady state error is the purpose and two-level fuzzy hybrid is the appropriate control method when having the lowest settling time is important.

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