A Neuro Fuzzy Controller for DC-DC Converters

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ABSTRACT – A new type of controller for DC-DC converters is presented. The proposed neuro-fuzzy controller combines fuzzy logic with neural networks to adjust parameters of the fuzzy controller to the most appropriate. Neither the exact mathematical models of the DC-DC converters nor the tuning process of the parameters of the fuzzy controller are needed in the proposed scheme. Simulation results are presented to show the above process and transient, steady state responses, and load regulation of the given system.

1. INTRODUCTION

Since neural networks(NNs) are known to have learning capability, adaptation, and fault tolerance, so that the NNs are appropriate to control systems which are ill-defined and, therefore, hard to be modeled. Recently, soft computing methods such as neural networks(NNs) and fuzzy logic have been attractive in many fields of industrial applications [1]-[6].

The exact modeling of a power circuit which contains several switching devices is not easy due to the non-linear and time-varying characteristics of the switching devices. Therefore, controlling the system effectively without exact mathematical information is very important and soft computing methods are appropriate to solve this kind of problem. As a result, many researches about NNs and fuzzy logic based on linguistic rules for switching power converters have been developed [1]-[5].

Among them, a fuzzy control method applied to buck/boost converter was presented [1], and it was extended to buck, boost converter [2], where the inputs of the fuzzy controllers are the regulated voltage error and changed value of the error, and controlled output is the duty cycle of the main switch. These controllers show somewhat has better dynamic performance and less steady state error than those of conventional controllers. However, there are too many fuzzy rules which need more computation time and the additional process in the process of optimizing the rule size. To reduce the processing time of the fuzzy controller, fuzzy singletons are used to describe the fuzzy variables[3]. In that scheme, fuzzified values of control inputs are used in inference process with fuzzy singletons, and for any combination of control inputs, there are maximum of four rules which have to be adopted. Even though, a high speed switching converter with largely reduced processing time could be implemented using high performance digital control system, however, the optimizations of fuzzy singleton values are still problem. Furthermore, there are several parameters should be adjusted in the controller, such as the gain factor and the normalization factor sets.

In this paper, to overcome the difficulties of the conventional fuzzy controllers, a neuro-fuzzy control method is proposed. In general, the performances of the fuzzy controller mainly depends on the adopted rule size and the values of tuning parameters. Especially, center values at fixed type of membership functions and fuzzy singleton values are critical. The proposed method combines fuzzy logic based on linguistic rules with a simple NNs trained by on-line error back propagation algorithm.

The NNs are used to learn the characteristics of controlled system, so that the NNs adjust fuzzy singleton values for the optimal values. To minimize the given performance index, learned parameters are updated until the performance index is less than the given threshold value. The input of the controller is the same as the fuzzy controller, and the controlled output is the duty ratio for switching device in the converter.

This on-line training procedure eliminates the unnecessary time consuming, and the simulation results are presented to verify the advantages of the proposed method.

2. FUZZY LOGIC APPROACH IN THE POWER CONVERTERS

The fundamental advantage of the fuzzy logic controller over the conventional controller is a less dependence of the mathematical model as known widely.
Fig. 1 shows the fuzzy controller for the power converters. (Because the fuzzy logic approach is widely known, that scheme wouldn't be carefully expressed in this paper)

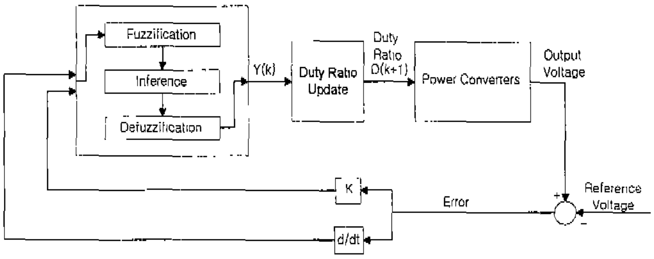

Fig. 1. Block diagram of a fuzzy control scheme for DC-DC converters

The controlled system, power converters, can be handled as unknown box. The controller for the unknown system can be designed only with the output of controlled system, or output voltage. The output of the controller is duty ratio, $D(k+1)$, for converter switching action.

$$D(k+1) = D(k) + \delta Y(k) \tag{1}$$

where δ *is a gain factor of the fuzzy controller.*

The duty ratio can be updated per switching period, and adjusting the gain factor effects the performance of the controller. In fact, the adjusting process is very a important step for a good regulated output voltage.

Criterions of the used linguistic rules in the controller are as follows. If the duty ratio is increased, then output voltage is increased.

1. *Criterions of the error (err)*
   i) When the error is positive (negative) big, change of duty ratio must be negatively (positively) large.
   ii) When the error is positive (negative) small, change of duty ratio must be negatively (positively) small.
2. *Criterions of the change of error (c_err)*
   i) When the error is positive (negative) value, duty ratio must be decreased (increased) through the change of error.
   ii) When the error value is zero(nearly zero) and the change of error is positive or negative value, duty ratio must be changed a little bit

The fuzzy rules are the following form.

Rule i : If err is Fa and c_err is Fb, then Y is Zi

There are many methods to interpret the fuzzy rules and defuzzification[6]. Among them, mini and product implication methods for interpretation, and center of gravity method for defuzzification are widely used. In this paper, mini method and center of gravity method are available.
The resultant equations are as follows.

$$Y = \frac{\sum_{i=1}^{n} fi \cdot Zi}{\sum_{i=1}^{n} fi} \tag{2}$$

where $fi = \min\{\mu(err), \mu(c\_err)\}$

Zi = *Fuzzy singleton*
(entries in a rule table, Table 1)

The used rule table is shown in Table 1. The entries of the rule table are derived by the above criterions.

Table 1. Rule table

c_er / err	NB	NS	Z	PS	PB
PB	-0.4	-0.45	-0.5	-0.7	-1
PS	-0.1	-0.2	-0.3	-0.4	-0.5
Z	0.15	0.1	0.0	-0.1	-0.15
NS	0.5	0.4	0.3	0.2	0.1
NB	1	0.7	0.5	0.45	0.4

Boost converter is used to simulate a fuzzy controller, and the simulation specifications are listed in Table 2, 3.

Table 2. Converter parameters.

Ind-Uctor, L	Cap-acitor, C	Load Resistor , R	R in L, rL	R in C, rC
250uH	1200uF	25ohm	0.01	0.001

Table 3. Design parameters.

Input, Vin(v)	Reference(v)	Switching feq.
15(v)	25(v)	20kHz

An output voltage of the power converter using a fuzzy controller is shown in Fig. 2. The same converter output using the current mode controller is shown in Fig. 3.

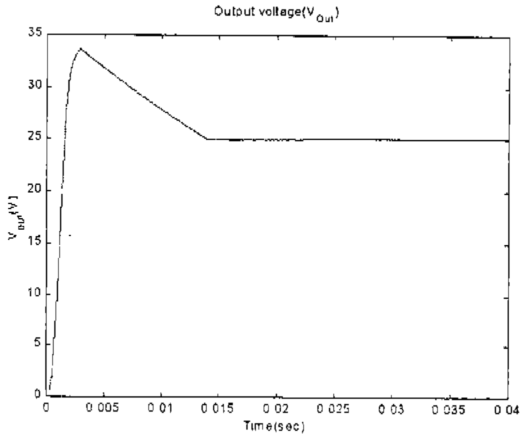

Fig. 2. Voltage response of a boost converter using the fuzzy controller

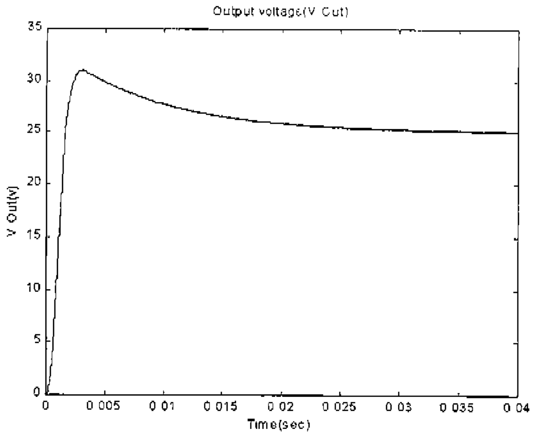

Fig. 3. Voltage response of a boost converter using the current mode controller

From the Fig. 2, 3, the converter with fuzzy controller has fast transient response compared with the current mode controlled converter. However, a critical disadvantage of the fuzzy control method is that the exact information of the controlled system, or expert knowledge, is needed. That is a tuning problem of parameters. For the more, even when the expert knowledge is known, the optimization of parameters (number of rules, fuzzy set values, etc) may be a difficult.

3. NEURO-FUZZY CONTROL METHOD IN THE POWER CONVERTERS

Conventional fuzzy logic system using the fuzzy singleton is commonly expressed with (2). Suppose that the input fuzzy values are roughly determined with the triangular membership functions as shown in Fig. 4. Input values are to be normalized. In this case, performance of the controller is mainly depends on the fuzzy singleton values, entries of Table 1.

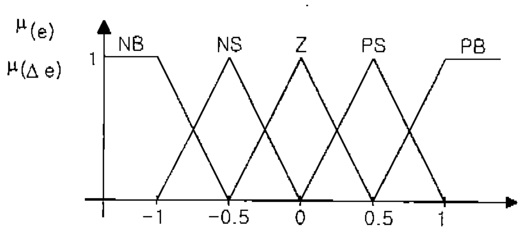

Fig. 4. Roughly determined input fuzzy values

Information of the dynamic characteristics of controlled system is needed to determine the entries in Table 1. In this case, the training algorithm for fuzzy logic systems [6] can be adopted. Fuzzy singletons are determined with the on-line learning algorithm, error back-propagation, to minimize the error energy function, *Ef*, such as

$$Ef = \frac{1}{2} Err^2 \qquad (3)$$

where $Err = V\_Out - V\_Ref$

To train *Zi* in the fuzzy logic system, (2),

$$Zi(k+1) = Zi(k) - \alpha \frac{\partial Ef}{\partial Zi}\Big|_k \qquad (4)$$

From (4),

$$\begin{aligned} \frac{\partial Ef}{\partial Zi} &= Err \cdot \frac{\partial V\_Out}{\partial Zi} \\ &= Err \cdot \frac{\partial V\_Out}{\partial Y} \cdot \frac{\partial Y}{\partial Zi} \end{aligned} \qquad (5)$$

where $\partial Y / \partial Zi = fi \Big/ \sum_{i}^{n} fi$

Y = Output of the fuzzy logic controller

To calculate the Jacobian, $\partial V\_Out / \partial Y$ in (5), output voltage should be expressed with the fuzzy logic system, (2). In the boost converter, output voltage at steady state can be expressed as

$$V\_Out = \frac{Vin}{1-D(k+1)}$$

So that,

$$\begin{aligned}\frac{\partial V\_Out}{\partial Y} &= \left.\left(\frac{Vin}{1-D(k+1)}\right)\middle/\partial Y\right. \\ &= \left.\left(\frac{Vin}{1-(D(k)+\delta Y(k))}\right)\middle/\partial Y\right. \\ &\fallingdotseq \frac{\delta Vin}{[1-(D(k)+\delta Y(k))]^2}\end{aligned} \tag{6}$$

In (6), for the steady state, denominator value must be constant. Finally, the resultant learning equation for *Zi* is

$$Zi(k+1) = Zi(k) - \alpha \cdot \varepsilon \cdot \frac{Err \cdot fi}{\sum_{i}^{n} fi} \tag{7}$$

where α = *learning factor*
ε = *Jacobian, or constant*

The block diagram of the proposed control scheme is shown in Fig. 5.

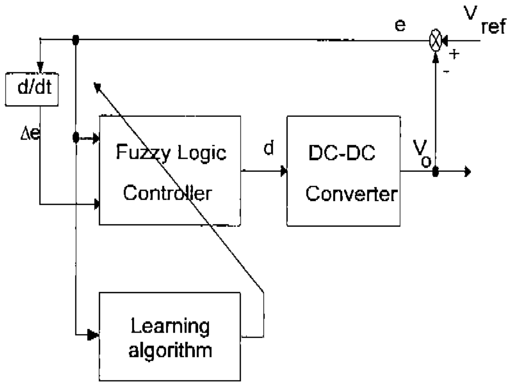

Fig. 5 Proposed Neuro-Fuzzy controller for DC-DC converters

4. SIMULATION RESULTS

Converter and Design parameters are the same as those of the previous simulation, Table 2, 3.

Fig. 6 shows the output voltage using the proposed on-line learning algorithm, and Fig. 7 shows that with learned data.(off-line learning).

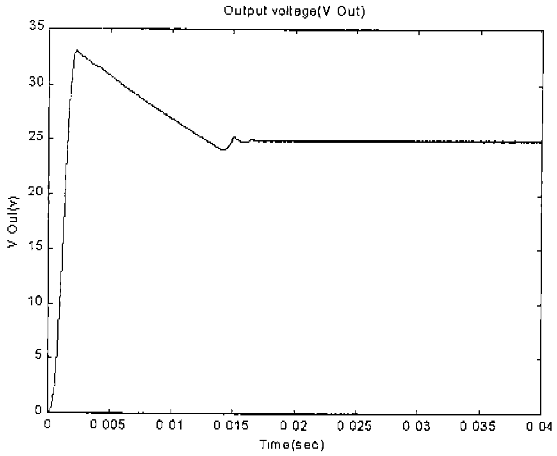

Fig. 6. Output voltage using the on-line learning algorithm

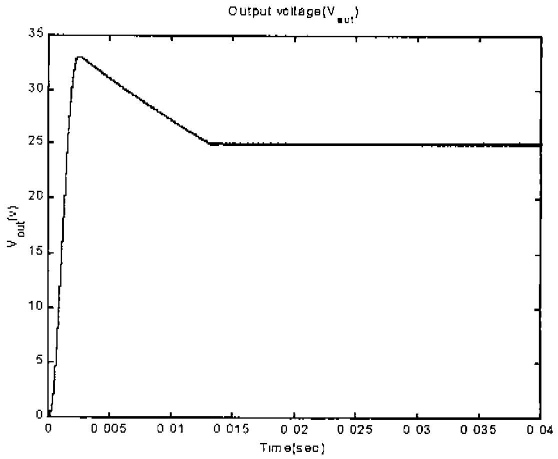

Fig. 7. Output voltage with the learned data(off-line learning algorithm)

Comparing with Fig. 6 and 7 and comparing with Fig. 2, the proposed on-line learning algorithm is available. (For two cases, learning rate ($\eta=\alpha\varepsilon$) is 0.065) Especially, the off-line learning controller has better transient response than the previous conventional fuzzy control method.

Moreover, the change of learning rate effects the transient response of the system. In this control system, increasing the value of learning rate, reduce the transient response time and overshoot voltage. Fig. 8 and 9 shows the response with 0.65 and 0.03 respective.

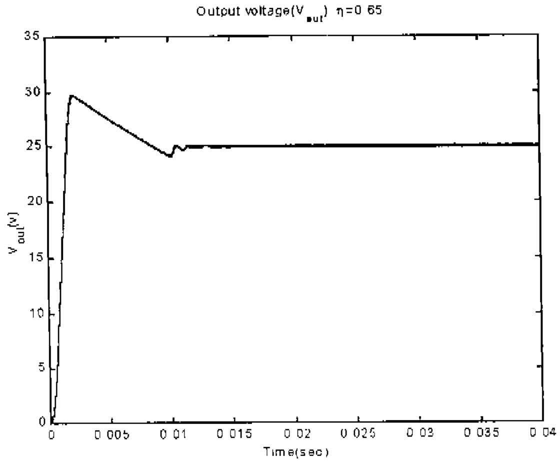

Fig. 8. Output voltage using the on-line learning algorithm when the learning rate(η) is 0.65

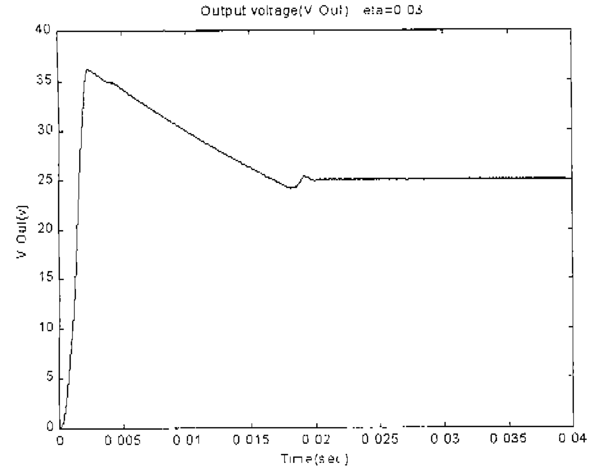

Fig. 9. Output voltage using the on-line learning algorithm when the learning(η) is 0.03

5. CONCLUSIONS

An on-line neuro-fuzzy control algorithm for DC-DC converters is proposed and verified with boost converter in this paper. The proposed scheme basically used to identify nonlinear systems, but it applied to controlling power converters effectively.

The main disadvantage of the fuzzy controller which is a parameter tuning problem could be removed. Moreover, output response is better than that of the conventional fuzzy control method. The change of learning rate effects the transient response. The proposed method can be applied to both of on-line and off-line learning controllers, and it takes very little time to learn the controlled system dynamics. In this paper, the fuzzy singleton values are learned only. ,however, for a better performance, the other parameters which were roughly determined in this simulation could be learned using the same algorithm.

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