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DC-DC 컨버터를 위한 강인한 성능을 가지는 퍼지제어기의 설계 및 구현

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Design and Implementation of Fuzzy Controller with Robust Performance for DC-DC Converters

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요 약

본 논문에서는 퍼지 논리에 기초를 둔 DC-DC converter를 위한 범용 FLC의 방식을 제안하였다. 제안한 FLC는 기존의 제어기와 비교할 때, 오버슈트 문제와 파라메터 변화에 대한 민감도 면에서 향상된 성능을 나타내었다. 이러한 성능 향상은 FLC 규칙들이 다양한 동작 영역에서 각각 적합하게 설정됨으로써 소신호 응답과 대신호 응답 모두 효과적으로 동작하도록 설계되었기 때문이다. 그 적용 예로 부스터(booster)에 대한 시뮬레이션 결과는 제안된 제어 기법의 타당성을 보여주고 있다.

ABSTRACT

This paper proposes a fuzzy logic controller(FLC) for DC-DC converters in order to obtain good performances that can not be achieved by linear control techniques in the presence of wide parameter variations. While the standard controller uses error and derivative of error, the proposed controller uses state variables. Such method is very efficient in case of DC-DC converters and can guarantee both stable small-signal responses and improved large-signal responses. The presented approach method is general and can be applied to any dc-dc converter topologies. Through the simulations of booster, we verify the proposed control technique can give a satisfactory performance.

Key Words : Fuzzy logic controller, Control technique, DC-DC Converters, Booster

1. Introduction

DC-DC converter is used in various type DC power conversions and switching mode power supply(SMPS). For more efficient usage in various application areas, the non-linear control of the dc-dc converter is frequently studied until now[1 2].

Conventional control approaches such as voltage mode and current control need accurate tuning procedures for a wanted performance. Such controls can be easily implemented by analog circuits. But the control performances are dependent on the operating points, and the selection of control parameter is difficult due to the effects by various uncertainties and disturbances such as various parasitic elements, time varying load and varying input voltage. Especially, the stability for large signal input results in a limited bandwidth and a deteriorated converter performance. The control of the dc-dc converter with high order state variables needs considerable design efforts and is more difficult to design.

Recently proposed fuzzy logic control(FLC) uses much flexible approach different to conventional methods[4 8]. FLC need not accurate mathematical models and complex computations. The method depends on the human's understanding composed of linguistic forms, can apply to nonlinear systems.

FLC method is general because same control rules can apply to various type dc-dc converters. But in this case, scaling factors must be tuned according to converter topology and given parameter.

In this paper, a fuzzy controller is considered only using one inductor current and one output voltage, which is different to other FLC methods. The usefulness of the proposed method is shown as simulation tests based on the design procedures for the boost type converter, which is selected because it is very complex system in that it is non-minimum phase system and has widely varying performances according to operating points.

2. Modeling of DC-DC Converter

An averaged model of the dc-dc converter can be obtained by the state space average method[3][9]. Boost type converter(booster) is given as Fig. 1 (a), where the most significant stray component, internal resistance of inductor L, is considered as rL, and the load is represented as an energy consuming equivalent resistance R. The operation of the boost converter(booster) is classified as mode 1 and mode 2. In the mode 1 as Fig. 1 (b), semiconductor switch SW1 is on and diode switch SW2 is off so that inductor current increases and output capacitor energy is consumed in load. In the mode 2 as Fig. 1 (c), semiconductor switch SW1 is off and diode switch SW2 is on so that inductor energy is transferred to the capacitor for filling up the consumed energy. The transfer functions can be derived from the state space model[3] obtained by averaging these operating modes as follows;

- DC gain : $G_{dc} = V_o / V_i$

$$G_{dc} = G_{ideal}(1-D)^2 \frac{R}{R'} \tag{1}$$

- AC transfer function : $G_{ac}(s) = \widehat{v_o}(s) / \widehat{v_i}(s) =$

$$\frac{(1-D)R}{R'} \frac{1}{s^2 + LCR + s(L/R' + Rr_L C/R') + 1} \tag{2}$$

- Control transfer function : $G_d(s) = \widehat{v_o}(s) / \widehat{d}(s) =$

$$\frac{V_o((1-D)^2R - r_L)}{(1-D)R'} \frac{(1 - s\frac{L}{(1-D)^2R - r_L})}{s^2 + LCR + s(L/R' + Rr_L C/R') + 1} \tag{3}$$

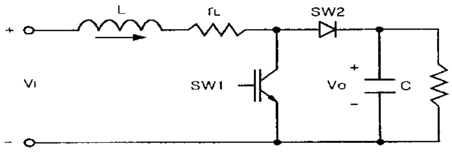
The parameter used in the above equations are defined as follows;

$$G_{ideal} = 1/(1-D) \tag{4}$$

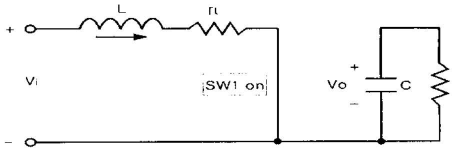
$$D = T_{on}/T \tag{5}$$

$$R' = r_L + R(1-D)^2 \tag{6}$$

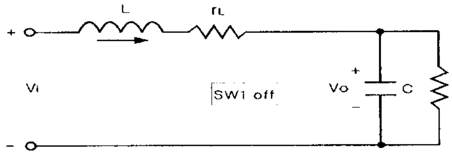
In ideal condition, DC gain is determined by the duty ratio of (5). But the real DC gain is affected by the internal resistance and load as (1). Both AC gain of (2) and dynamic transfer function of (3) are also determined by various parameters, especially duty ratio D.



(a) Booster circuit



(b) Operating mode 1



(c) Operating mode 2

Fig. 1 Booster circuit and each operating mode

3. Application of Fuzzy Control DC-DC Converters

3.1 A Suitable Fuzzy Control Methods for DC-DC Converters

Common fuzzy control approaches which utilize only the output voltage and its rate of change were already presented in literature[5,6], but they show poor dynamic performances. The basic idea of a suitable fuzzy controller for dc-dc converters is shown in Fig. 2. The converter is represented by a "black box" from which we only extract the terminals corresponding to input voltage Vi, output voltage Vo, one inductor current iL, and controlled switch S. As we can see, only two state variables are sensed: the output voltage and one inductor current. From these measurements, the fuzzy controller provides a signal proportional to the converter duty cycle which is they applied to a standard pulse width modulation (PWM) modulator.

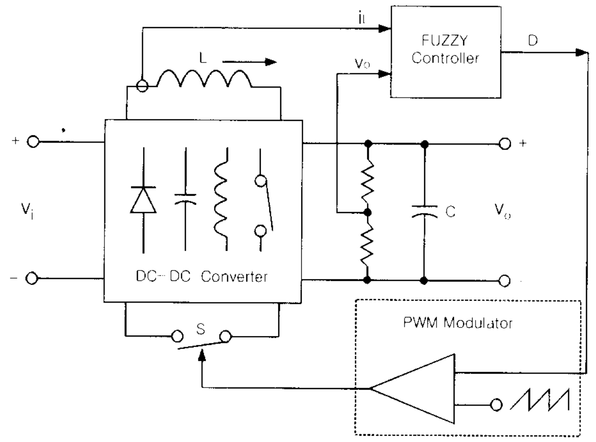


Fig. 2 Block diagram of fuzzy control scheme of dc-dc converter

3.2 A Fuzzy Controller Structure

The first important step in the fuzzy controller definition is the choice of the input variables. In order to improve operation, we need additional information on the energy stored in the converter, *i.e.*, an inductor current must be sensed. Accordingly, in the proposed fuzzy controller we use three input variables: 1) output voltage error ε_v, 2) inductor current error ε_i, and 3) inductor current i_L which is used for current limiting.

A block diagram of the fuzzy controller structure is shown in Fig. 3. While the output voltage reference is usually available as an external signal, the inductor current reference (I_{Lref}) depends on the operating point. For this reason it is computed by means of a low-pass filter in the assumption that the dc value of the current is automatically adjusted by the converter according to an energy balance condition. The controller output variable is the switch duty cycle which is obtained by adding the outputs of two different fuzzy controllers. One (fuzzy-P) gives the proportional part δ_P of the duty cycle as a function of ε_i, ε_v, and i_L. The other (fuzzy-I) gives the increment $\Delta\delta_I$ which is them integrated to provide integral term δ_I of the duty cycle δ. This structure allows selection of different control laws for the "proportional" part and the "integral" part of the duty cycle; in this way system stability and a fast large-signal dynamic response with a small overshoot can be achieved with proper handling of the proportional and integral part as described hereafter.

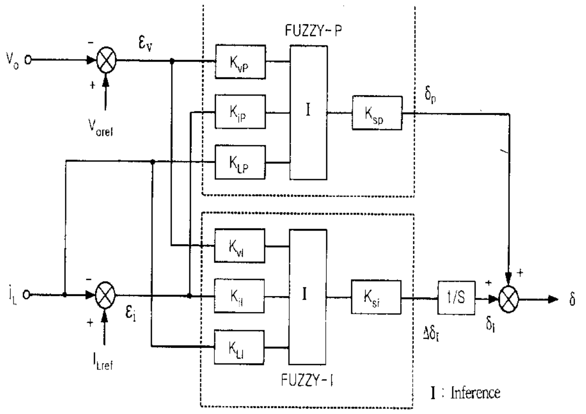


Fig. 3 Fuzzy controller structure

3.3 Membership Functions

Fuzzy sets must be defined for each input and output variable. As shown in Fig. 4, five fuzzy subsets[positive big(PB), positive small(PS), zero (ZE), negative small(NS), and negative big(NB) have been chosen for input variables ε_i, and ε_v, while only two fuzzy subsets[normal operation(NORM) and current limit(LIMIT)] have been selected for the input current since the purpose is to handle only the current limit condition. For the output variables, seven fuzzy subsets have been used(PB, PM, PS, ZE, NS, NM, and NB) in order to smooth the control action. As shown in Fig. 4, triangular and trapezoidal shapes have been adopted for the membership functions; the value of each input and output variable is normalized in [-1, 1] by using suitable scale factors.

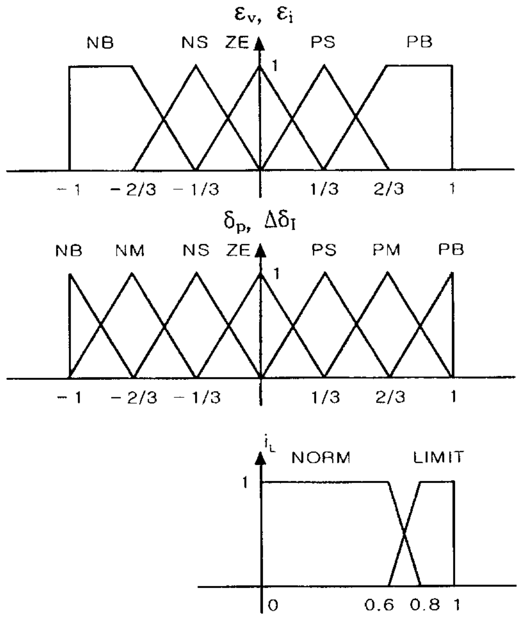


Fig. 4 Membership functions for εi, εv, iL, δP, and $\Delta\delta I$

3.4 Determination of Control Rules

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.

First, when the output voltage is far from the set point(ε_v is PB or NB), the corrective action done by the controller must be strong(duty cycle close to zero or one) in order to have the dynamic response as fast as possible, obviously taking into account current limit specifications. Second, when the output voltage error approaches zero(ε_v is NS, ZE, and PS), the current error should be properly taken into account similarly to current mode control in order to ensure stability around the working point. Finally, when the current approaches the limit value, suitable rules must be introduced in order to perform the current limit action while preventing large overshoots. The selected control rules are described hereafter.

1) Far From the set point: When the output voltage is far from the set point(ε_v is PB or NB), the corrective action must be strong; this means that δ_P should be NB(or PB) while $\Delta\delta_I$ should be zero(ZE) in order to prevent the continuous increase(or decrease)of integral term δ_I that would cause overshoots. The basic control rues are

- if ε_v is PB and i_L is NORM,
  then δ_P is PB and $\Delta\delta_I$ is ZE
- if ε_v is NB and i_L is NORM,
  then δ_P is NB and $\Delta\delta_I$ is ZE

which state that far from the set point, the control action is primarily determined by the output voltage error. This control strategy can be adopted, provided the existence of the current limit.

2) Close to the set point: In this region, the current error must be properly taken into account in order to ensure stability and speed of response. The goal of the fuzzy controller in this region is to achieve a satisfactory dynamic performance with small sensitivity to parameter variations. The control rules can be written according to energy balance conditions. Assuming that the inductor current is far from the limit the following criteria hold.

① If ε_v and ε_i are both zero, δ_P, and $\Delta\delta_I$ must be zero too(steady-state condition); in fact, in the steady state, the duty cycle is determined only by the integral term that should be kept constant.

② If output voltage error ε_v is negative, and the inductor current is greater than its reference value, ($\varepsilon_i < 0$), δ_P, and $\Delta\delta_I$ must be decreased.

③ If output voltage error ε_v is positive, and the inductor current is lower than its reference value, ($\varepsilon_i > 0$), δ_P, and $\Delta\delta_I$ must be positive; in fact, in this condition the system energy must be increased.

④ If the output voltage error is positive, and the inductor current is greater than its reference value(or vice versa), both δ_P, and $\Delta\delta_I$ must be kept to zero in order to prevent undershoot or overshoot, awaiting for a partial discharge of the inductor energy on the output capacitor before taking some control action.

According to these criteria, the rule sets shown in Table 1 and Table 2 are derived for δ_P, and $\Delta\delta_I$.

Table 1 Rule table Fuzzy-P assuming that i_L is NORM

$\varepsilon_I/\varepsilon_V$	NB	NS	ZE	PS	PB
PB	NB	PS	PM	PB	PB
PS	NB	ZE	PS	PM	PB
ZE	NB	NS	ZE	PS	PB
NS	NB	NM	NS	ZE	PB
NB	NB	NB	NM	NS	PB

Table 2 Rule table Fuzzy-I assuming that i_L is NORM

$\varepsilon_I/\varepsilon_V$	NB	NS	ZE	PS	PB
PB	ZE	PS	PM	PS	ZE
PS	ZE	ZE	PS	PM	ZE
ZE	ZE	NS	ZE	PS	ZE
NS	ZE	NM	NS	ZE	ZE
NB	ZE	NS	NM	NS	ZE

3) Current Limit Operation: Current limit operation is governed by the following strategy.

① Current limitation is achieved by choosing the value of according to the output voltage error. For example, if ε_V is PB, δ_P is kept zero in order to limit the current value; instead, when ε_V is approaching zero, δ_P must go negative so as to avoid unwanted overshoots(e.g., at start-up with light load). The fuzzy rules that implement this strategy are

- if i_L is LIMIT and ε_V is PB then δ_P is ZE
- if i_L is LIMIT and ε_V is PS then δ_P is NS
- if i_L is LIMIT and ε_V is ZE then δ_P is NB
- if i_L is LIMIT and ε_V is NS then δ_P is NB
- if i_L is LIMIT and ε_V is NB then δ_P is NB

② As long as the current is close to the limit value, the integral action must be disabled in order to prevent overshoots; the fuzzy rule is

- if i_L is LIMIT then $\Delta\delta_P$ is ZE

4. Design of FLC Parameters

In general, there are no precise criteria to select gains, fuzzy set characteristics, and fuzzy algorithm complexity. Only general guidelines for the design of the FLC can therefore be given.

4.1 Membership Function

Selection of the membership functions was described in the previous section. The fuzzy partition(number of terms for each input and output variable) and the membership function shape may vary depending on the desired granularity of the control action. Obviously, increasing the number of labels of the input variables increases the number of rules needed to perform a proper control action.

4.2 Scaling Factors

For the purpose of generality, the universe of discourse for each fuzzy variable was normalized in [-1, 1]; this procedure involves a proper scale mapping for the input and output data. The choice of input scale factors(k_{VP}, k_{IP}, and k_{LP} for the fuzzy-P controller and k_{VI}, k_{II}, and k_{LI} for the fuzzy-I controller) and output scale factors($k\delta_P$ and $k\delta_I$) greatly affects the bandwidth and the overall performance of the controller. In order to select a good guess of the scale factors, advantage can be taken of the results of the linear control analysis. The output scale factors $k\delta_P$ and $k\delta_I$ can be related to gains k_P and k_I of a PI controller. Instead, input scale factors can be basically chosen according to the following guidelines. k_{VP} determines the regions where control is primarily governed by the output voltage error and those where it is governed by both state variable errors. k_{VI} should be chosen so that the maximum steady-state error falls inside the NS-ZE-PS since outside this interval, no integration is performed. In addition to the previous guidelines, some heuristic tuning can be used in order to improve converter performances. Note that while rules and membership functions are valid for any dc-dc converter, design of the scale factors must be done according to converter topology parameters and desired performances.

4.3 Fuzzy Algorithm

The choices for this application are the fuzzy singletons(selected for the fuzzification process), the Mamdani's min fuzzy implication(used together with the max-min compositional rule of inference methods), and the Center of Area method(selected for the defuzzification process). With these choices, the inferred value δ_P, (or $\Delta\delta_I$) of the control action in correspondence to the value ε_i, ε_v, iL is

$$\delta_P \frac{\sum_{j=0}^{n} \alpha_j D_j}{\sum_{j=0}^{n} \alpha_j} \tag{7}$$

where D_j is the singleton value of the fuzzy output variable using the *j*th rule, and α_j is the degree of fulfillment(DOF) of the *j*th rule that, using the min operator, can be expressed as

$$\alpha_j = \min\{\mu_{Aj}(\varepsilon_i),\ \mu_{Bj}(\varepsilon_v),\ \mu_{Cj}(i_L)\} \tag{8}$$

where A_j, B_j, and C_j are the input fuzzy variables corresponding to the *j*th rule.

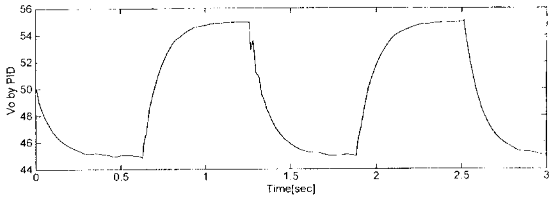
4.4 Tuning of Control Rules

Even though the proposed fuzzy control rules are general, some slight modifications can be done depending on desired performances. The rule modification can be accomplished by using the linguistic trajectory in Table 1 and adjusting some rules in order to optimize the system response in the linguistic phase plane.

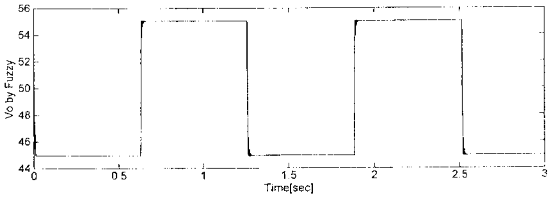
5. Simulated Results

In this section, the validity of the proposed control method is shown by the simulation of control in the boost converter. Transfer functions of (2)-(5) are used as plants, and performance comparisons of proposed method and conventional PID method are given by using MATLAB/SIMULINK as a simulation tools. In the system model as Fig. 5, both PID and Fuzzy control can be simulated so that each performance according to input voltage fluctuation, command following and load disturbance can be analyzed. Test results such as command tracking and output voltage regulation are performed. The regulation test includes the regulation according to both the load variation and the input voltage fluctuation.

Fig. 6 shows the compared performance of PID control and FLC when 5V voltage-up command is given from the present operating point and 5V voltage-down command follows. In PID control case, damping coefficient is designed to be around 0.7. In FLC case, scaling factors are selected by the method supposed in the section 4. Test results shows that while PID control is difficult to improve both response speed and stability, FLC can control this due to its non-linear control capability. So FLC shows fast response with low overshoot. Fig. 7 shows that the regulation characteristics in case that load is changed to light load from full load and vise verse. Figure 8 shows that voltage regulation in case that an input voltage disturbance occurs 1V from the present value. FLC shows a rapid response, but PID shows also a good response. However, when the input disturbance exists, PID control results in large voltage variations, but FLC shows comparatively small fluctuation.



(a) PID controller



(b) Fuzzy controller

Fig. 6 Control performance of output voltage in case of command tracking

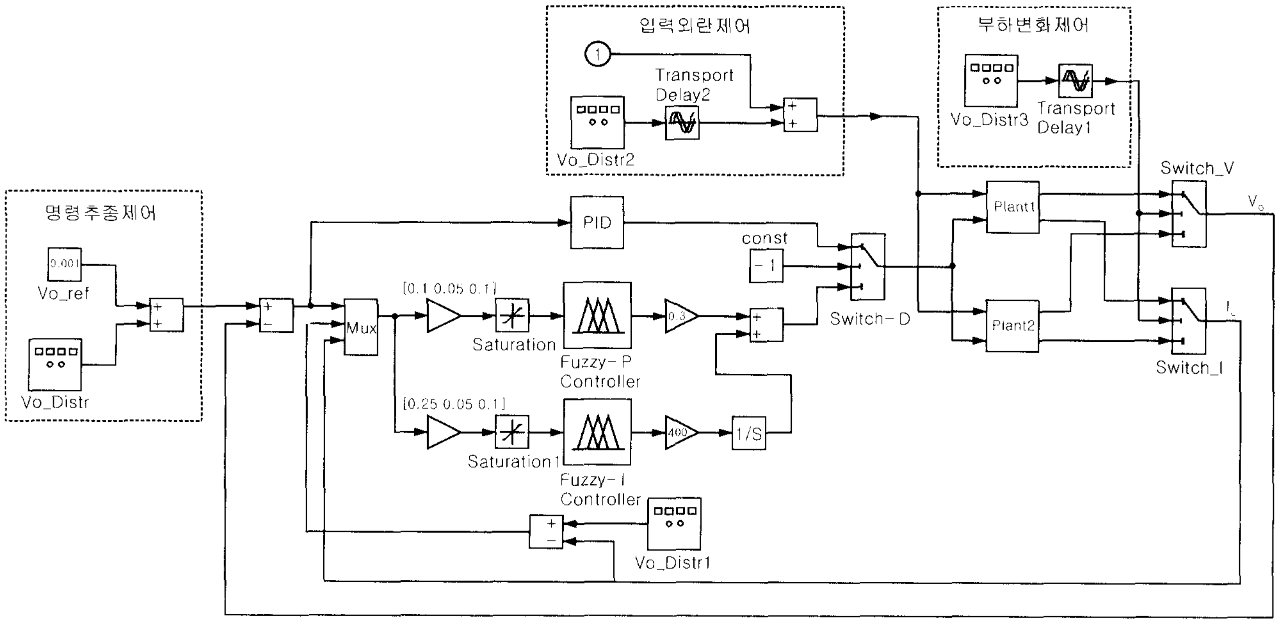
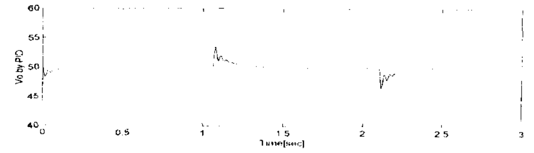
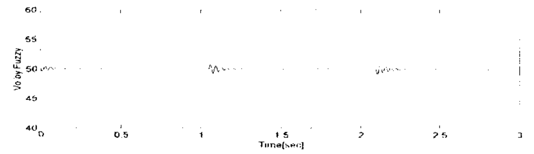


Fig. 5 Simulation Diagram Using SIMULINK

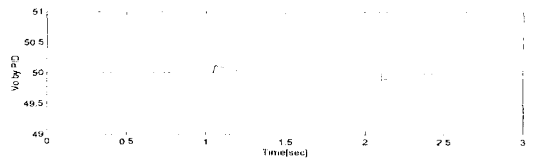


(a) PID controller

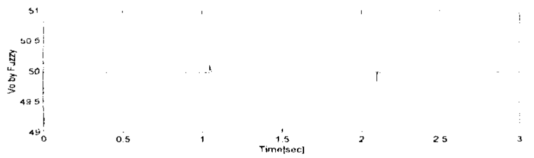


(b) Fuzzy controller

Fig. 7 Control performance of output voltage by load variation



(a) PID controller



(b) Fuzzy controller

Fig. 8 Control performance of output voltage by input voltage variation

Table 3 Booster parameters

V_i = 20V	I_{lim} = 10A
V_o = 50V	f_s = 20kHz
L = 1000μH	R = 40Ω (5-40Ω)
C = 4700μF	k_{LP} = k_{LI} = 0.1
k_{vP} = 0.05	k_{vI} = 0.05
k_{iP} = 0.25	k_{iI} = 0.05
$k_{\delta P}$ = 0.3	$k_{\delta I}$ = 400

A Conclusion is that fuzzy control is superior to PID control in especially transient characteristic and shows that steady state response is also good. The reason is that fuzzy control can program the nonlinear control algorithm which is impossible in conventional linear control.

6. Conclusion

This paper proposes a fuzzy logic controller for dc-dc converters in order to obtain good performances that can not be achieved by linear control techniques in the presence of wide parameter variations. While the standard controller uses error and derivative of error, the proposed controller uses state variables. Such method is very efficient in case of dc-dc converters and can guarantee both stable small-signal responses and improved large-signal responses. The presented approach method is general and can be applied to any dc-dc converter topologies. Through the simulations of booster, we verify the proposed control technique can give a satisfactory performance.

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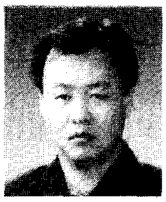
저자소개



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