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Fuzzy Controllers for Boost DC-DC Converters

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Abstract: *This paper proposes a novel design procedure of proportional- derivative (PD)-like fuzzy logic controller (FLC) for dc–dc converters. The design procedure allows the state space model of the converter and linear control design techniques to be used in the initial stages of FLC design. This simplifies the design and the stability assessment of the FLC. By exploiting the fuzzy logic structure of the controller, heuristic knowledge is incorporated in the design, which results in a nonlinear controller with improved performance over linear PD controllers.*

Keywords: *Boost converter, Fuzzy control, and Proportional–Derivative (PD) control.*

I. Introduction

FUZZY logic control (FLC) has been successfully applied to a wide variety of engineering problems, including dc-to dc converters [1]–[4]. It has been shown that fuzzy control can reduce development costs and provides better performance than linear controllers [5], [6]. With advances in digital hardware and digital control techniques, it is becoming feasible to implement control schemes such as fuzzy logic for power converters.

Fuzzy control is an attractive control method because its structure, which consists of fuzzy sets that allow partial membership and “if. . . then. . .” rules, resembles the way human intuitively approaches a control problem. This makes it easier for a designer to incorporate heuristic knowledge of a system into the controller. Fuzzy control is of great value for problems where the system is difficult to model due to complexity, nonlinearity, and/or imprecision. DC–DC converters fall into this category because they have a time-varying structure and contain elements that are nonlinear and have parasitic components.

In this paper, PD fuzzy controller is designed and implemented for Boost dc-dc converters. Its stability and small signal dynamic performance can be assessed using control techniques and the state space model of the converter. The aim of using P-D controller is to increase the stability of the system by improving control since it has an ability to predict the future error of the system response. In order to avoid effects of the sudden change in the value of the error signal, the derivative is taken from the output response of the system variable instead of the error signal. Therefore, D mode is designed to be proportional to the change of the output variable to prevent the sudden changes occurring in the control output resulting from sudden changes in the error signal.

Normally, power electronic systems based on conventional control methods [7] failed to perform satisfactorily under parameter variations, nonlinearity, load disturbance, etc. Many efforts have been made to improve the performance of the controller in power converters. State feedback controllers, self-tuning controllers and model reference adaptive controllers, etc., were adopted for the control of power electronic systems [8]. But these controllers also need accurate mathematical models and are therefore sensitive to parameter. Fuzzy control can provide better performance over the conventional PI controller for the DC-to-DC Buck converter [9]. One major problem in these controlled converters is the high starting current. In PD Fuzzy Logic Controllers, the Controller which generates control input $du[k]$ from the error $e[k]$ and error rate $de[k]$. Computer simulations are carried out for different cases on FLC and the results are presented and evaluated.

II. Boost Converters

A boost converter (step-up converter), as its name suggests steps up the input DC voltage value and provides at output. This converter contains basically a diode, a transistor as switches and at least one energy storage element. Capacitors are generally added to output so as to perform the function of removing output voltage ripple and sometimes inductors are also combined with. Its operation is mainly of two distinct states: During the ON period, Switch is made to close its contacts which results in increase of inductor current. During the OFF period, Switch is made to open and thus the only path for inductor current to flow is through the fly-back diode ‘D’ and the parallel combination of capacitor and load. This enables capacitor to transfer energy gained by it during ON period. Fig. 1 shows the arrangement and parameters of the modeled circuit of the Boost converter.

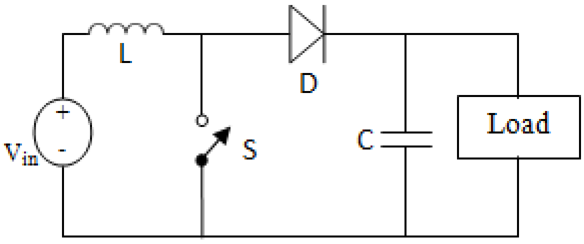

Fig1: Boost Converters

III. State Space Modeling Of Boost Converter

The state-space averaging method, different from the other averaging technique, is a mainstay of modern control theory. The state-space averaging method makes use of the state-space description of dynamical systems to derive the small-signal averaged equations of converters. A benefit of the state-space averaging procedure is the generality of its result: a small-signal averaged model can always be obtained, provided that state equations of the original converter can be written. The state space equations of a Boost regulator in turn on and turn off modes by considering all the system parameters is as shown below:

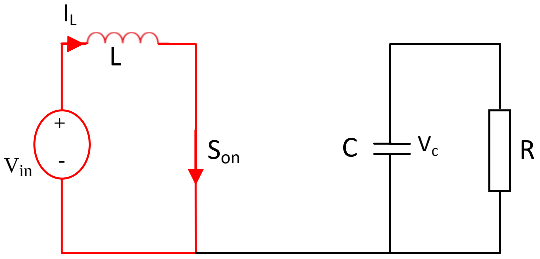

Fig 2: Boost converter in ON –Mode

From Figure 2,

$v_{in} - L\, di_L / dt = 0$ …..(1)

$v_c / R + C\, dv_c / dt = 0$ …..(2)

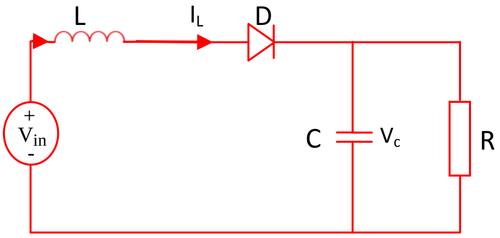

Fig 3: Boost converter in OFF –Mode

From Figure 3,

$v_{in} - v_c - L\, di_L / dt = 0$ …..(3)

$i_L - v_c / R + C\, dv_c / dt = 0$ …..(4)

In state space form

$$\begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_C}{dt} \end{bmatrix} = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} v_{in} ; V_o = \begin{bmatrix} 0 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ v_C \end{bmatrix} \quad \text{…….(5)}$$

IV. Review of Fuzzy Logic Control

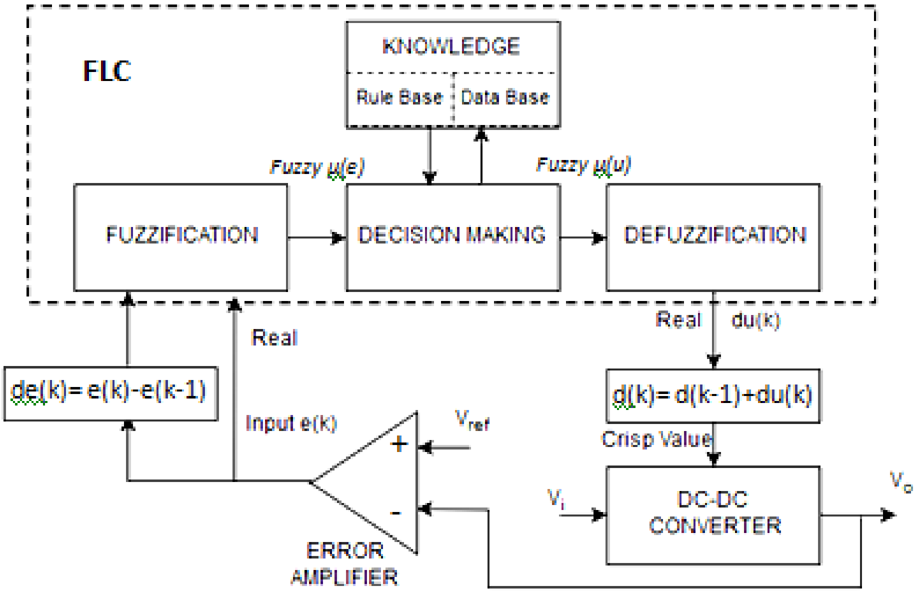

Fig 4: Conventional Fuzzy Logic controller

The design of fuzzy controllers does not require an exact mathematical model. Instead, they are designed based on general knowledge of the plant. Fuzzy controllers can be designed to adapt to varying operating points.
The conventional FLC shown in Fig.4 consists of the following components:

1) Fuzzification interface that converts its input into information that the inference mechanism can use to activate and apply rules
2) Rule base that contains the expert's linguistic description of how to achieve good control
3) Inference mechanism that evaluates which control rules are relevant in the current situation
4) Defuzzification interface that converts the conclusion from the inference mechanism into the control input to the plant.

There are two inputs for the fuzzy controller for the boost converters:
The first input is the error *e* in the output voltage given by (6),
$e[k] = V_{ref} - V_o$ …..(6)
where *Vo* is actual output voltage of DC–DC converter at the kth sampling time, *Vref* is reference output voltage.

The second input is the difference between successive errors and is given by (7)
$de[k] = e[k] - e[k-1]$……(7)
The two inputs are then fed into the fuzzy controller. The output of the fuzzy controller is the change the duty cycle *du(k)*. Duty ratio d(k), at the kth sampling time is calculated by adding the fuzzy controller output *du(k)* to the previous sampling period's duty cycle $d[k-1]$

$d[k]=d[k-1]+du[k]$ ……(8)

1.1 Fuzzification

The first step in the design of a fuzzy logic controller is to define membership functions for the inputs. Each universe of discourse is divided into fuzzy subsets. In this paper, there are 7 fuzzy subsets in the fuzzy controller for the boost converter: {NB, NM, NS, Z, PS, PM, PB} where N indicates negative, Z represents zero, and P indicates positive. There are tradeoffs when selecting the number of fuzzy subsets, as well as the shape of membership functions. More fuzzy subsets result in finer control and less oscillation, while increasing the size of memory. The membership function for fuzzification $\mu(e)$ is the Gaussian one shown in Fig.5.

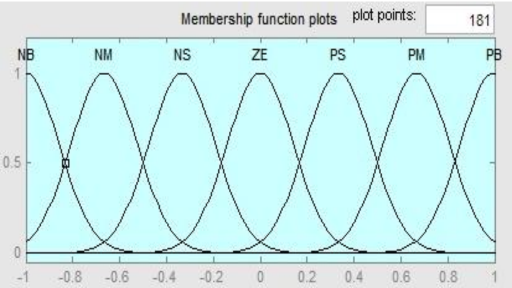

Fig 5: Membership function µ (e)

1.2 Rule Base

The rule base is derived from general knowledge of dc–dc converter behavior, and is adjusted based on experimental results. There is a tradeoff between the size of the rule base and the performance of the controller. A 7 × 7 rule base was also designed and implemented for the boost converter. Rule Base is normally expressed as a set of Fuzzy Linguistic rules. The *k- th* linguistic control rule can be expressed as:

R_k *: IF e[k] is* A_k *AND de[k] is* B_k *THEN du[k] is* C_k ……..(9)

Where A_k and B_k (Antecedent), C_k (Consequent) are fuzzy variables characterized by fuzzy membership functions.

Each universe of discourse is divided into seven fuzzy subsets: PB (Positive Big), PM (Positive Medium), PS (Positive Small), Z (Zero), NS (Negative Small), NM (Negative Medium) and NB (Negative Big).

The set of fuzzy rules normally can be summarized in a table as shown in Table. 1.

Error

	e de	NB	NM	NS	Z	PS	PM	PB
Change of Error	NB	PB	PB	PB	PB	PM	PS	Z
	NM	PB	PB	PB	PM	PS	Z	NS
	NS	PB	PB	PM	PS	Z	NS	NM
	Z	PB	PM	PS	Z	NS	NM	NB
	PS	PM	PS	Z	NS	NM	NB	NB
	PM	PS	Z	NS	NM	NB	NB	NB
	PB	Z	NS	NM	NB	NB	NB	NB

Table 1: Rule Table for a PD-like FLC to calculate *du(k)*

1.3 Inference Mechanism

The inference result of each rule consists of two parts, the weighting factor, w_i, of the individual rule, and degree of change in duty ratio *Ci*, according to the rule. The weighting factor w_i is obtained by means of Mamdani's MIN fuzzy implication of membership degrees $\mu_e(e)$ and $\mu_{de}(de)$, C_i is retrieved from control rule table. The inferred output of each rule using Mamdani's MIN fuzzy implication is written as:

$w_i = min\{\mu e(e),\mu de(de)$ ……(10)

The change in duty cycle inferred by the i^{th} rule:

$z_i = w_i \times c_i$ ….(11)

Since the inferred output is a linguistic result, a defuzzification operation is performed next to obtain a crisp result.

4.4. **Defuzzification**

The last component of FLC is defuzzification. Several defuzzification methods have been proposed [10,11]. They are Center of Area (COA), Center of Sum (COS), Height Method (HM), Mean of Maxima (MOM), Center of Largest Area (COLA), and First of Maxima (FM) and Height Weighted Second Maxima (HWSM). Mean of Maxima (MOM) method is used in this paper.

V. Pd-Like Fuzzy Logic Controller

The equation for a conventional PD-controller is

$du[k] = K_p \cdot e[k] + K_D \cdot de[k]$ …..(12)

Where K_p and K_D are the proportional and the differential gain coefficients. Then a PD-like FLC consists of rules, the symbolic description of each rule given as in equation (9)

VI. Simulation Results And Discussion

6.1 CONTROL SYSTEM SETUP

The proposed PD-like fuzzy control algorithms and how these FLC will affect the performance of DC-DC Converters control are now investigated by simulations. Fig. 6 shows the arrangement and parameters of the modeled circuit of the Boost converter with the fuzzy logic controller. Converters controls are now investigated by simulations. Fig 6 can be expressed in the usual state variable matrix form as in Equation (5)

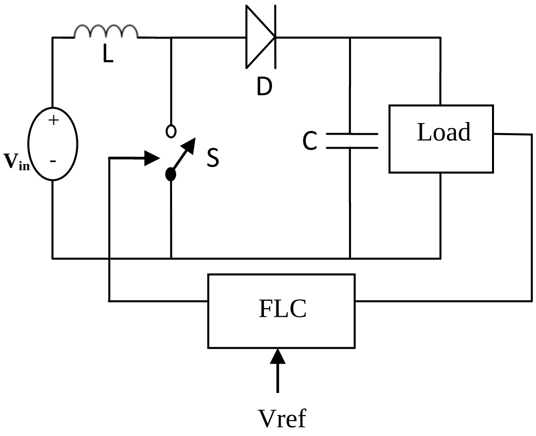

Fig 6: Fuzzy Control Circuit for Boost Converters

The parameters of the Boost converter are:

$L = 275\mu H$, $C = 540\mu F$, $Ro = 10\Omega$ to $100\ \Omega$, $Vs = 8V$ to $20\ V$.

The simulation results are attained for the start up of the Boost converter from the zero initial state. Basically, the membership functions for fuzzification and defuzzification associated with the PD-like FLCs are similar.Variation of output voltage with respect to time of boost converter for different line and load conditions are shown in Figure 8-12.

6.2 SIMULATION RESULTS

The control signal of fuzzy logic controller obtained from error signal e(k)and change in error signal de(k) is as shown in Figure 7

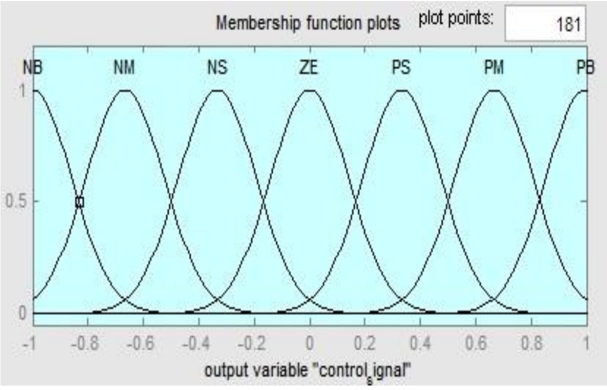

Fig 7: Membership function of the control signal ,du(k)

In this paper, simulation results were obtained for supply voltage changes from 8V to 20V and for resistance changes from 10 Ω to 100 Ω. Simulation results are compared and summarized in *Table 2* by examining the results provided in Figure: 8 to 12.

Case: 1 Minimum Line and Maximum load condition

In this condition, output voltage vs. Time as shown in "Figure 8" is simulated with the following settings: V_s= 8V and I_o = 2.5 mA. In this startup transient response of the boost converter using fuzzy control, the settling time was 0.15 ms at a nominal input voltage of 8 V.

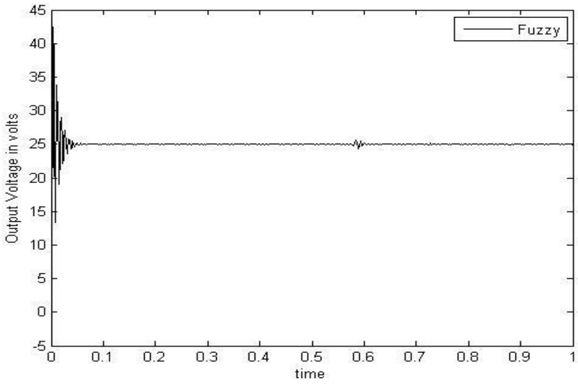

Fig 8: Output Voltage variation for Minimum Line and Maximum load condition

Case: 2 Minimum Line and Light load condition

In this condition, output voltage vs. Time as shown in "*Figure 9"* is simulated with the following settings: V_s= 10V and I_o =0.5 mA. In this startup transient response of the boost converter using fuzzy control, the settling time was 0.25 ms at a nominal input voltage of 10 V.

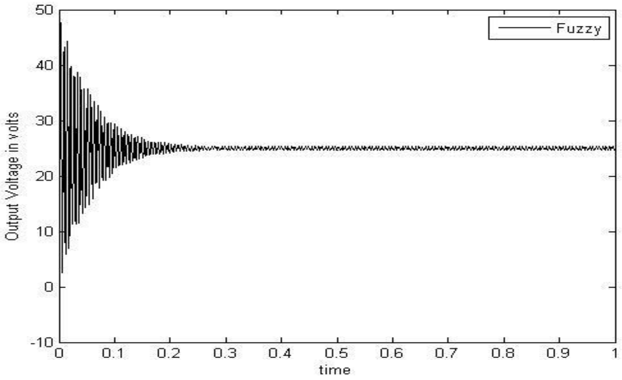

Fig 9: Output Voltage variation for Minimum Line and Light load condition

Case: 3 Midrange Line and Load condition

In this condition, output voltage vs. Time as shown in "*Figure 10"* is simulated with the following settings: V_s= 15V and I_o = 1 mA. In this startup transient response of the boost converter using fuzzy control, the settling time was 0.15 ms at a nominal input voltage of 15 V.

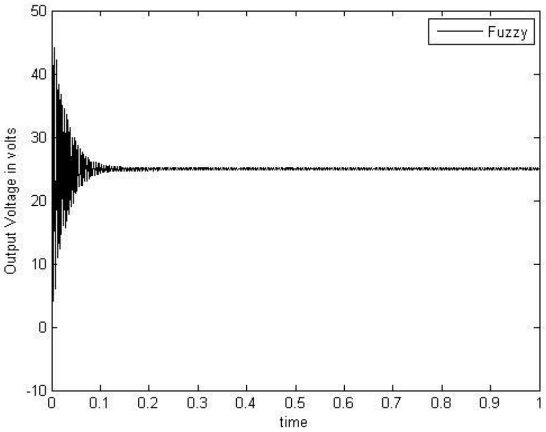

Fig 10: Output Voltage variation for Midrange Line and Load condition

Case: 4 Maximum Line and Maximum load condition

In this condition, output voltage vs. Time as shown in "*Figure 11"* is simulated with the following settings: V_s= 20V and I_o = 2 mA. In this startup transient response of the boost converter using fuzzy control, the settling time was 0.05 ms at a nominal input voltage of 20 V.

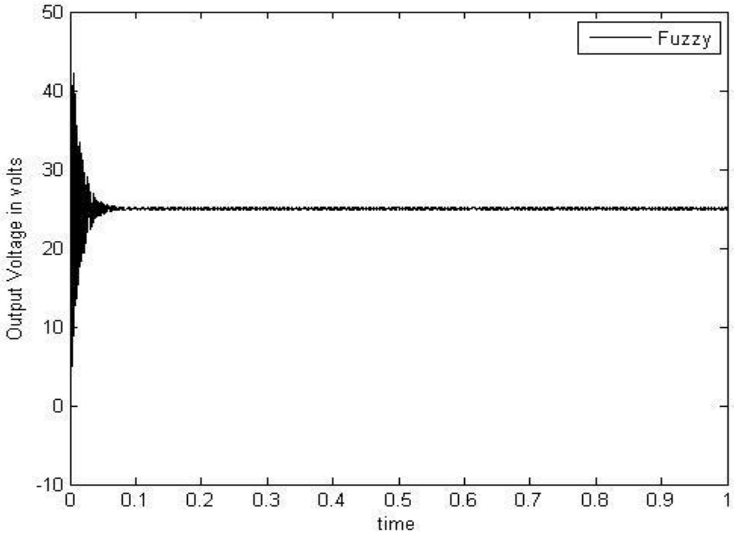

Fig 11: Output Voltage variation for Maximum Line and Maximum load condition

Case: 5 Maximum Line and Light Load condition

In this condition, output voltage vs. Time as shown in "*Figure 12"* is simulated with the following settings: V_s= 20 V and I_o = 0.5 mA. In this startup transient response of the boost converter using fuzzy control, the settling time was 0.25 ms at a nominal input voltage of 20 V.

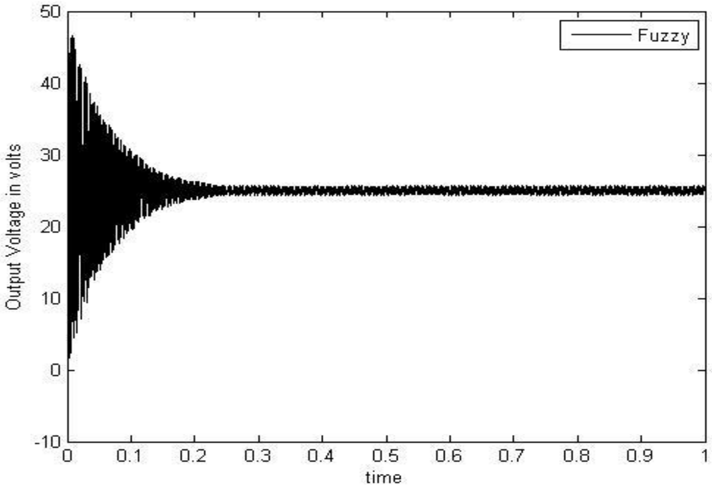

Fig 12: Output Voltage variation for Maximum Line and Light Load condition

Cases	**Damping Ratio(□)/ Damping Type**	**Settling Time Ts (ms)**
Minimum Line and Maximum load condition	0.103 (Under Damped)	0.15
Minimum Line and Light load condition	0.026 (Under Damped)	0.25
Midrange Line and Load condition	0.087 (Under Damped)	0.15
Maximum Line and Maximum load condition	0.121(Under Damped)	0.05
Maximum Line and Light Load condition	0.04(Under Damped)	0.25

Table 2: Simulation Results for Various Line and Load Settings

Simulation results of PD-FLC for different line and load conditions are summarized as shown in Table 2.From the table, the settling increased as the input voltage increased from 8 to10 V. The settling time is maximum for input voltage of 10V (Ts = 0.25 ms). When the input voltage increased from 10 to 20 V, the settling time decreased to 0.05ms.From load transient response of the boost converter, when the load increased from 0.5A to 2.5A, the settling time decreased from maximum value (0.25 ms) to its minimum value (0.05ms) .

In various line and load conditions, there is oscillation in the output voltage and is only under damped using fuzzy control. Furthermore from the analysis, lower settling time (0.05ms) is for the maximum line and maximum load condition.

VII. Conclusion

PD fuzzy controllers were designed for the boost converter. The fuzzy controllers were designed based on an in-depth knowledge of the plant and computer simulations. Design of the fuzzy controller did not require a detailed mathematical model. The designed fuzzy controller resulted in less oscillation while increasing load and better performance in all operating conditions. The proposed fuzzy controller also yielded good settling time, particularly under load increases. Overall the designed fuzzy controller acts as an universal controller for all nonlinear operating conditions unlike conventional P,PI,PD and PID controllers which requires tuning of parameters for nonlinear operating conditions.

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