General-Purpose Fuzzy Controller for DC–DC Converters

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***Abstract*—In this paper, a general-purpose fuzzy controller for dc–dc converters is investigated. Based on a qualitative description of the system to be controlled, fuzzy controllers are capable of good performances, even for those systems where linear control techniques fail, e.g., when a mathematical description is not available or is in the presence of wide parameter variations.**

The presented approach is general and can be applied to any dc–dc converter topologies. Controller implementation is relatively simple and can guarantee a small-signal response as fast and stable as other standard regulators and an improved large-signal response. Simulation results of Buck-Boost and Sepic converters show control potentialities.

***Index Terms*—Fuzzy logic, control techniques, dc–dc converters**

I. Introduction

DC-DC CONVERTERS are an intriguing subject from the control point of view due to their intrinsic nonlinearity. Common control approaches such as *voltage control* and *current injected control* (and its derivations like *standard control module* and *average current control*) [1] require a good knowledge of the system and accurate tuning in order to obtain desired performances. These controllers are simple to implement and easy to design, but their performances generally depend on the working point so that the presence of parasitic elements, time-varying loads, and variable supply voltages can make the selection of the control parameters which ensure proper behavior in any operating conditions difficult. Achieving large-signal stability often calls for a reduction of the useful bandwidth, so affecting converter performances. Moreover, application of these control techniques to high-order dc–dc converters, e.g., Cuk and Sepic topologies, may result in a very critical design of control parameters and difficult stabilization.

A completely different approach is offered by the fuzzy logic control (FLC) which does not require a precise mathematical modeling of the system nor complex computations [2]–[4]. This control technique relies on the human capability to understand the system's behavior and is based on qualitative control rules. Thus, control design is simple since it is only based on linguistic rules of the type: "*If the output voltage error is positive and its rate of change is negative, then reduce slightly the duty cycle,*" and so on. This approach relies on the basic physical properties of the systems, and it is potentially able to extend control capability even to those operating conditions where linear control techniques fail, i.e., large-signal dynamics and large parameter variations. Of course, fuzzy controllers cannot provide, in general, better small-signal response than standard regulators. However, since fuzzy control is based on heuristic rules, application of nonlinear control laws to face the nonlinear nature of dc–dc converters is easy.

The FLC approach is general in the sense that almost the same control rules can be applied to several dc–dc converters. However, some scale factors must be tuned according to converter topology and parameters.

In our proposal, the fuzzy controller requires only sensing of one inductor current and the output voltage, and its implementation is relatively simple. Results of the control design are in two lookup tables stored in EPROM in the control circuit. Owing to control simplicity, standard discrete electronic circuitry can be used, resulting in a control speed similar to that of other standard regulators.

The proposed control technique was tested on Buck-Boost and Sepic converters in order to verify the theoretical forecasts. Simulated results confirm validity of the solution.

II. Basics of Fuzzy Logic Controllers

FLC is one of the most successful applications of fuzzy set theory, introduced by Zadeh in 1965 [2]. Its major features are the use of linguistic variables rather than numerical variables. *Linguistic variables*, defined as variables whose values are sentences in a natural language (such as *small* and *large*), may be represented by *fuzzy sets*.

A fuzzy set is an extension of a crisp set where an element can only belong to a set (full membership) or not belong at all (no membership). Fuzzy sets allow *partial membership* which means that an element may partially belong to more than one set.

A fuzzy set *A* is characterized by a *membership function* μ_A that assigns to each object in a given class a grade of membership to the set. Of course, the grade of membership can range from 0 (no membership) to 1 (full membership); we therefore write

$$\mu_A: X \rightarrow [0,1] \tag{1}$$

which means that the fuzzy set A belongs to a universal set X (usually called *universe of discourse*) defined in a specific problem. A fuzzy set A is called a *fuzzy singleton* when there

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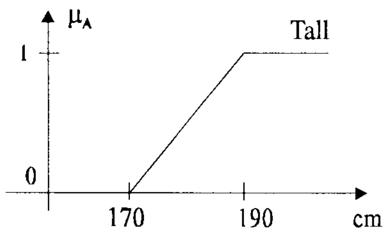

Fig. 1. Membership function related to the fuzzy set labeled *Tall*.

is only one element x_o with $\mu_A(x_o) = 1$, while all of the other elements have a membership grade equal to zero.

For example, if X is the human height, the linguistic variable *Tall* may be the label of a fuzzy set which has the membership function μ_A shown in Fig. 1.

By this definition, all of the people who are taller than 190 cm have a membership grade of one, while those below 170 cm have a zero membership grade to this set. A man who is 180 cm tall has a membership grade of 0.5.

This approach allows characterization of the system behavior through simple relations (*fuzzy rules*) between linguistic variables. Usually, fuzzy rules are expressed in the form of *fuzzy conditional statements* R_i of the type

$$R_i\text{: if } x \text{ is small THEN } y \text{ is large} \tag{2}$$

where x and y are fuzzy variables, and *small* and *large* are labels of fuzzy sets. If there are n rules, the *rule set* is represented by the union of these rules

$$R = R_1 \text{ else } R_2 \text{ else } \cdots R_n. \tag{3}$$

A fuzzy logic controller is based on a collection, R, of control rules. The execution of these rules is governed by the *compositional rule of inference* [2]–[4].

The general structure of an FLC is represented in Fig. 2 and comprises four principal components: 1) a *fuzzyfication interface* which converts input data into suitable linguistic values; 2) a *knowledge base* which consists of a data base with the necessary linguistic definitions and control rule set; 3) a *decisionmaking logic* which, simulating a human decision process, infers the fuzzy control action from the knowledge of the control rules and the linguistic variable definitions; and 4) a *defuzzyfication interface* which yields a nonfuzzy control action from an inferred fuzzy control action.

III. Application of Fuzzy Control to DC–DC Converters

The basic scheme of a general-purpose fuzzy controller for dc–dc converters is shown in Fig. 3. The converter is represented by a "black box" from which we only extract the terminals corresponding to input voltage u_g, output voltage u_o, one inductor current i_L, and controlled switch S. As we can see, only two state variables are sensed; the output voltage and one inductor current. The latter is the inductor current for second-order schemes (i.e., Buck, Boost, and Buck-Boost) and the input inductor current for fourth-order schemes (i.e., Cuk and Sepic).

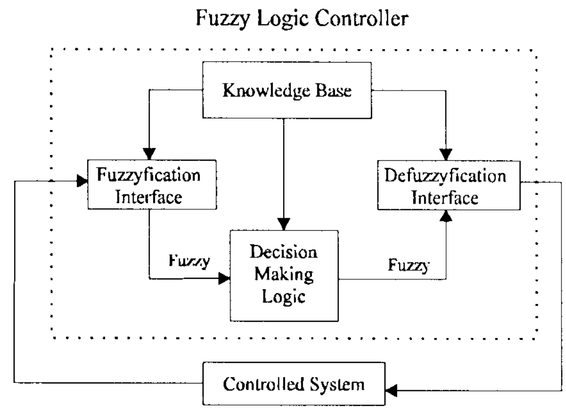

Fig. 2. Basic configuration of FLC.

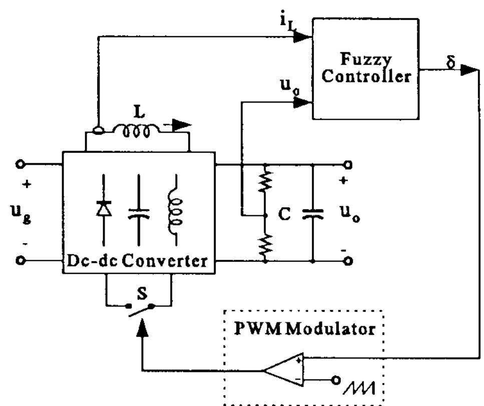

Fig. 3. Block diagram of fuzzy control scheme of dc–dc converters.

From these measurements, the fuzzy controller provides a signal proportional to the converter duty cycle which is then applied to a standard pulse width modulation (PWM) modulator.

A. Fuzzy Controller Structure

The first important step in the fuzzy controller definition is the choice of the input variables. 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. In order to improve operation, we need additional information on the energy stored in the converter, i.e., an inductor current must be sensed. This approach allows substantial improvement of converter dynamic performances similarly to that obtained in analog current-controlled converters [1].

Accordingly, in the proposed fuzzy controller we use three input variables: 1) output voltage error ε_u; 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. 4. While the output voltage reference is usually available as an external signal, the inductor current reference $(I_{L\mathrm{Ref}})$ 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 a power balance condition.

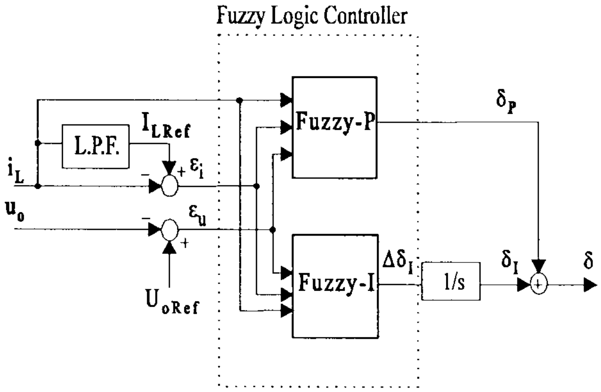

Fig. 4. Fuzzy logic controller structure.

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_u, and i_L. The other (fuzzy-I) gives the increment $\Delta\delta_I$ which is then 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.

B. Membership Functions

Fuzzy sets must be defined for each input and output variable. As shown in Fig. 5, 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_u, 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. 5, 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.

C. Derivation 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_u 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_u 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.

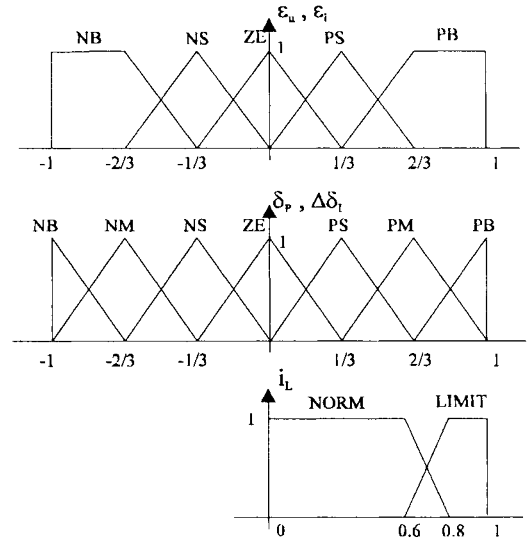

Fig. 5. Membership functions for ε_i, ε_u, i_L, δ_P, and $\Delta\delta_I$.

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_u 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 rules are

if ε_u is PB and i_L is NORM, then δ_P is PB and $\Delta\delta_I$ is ZE

if ε_u 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_u 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_u is negative, and the inductor current is greater than its reference value, ($\varepsilon_i < 0$), δ_P,

TABLE I
RULE TABLE FOR FUZZY-P ASSUMING THAT i_L IS NORM

$\varepsilon_i \backslash \varepsilon_u$	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 II
RULE TABLE FOR FUZZY-I ASSUMING THAT i_L IS NORM

$\varepsilon_i \backslash \varepsilon_u$	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

and $\Delta\delta_I$ must be negative; in fact, in this condition the system energy must be decreased.

3) If output voltage error ε_u 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 Tables I and II are derived for δ_P and $\Delta\delta_I$. Figs. 6 and 7 give a graphical representation of Tables I and II.

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

1) Current limitation is achieved by choosing the value of δ_p according to the output voltage error. For example, if ε_u is PB, δ_p is kept zero in order to limit the current value; instead, when ε_u 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

$$\begin{array}{c} \text{if } i_L \text{ is LIMIT and } \varepsilon_u \text{ is} \\ \text{then } \delta_p \text{ is} \end{array} \begin{array}{|c|c|c|c|c|} \hline PB & PS & ZE & NS & NB \\ \hline ZE & NS & NB & NB & NB \\ \hline \end{array}.$$

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

$$\text{if } i_L \text{ is LIMIT, then } \Delta\delta_i \text{ is ZE.}$$

An external action is also performed during limit operation. Since the reference value of the inductor current takes a wrong value during this operation (it becomes equal to $I_{\rm lim}$), the

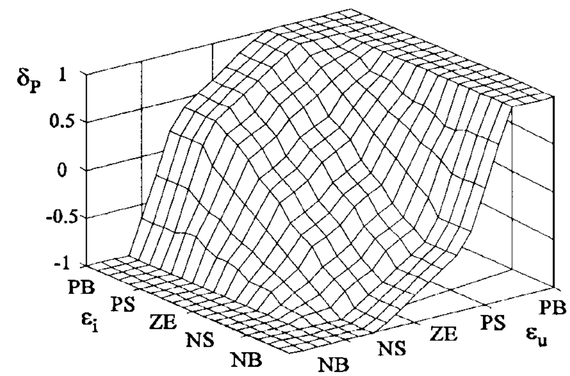

Fig. 6. Graphic representation of Table I.

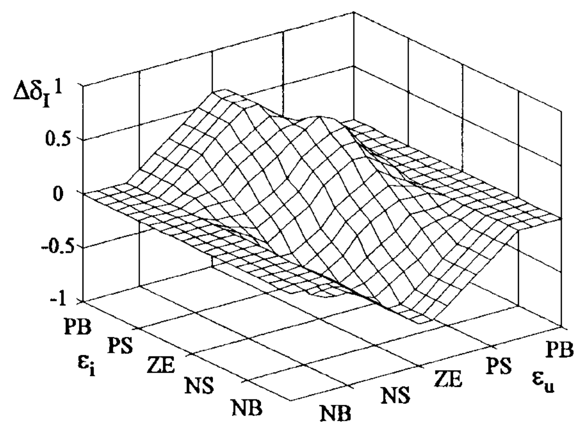

Fig. 7. Graphic representation of Table II.

capacitor of the low-pass filter generating the current reference is reset to zero as long as the current is close to $I_{\rm lim}$. It is important to note that the heuristic approach described in this paragraph remains valid irrespective of converter topology.

IV. 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.

A. 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.

B. 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.

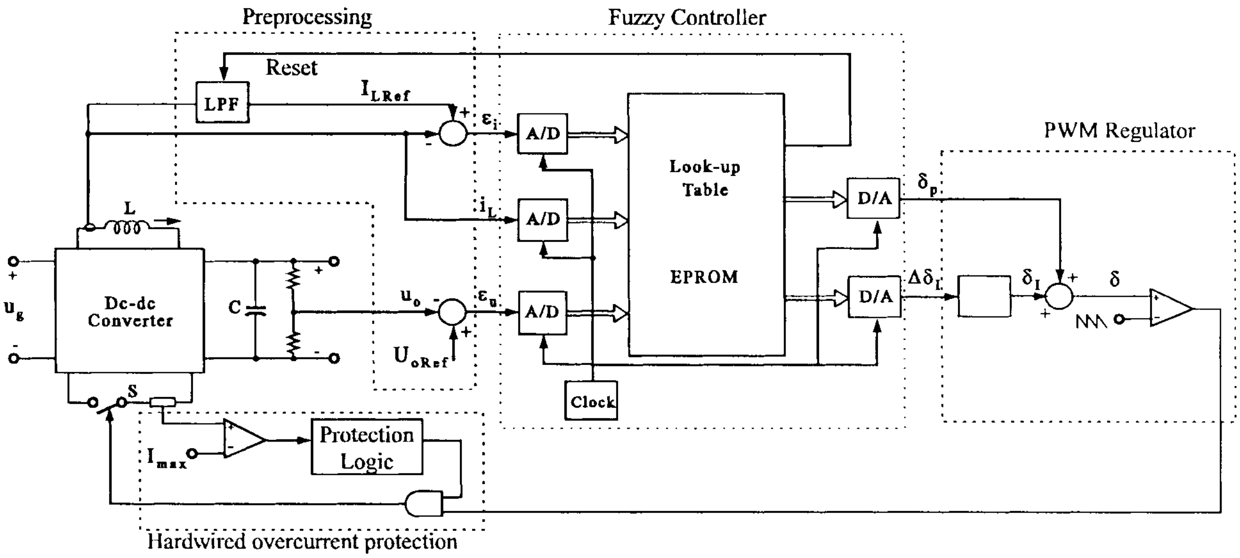

Fig. 8. Basic controller structure.

The choice of input scale factors (k_{uP}, k_{iP}, and k_{iLp} for the fuzzy-P controller and k_{uI}, k_{iI}, and k_{iLI} for the fuzzy-I) 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. Near the working point, given the choice of the membership functions as shown in Fig. 5, the normalized outputs δ_{nj} of the rule tables can be approximated by the function

$$\delta_{nj} = \alpha_j(\varepsilon_u + m_j \cdot \varepsilon_i) \qquad j = P, I \tag{4}$$

where $m_j = k_{ij}/k_{uj}$ and $\alpha_j = k_{uj}$ for $j = P, I$. In this way, if the ratio m_j is the same for $j = P, I$ ($m_P = m_I = m$), then 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 with the following equation:

$$k_{\delta j} = k_j/k_{uj} \qquad j = P, I. \tag{5}$$

The selection of k_P and k_I is based on the same guidelines as standard PI controller design which has to compensate the following power stage transfer function:

$$\frac{\hat{\psi}(s)}{\hat{\delta}(s)} = \frac{\hat{\varepsilon}_u(s)}{\hat{\delta}(s)} + m \cdot \frac{\hat{\varepsilon}_i(s)}{\hat{\delta}(s)} = \frac{\hat{u}_o(s)}{\hat{\delta}(s)} + m \cdot \frac{\hat{i}_L(s)}{\hat{\delta}(s)} \cdot \frac{s \cdot \tau}{1 + s \cdot \tau} \tag{6}$$

where $\hat{}$ stands for small-signal perturbation, τ is the time constant of the low-pass filter, and $\hat{u}_o(s)/\hat{\delta}(s)$ and $\hat{i}_L(s)/\hat{\delta}(s)$ are the converter transfer functions in continuous conduction mode, derived from time-averaging techniques.

This procedure allows a preliminary design of coefficients $k_{\delta P}$ and $k_{\delta I}$. Instead, input scale factors can be basically chosen according to the following guidelines.

- k_{uP} As shown in Fig 5, it determines the regions where control is primarily governed by the output voltage error and those where it is governed by both state variable errors.

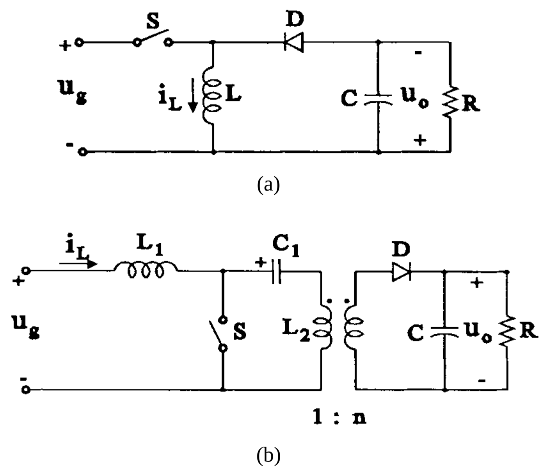

Fig. 9. (a) Buck-Boost converter and (b) Sepic converter.

- k_{uI} It should be chosen so that the maximum steady-state error falls inside the NS-ZE-PS since outside this interval, no integration is performed.
- m_P, m_I In a first step, both coefficients can be chosen equal to a value m, selected by analyzing (6) or by qualitative considerations on the desired behavior of the two state variable errors. Moreover, since the function ψ is a weighted sum of the state errors, it resembles the sliding mode-control function [9] so that m corresponds to the slope of the sliding line. Design can be done accordingly.
- k_{iL} It is set equal to $1/I_{\lim}$.

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.

TABLE III
CONVERTER PARAMETERS

BUCK-BOOST	
U_g = 12V	I_{lim} = 10A
U_o = 20V	f_s = 50 kHz
L = 360 μH	τ = 400 μs
C = 100 μF	R = 20 -150 Ω
k_{uP} = 0.070	k_{uI} = 0.052
k_{iP} = 0.20	k_{iI} = 0.15
$k_{\delta p}$ = 15	$k_{\delta I}$ = 15700
SEPIC	
U_g = 15V	I_{lim} = 6 A
U_o = 20V	f_s = 50 kHz
L_1 = 700 μH	C_1 = 6.8 μF
L_2 = 380 μH	C_2 = 200 μF
R = 20-200 Ω	τ = 600 μs
n = 1.5	
k_{uP} = 0.20	k_{uI} = 0.20
k_{iP} = 0.20	k_{iI} = 0.20
$k_{\delta p}$ = 5	$k_{\delta I}$ = 15700

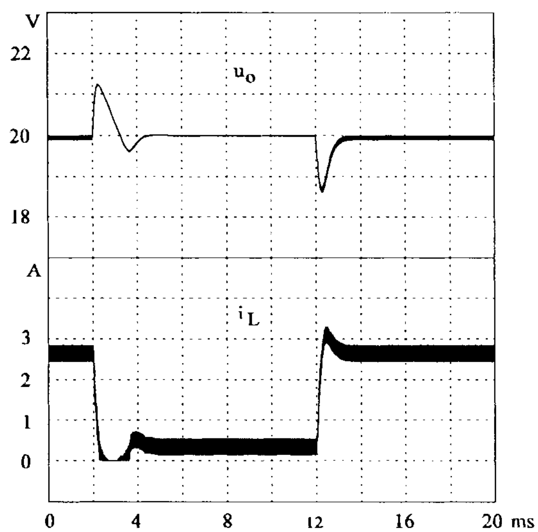

Fig. 10. Simulated response of output voltage and inductor current of a Buck-Boost converter to load-step variations.

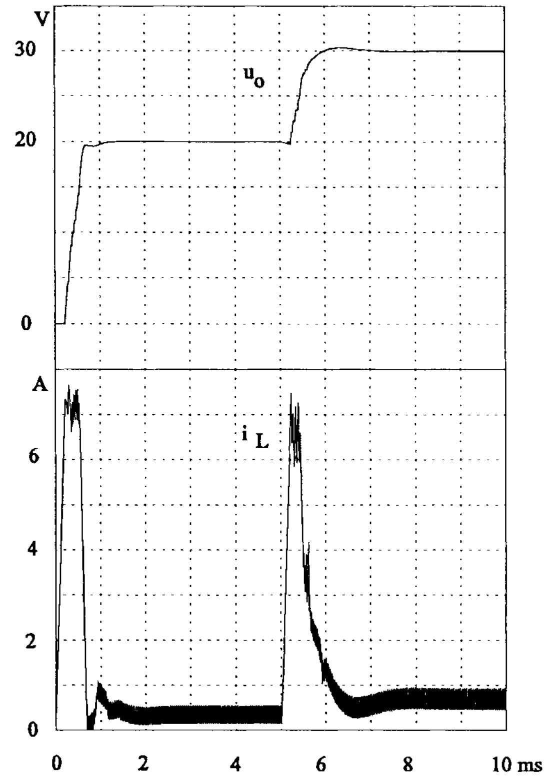

Fig. 11. Output voltage and inductor current during start-up at light load followed by output-voltage reference variation.

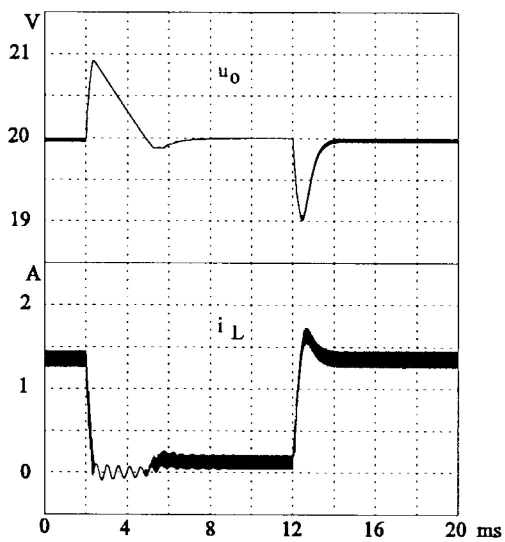

Fig. 12. Simulated response of output voltage and inductor current of a Sepic converter to step-load variations.

C. Fuzzy Algorithm

There are numbers of ways to define the fuzzy implications, the sentence connectives *and* and *else* used for the fuzzy rules, and the inference mechanism; criteria and properties can be found in literature [3] and [4].

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 $\varepsilon_i, \varepsilon_u, i_L$ is

$$\delta_P = \frac{\sum_{j=1}^{n} \alpha_j D_j}{\sum_{j=1}^{n} \alpha_j} \tag{7}$$

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

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

where $A_j, B_j,$ and C_j are the input fuzzy variables corresponding to the jth rule.

D. 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 Tables I and II and adjusting some rules in order to optimize the system response in the linguistic phase plane.

E. Low-Pass Filter Time Constant τ

The choice of τ can heavily affect the system behavior. τ should be suitably higher than the switching period in order to provide a ripple-free current reference, but small enough to allow fast converter response. In practice, values close to the natural time constants of the system give the best results.

V. Control Implementation

Fig 8. shows a possible control implementation. The scheme includes three basic sections: 1) a *preprocessing* section where controller input $(\varepsilon_u, \varepsilon_i, i_L)$ is evaluated; 2) a *fuzzy controller* which is based on a lookup table that stores the values of δ_P and $\Delta\delta_I$ as a function of the input variables (it is easily implemented by an EPROM); and 3) a *PWM regulator* which performs the integration of $\Delta\delta_I$, adds δ_P and δ_I together, and compares δ with the ramp signal to generate the switching pattern.

In the fuzzy controller block, signals of ε_u, ε_i, and i_L are fed to analog-to-digital converters (ADC's) whose outputs represent the addresses of the EPROM. The ADC's can have a small number of bits since high precision is not needed. Digital-to-analog converters (DAC's) give outputs δ_P and $\Delta\delta_I$. The EPROM also provides the reset signal for the low-pass filter during current limit operation. A hardwired overcurrent protection is also needed.

VI. Simulated Results

Control operation was verified by simulation. Several topologies have been tested, and results of Buck-Boost and Sepic converters are reported. The basic schemes are shown in Fig. 9(a) and 9(b), respectively. Their parameters are listed in Table III.

A. Buck-Boost

The converter behavior in the case of step-load changes from full load to light load and vice versa is shown in Fig. 10. Output voltage u_o and inductor current i_L behave well in terms of both overshoot and response speed. In particular, for the given choices of k_{up} and k_{ui}, the dynamic response is comparable to that of current mode control.

Fig. 11 shows output voltage and inductor current behavior during a start-up under a light-load condition (worst case), followed by a step in the output voltage reference from 20 V to 30 V. In both cases, the output voltage error is initially NB so that a strong action is applied, causing a current limit action. The overshoot on the output voltage is almost avoided at start-up, while it is limited at 2% of the nominal value in the other case in spite of a high limit current value. The robustness to wide parameter variations was also verified.

B. Sepic

The same rule set used for the Buck-Boost converter was applied to the Sepic converter. Fig. 12 shows the converter behavior under fuzzy control in the case of a step-load variation from full load to light load and vice versa. Good performances in terms of both overshoot and response speed are achieved even in this fourth-order converter. Note that as soon as the load is disconnected, the control opens the switch, and the converter turns in a discontinuous conduction mode. In this way, no energy goes to the output because the diode D is off.

It is interesting to note that these performances are similar to those obtained using sliding mode control as can be seen by the experimental results reported for a Sepic converter in [9].

VII. Conclusion

A general-purpose controller for dc–dc converters based on the fuzzy logic is presented. As compared to standard controllers, it provides improved performances in terms of overshoot limitation and sensitivity to parameter variations.

This is possible since FLC rules can be assigned separately for the various regions of operation, resulting in effective small-signal and large-signal operation.

Simulation results of Buck-Boost and Sepic converters confirm the validity of the proposed control technique.

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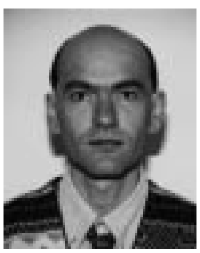

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