A FUZZY CONTROLLER SYNTHESIS FOR A BOOST CONVERTER

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Abstract: The aim of this paper is to develop an accurate small signals model for a Boost converter operating in continuous conduction mode, and including the internal resistors of elements. This model is then used to synthesise a fuzzy logic controller that guarantees the output voltage regulation with desired performances. A comparative study illustrates the efficiency, the robustness and the flexibility of the proposed approach relatively to a classical PID controller.

Keywords: Power Converter, Continuous Conduction Mode, Small Signals Model, PID Controller, Fuzzy Controller.

1. INTRODUCTION

The DC-DC converters are widely used in many industrial applications where high performances are required. To guarantee the desired performances, a mathematical model is required to synthesise a suitable controller. A typically used model is the averaged model, which describes the converter behaviour on the operating point (Erickson and Maksimovic, 1999). Nevertheless, the required performances are only guaranteed for the corresponding point and the design assumptions do not consider some non-linear phenomena, such as the sub-harmonic or pseudo-chaotic motions. To overcome these restrictions, the model based on the recurrence method can be used (Hamill, *et al*, 1992). However, the application of this model for complex plants is difficult (Sehab, *et al*, 2002). As a trade-off between the previous approaches, the small signals model, which describes the system behaviour around the operating point, can be used. This model is simpler than recurrence based model and more accurate than the averaged one (Erickson and Maksimovic, 1999; Severns and Bloom, 1985). Based on this model, many controllers have been developed, using classical methods (Ahmed, *et al*, 2003; Rafiei, *et al*, 2003; Vidal-Idiarte, *et al*, 2004) or fuzzy logic (So, *et al*. (1996), Mattavelli, *et al* (1997), Raviraj et Sen (1997), Shi and Sen (2001), Viswanathan *et al* (2002), Diordiev *et al*, (2003)).

A comparative study between three control methods using the small signals model for a Buck converter (Raviraj and Sen, 1997) showed the efficiency and robustness of fuzzy logic control compared to a classical proportional integral (PI) and sliding mode controllers. In the same area, Viswanathan *et al* (2002) presented a universal fuzzy logic controller, which, unlike the PI case, ensures good performances despite the operating point variations. In (Diordiev *et al*, 2003), the authors use a conventional PID controller with a fuzzy logic based gain controller for DC-DC converter regulation. The PID controller parameters are deduced from the approximated linear model of the DC-DC converter. In order to compensate the neglected non linear components and to improve the overall performances of the controller, the PID controller output gain is tuned using a fuzzy logic system. These works are generally based on a simplified small signals model, which considers the switches as ideal and neglects the equivalent series resistors of both inductor and capacitor and considering that in all operating point the converter output voltage increases by increasing the duty cycle and vice versa. However, the system losses analysis (Erickson and Maksimovic, 1999) shows that the converter efficiency tends to zero when the steady state value of duty cycle approaching one.

The objective of this paper is to synthesise a fuzzy logic controller that is able to ensure both good performances of regulation, robustness and flexibility. For this, we develop an accurate Boost small signals model including the equivalent series resistors of both inductor and capacitor, and considering non-ideal switches by using the conduction resistors of both switch elements. To validate the proposed approach, several simulation results and a comparative study with a frequency domain designed PID controller will be presented.

2. SMALL SIGNALS MODEL

In the aim of obtaining an accurate model, this section will be dedicated to the development of a small signals model of the Boost converter. For this, we consider the Boost converter scheme of figure 1, with r_L, r_{SW}, r_{VD}, and r_C denoting the resistors of inductor L, switch sw, diode VD and capacitor C, respectively. R is the load, $v_g(t)$ the supply voltage, $u_0(t)$ the output voltage and $i_L(t)$ the inductor current.

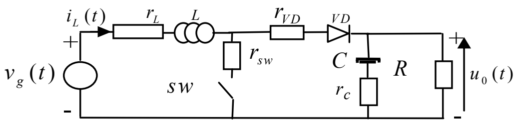

Fig. 1. The Boost converter scheme

In the continuous conduction mode (CCM) i.e., $i_L(t) > 0$, we have two topologies depending on the position of switch sw, as shown in figure 2.

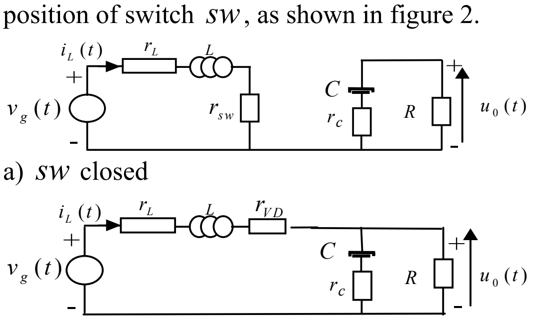

Fig. 2. The Boost CCM topologies

In the first topology (Fig. 2-a), the system can be presented by the following equations:

$$L\frac{d}{dt}i_L(t) = v_g(t) - \left(r_L + r_{SW}\right)\ i_L(t) \tag{1-a}$$

$$\frac{d}{dt}v_C(t) = -\frac{1}{C\left(R + r_C\right)}v_C(t) \tag{1-b}$$

$$u_O(t) = \frac{R}{R + r_C}v_C(t) \tag{1-c}$$

where $v_C(t)$ is the voltage across the capacitor element C.

The second topology (Fig. 2-b) gives:

$$L\frac{d}{dt}i_L(t) = v_g(t) - \left(r_L + r_{VD} + \frac{R\ \ r_C}{R + r_C}\right)i_L(t) - \frac{R}{R + r_C}v_C(t) \tag{2-a}$$

$$\frac{d}{dt}v_C(t) = \frac{1}{C\left(R + r_C\right)}\left(R\ \ i_L(t) - v_C(t)\right) \tag{2-b}$$

$$u_O(t) = \frac{R}{R + r_C}\left(v_C(t) + r_C i_L(t)\right) \tag{2-c}$$

To obtain the small signals model, we assume that each variable can be written as the sum of a constant (direct) component (noted in upper-case letter) and a small varying one (noted in hat lower-case letter). Hence, $v_g(t) = V_g + \hat{v}_g(t)$, $u_O(t) = U_O + \hat{u}_0(t)$ $v_C(t) = V_C + \hat{v}_C(t)$, $i_L(t) = I_L + \hat{i}_L(t)$.

For a switching period T, a duty cycle $d(t) = D + \hat{d}(t)$, and the switch sw assumed closed during $Td(t)$, the system dynamic can be described by the equations set (3).

If we suppose that the input voltage is perfectly continuous, i.e., $\hat{v}_g = 0$, the steady state dynamic of the system will be expressed by :

$$0 = V_g - \left(r_L + r_{SW}\right)DI_L - \left(r_L + r_{VD} + \frac{Rr_C}{R + r_C}\right)D'I_L - \frac{R}{R + r_C}D'V_C \tag{4-a}$$

$$0 = \frac{1}{C\left(R + r_C\right)}\left\{-V_C + D'RI_L\right\} \tag{4-b}$$

$$U_O = \frac{R}{R + r_C}\left\{V_C + D'r_C I_L\right\} \tag{4-c}$$

$$L\frac{d}{dt}\left(I_L + \hat{i}_L(t)\right) = \left(D + \hat{d}(t)\right)\left\{\left(V_g + \hat{v}_g(t)\right) - \left(r_L + r_{SW}\right)\left(I_L + \hat{i}_L(t)\right)\right\} + \left(D' - \hat{d}(t)\right)\left\{\left(V_g + \hat{v}_g(t)\right) - \left(r_L + r_{VD} + \frac{R\ \ r_C}{R + r_C}\right)\left(I_L + \hat{i}_L(t)\right) - \frac{R}{R + r_C}\left(V_C + \hat{v}_C(t)\right)\right\} \tag{3-a}$$

$$\frac{d}{dt}\left(V_C + \hat{v}_C(t)\right) = \frac{1}{C\left(R + r_C\right)}\left\{-\left(D + \hat{d}(t)\right)\left(V_C + \hat{v}_C(t)\right) + \left(D' - \hat{d}(t)\right)\left(R\left(I_L + \hat{i}_L(t)\right) - \left(V_C + \hat{v}_C(t)\right)\right)\right\} \tag{3-b}$$

$$U_O + \hat{u}_O(t) = \frac{R}{R + r_C}\left\{\left(D + \hat{d}(t)\right)\left(V_C + \hat{v}_C(t)\right) + \left(D' - \hat{d}(t)\right)\left[\left(V_C + \hat{v}_C(t)\right) + r_C\left(I_L + \hat{i}_L(t)\right)\right]\right\} \tag{3-a}$$

with $D + D' = 1$.

which gives:

$$D'^2\left[\frac{R^2}{R+r_C}\right]+D'\left[-r_{SW}+r_{VD}+\frac{Rr_c}{R+r_c}-R\frac{V_g}{U_O}\right]+\left(r_L+r_{SW}\right)=0 \quad (5)$$

The solution of (5), gives the necessary direct component of the duty cycle $D=1-D'$, allowing the output voltage U_O to attain a reference voltage V_{ref}.

After defining the operating point by D, the next task is to synthesise a model giving the relation between the output voltage and the duty cycle around D.

By neglecting the second order terms (Erickson and Maksimovic, 1999), in equations set (3), the system's dynamic becomes:

$$L\frac{d}{dt}\hat{i}_L(t)=\hat{v}_g(t)-\alpha_1\hat{i}_L(t)+\alpha_2 I_L\hat{d}(t)-\frac{RD'}{R+r_C}\hat{v}_C(t) \quad \text{(6-a)}$$

with

$$\alpha_1=\left(r_L+Dr_{SW}+D'r_{VD}+D'\frac{Rr_C}{R+r_C}\right),$$

$$\alpha_2=\left(-r_{SW}+r_{VD}+\frac{Rr_C}{R+r_C}+\frac{D'R^2}{R+r_C}\right)$$

$$\frac{d}{dt}\hat{v}_C(t)=\frac{1}{C\left(R+r_C\right)}\left\{-\hat{v}_C(t)-RI_L\hat{d}(t)+RD'\hat{i}_L\right\} \quad \text{(6-b)}$$

$$\hat{u}_O(t)=\frac{R}{R+r_C}\left\{\hat{v}_C+r_C D'\hat{i}_L(t)-r_C I_L\hat{d}(t)\right\} \quad \text{(6-c)}$$

Using the Laplace transform of (6-a,b,c), and after some manipulations, the control to output voltage transfer function around the operating point is given by:

$$\frac{\hat{u}_O}{\hat{d}}=K\frac{\left(1+\frac{S}{\omega_3}\right)\left(1-\frac{S}{\omega_1}\right)}{\left(\frac{S}{\omega_2}\right)^2+\frac{1}{Q}\frac{S}{\omega_2}+1} \quad (7)$$

where

S: is the Laplace operator, $\omega_3=\frac{1}{r_C C}$,

$$\omega_1=\frac{1}{L}\left(\frac{\left(RD'\right)^2}{R+r_C}-r_L-r_{SW}\right),\ \omega_2=\sqrt{\frac{R'}{LC\left(R+r_C\right)}},$$

$$Q=\sqrt{R'\left(R+r_C\right)}\sqrt{\frac{C}{L}}\frac{1}{1+\frac{C}{L}\left[Rr_L+r_C r_L+Rr_C D'+\left(R+r_C\right)\left(Dr_{SW}+D'r_{VD}\right)\right]}$$

$$R'=r_L+Dr_{SW}+D'r_{VD}+D'\frac{Rr_C}{R+r_C}+\frac{\left(RD'\right)^2}{R+r_C}$$

and $K=\frac{R}{R'^2}\left(-r_{SW}-r_L+\frac{\left(RD'\right)^2}{R+r_C}\right)V_g$.

The transfer function (7) represents a good approximation of the real Boost behaviour around the operating point, due to the fact that all the internal resistors are considered.

This transfer function will be used in the next section to provide some information on the system features ; as overshoot, damping factor, phase margin, ...which are necessary for suitable controller synthesis.

3. FUZZY CONTROLLER SYNTHESIS

The developed small signals model allows obtaining a good approximation of the converter behaviour around the operating point. Nevertheless, its validity is restricted to a small zone around this point. Furthermore, the designer of classical controller is generally obliged to limit the system's bandwidth to 10% of the crossover frequency to eliminate the effects of the commutation harmonics (Erickson and Maksimovic, 1999). Thus the system order is reduced and, consequently the control signal frequency is also reduced. So, in addition to overcoming these problems, the controller to design must ensure good regulation performances (eliminate the steady state error, minimize the overshoot and the response time) and compensate the neglected nonlinearity in the modeling process. To attain this objective, we propose in the following the so called "Fuzzy Pseudo PID" controller, given in figure 3.

The control action $\hat{d}$ is obtained by the weighted sum of the fuzzy logic system (FLS) output $\hat{d}_1$ and its integral action using the gains G_1 and G_2. The FLS is a Takagi-Sugeno structure with error voltage $e=V_{ref}-u_0$ and its time derivative $\dot{e}$ as inputs. This system is constructed from the human experience formulated in a collection of fuzzy rules in the following form:

j^{th} rule: **IF** e *is* E_0^j AND $\dot{e}$ *is* E_1^j **THEN**

$$\hat{d}_1=C_j(e,\dot{e}) \quad (8)$$

with E_0^j, E_1^j are respectively the fuzzy sets of the error voltage e and its time derivative $\dot{e}$. C_j is the j^{th} output singleton.

The fuzzy control strategy is derived using the following knowledge on the system:

- When u_o is far from the reference V_{ref}, the change of duty cycle ($\hat{d}_1$) must be large to provide a small response time.
- When u_o approaches the reference, a small $\hat{d}_1$ is sufficient to reach the reference.

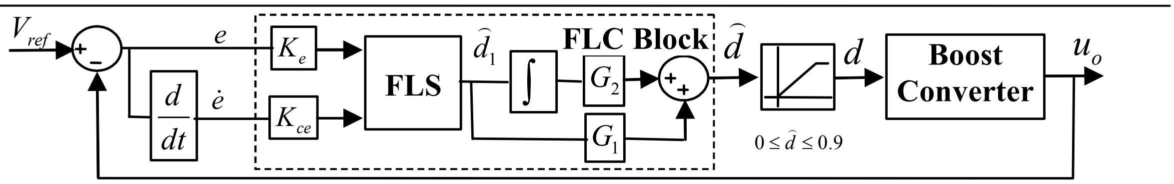

Fig. 3. The control system structure with fuzzy logic controller

- When u_o is in the vicinity of the reference with a sufficient approaching speed, the duty cycle must be unchanged to prevent the output overshoot.
- When u_o reaches the reference and continue growing up: first, we decrease the duty cycle change, then if u_o remains closer to the reference, the duty cycle changes must be zero otherwise, it must be negative.

Using the product as inference engine and the centre average for defuzzification, the FLS output can be formulated as follows:

$$\hat{d}_1 = \frac{\sum_{j=1}^{N} C_j(e,\dot{e}) \prod_{i=0}^{1} \mu_i^j(e^{(i)})}{\sum_{j=1}^{N} \prod_{i=0}^{1} \mu_i^j(e^{(i)})} \quad (9)$$

where N is the number of the fuzzy rules, and $\mu_i^j(e^{(i)})$ is the membership degree of $e^{(i)}$ to the set E_i^j. Thus the final control action $\hat{d}$ applied to the converter is given by:

$$\hat{d} = G_1\hat{d}_1 + G_2\int \hat{d}_1\, d\tau \quad (10)$$

Note that the inputs e and $\dot{e}$ are scaled respectively by K_e and K_{ce} in the aim to allow the normalisation of the fuzzy system inputs. i.e, $K_e=1/max(|e|)$, $K_{ce}=1/max(|\dot{e}|)$. Furthermore, according to the desired performances, the use of weighting gains G_1 and G_2 help to determine the participation rate of each action ($\hat{d}_1$ and $\int \hat{d}_1\, d\tau$) to the controller output $\hat{d}$. These gains are obtained by identification between FLC action in the vicinity of steady state and the PID controller one. Then, a refinement process using the guidelines given in (So, *et al.*, 1996) and (Escamilla-Ambrosio and Mort, 2002) is needed to attain the desired performances.
The saturation block (Fig. 3) is used to avoid that the switch *sw* remains closed during all the switching period.

4. SIMULATIONS AND RESULTS

The simulation is performed using the Boost converter given in figure 1 with the following parameters:
$V_g = 45\,\text{v}$, $L = 2120\mu H$, $r_L = 0.74\Omega$, $C = 100\mu\text{F}$,
$r_C = 0.18\Omega$, $r_{SW} = 0.3\Omega$, $r_{VD} = 0.24\Omega$, $R = 1.2K\Omega$.
To validate the obtained small signals model, we introduce a small variation (0.5%) in the duty cycle around its value in steady state. Hence, figure 4 illustrates the system open loop response, using model (7) and the detailed one obtained by resolving (1) and (2) with $T=2.10^{-5}$ sec. The observed deviation of the white response from the mean of the black one is due to the neglected second order component in the small signals modelling approach.
To evaluate the performances of the proposed controller, we present firstly the regulation results for a step reference variation. After that a comparative study with a frequency domain designed PID controller will be presented.

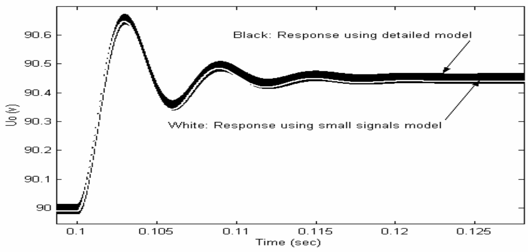

Fig. 4. The small signals model validation

To design the proposed controller, the FLS block must be constructed first. Hence, the inputs e and $\dot{e}$ are scaled respectively by $K_e = 0.2$, $K_{ce} = 7.10^{-4}$. For each input, we define five fuzzy sets, Negative Large (NL), Negative (N), Zero (Z), Positive (P) and Positive Large (PL), described by triangular membership functions, uniformly distributed on the normalised universe of discourse. Using all possible combinations, we obtain 25 fuzzy rules with 17 output singletons issued from the human expertise and presented in Table 1.

Tab.1. Inference Matrix

	NL	N	Z	P	PL
PL	0.25	0.36	0.49	0.81	1
P	0	0.04	0.16	0.36	0.64
Z	-0.16	-0.04	0	0.04	0.16
N	-0.64	-0.36	-0.16	-0.04	0
NL	-1	-0.81	-0.49	-0.36	-0.25

In order to eliminate the steady state error, we reinforce the integral action by choosing the following gains $G_1 = 10$ and $G_2 = 9700$.
Figure 5 illustrates the system response for a reference step variation from 75*v* to 100*v*. In this case, the proposed fuzzy controller ensures good performances despite the important change in the reference voltage. In fact, it guarantees a time response of 5*ms* and a zero overshoot. Indeed, from figure 6, we remark that the fast control dynamics allow to attain the desired performances.

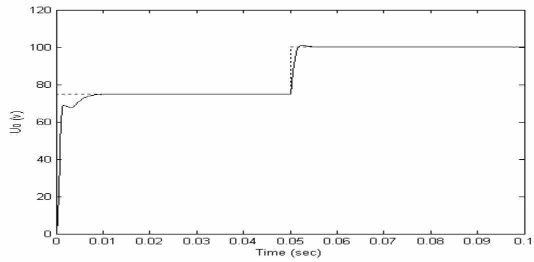

Fig. 5. The system response for a reference step variation

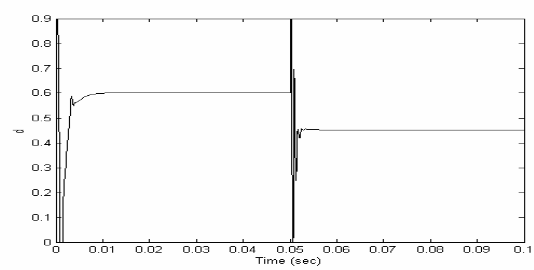

Fig. 6. The control action

To evaluate the performances and the robustness of the proposed controller, the following sub-sections present a comparative study with a frequency domain designed PID controller. Indeed, four cases are considered: without disturbances, load variation, supply voltage perturbation and the case of a time-varying system. The PID controller used in this study is the one tuned by (*Kolokolov et al., 2004*) for the same converter and given by :

$$W_{PID} = \frac{\hat{d}}{e} = G\frac{\left(1+\dfrac{S}{\omega_Z}\right)\left(1+\dfrac{\omega_L}{S}\right)}{\left(1+\dfrac{S}{\omega_P}\right)} \qquad (11)$$

where the parameter *G=0.5* gives the proportional action that enhance the response time. The integral part of this controller characterised by the reversed zero $\omega_L = 130$ allows obtaining a zero steady state error, $\omega_Z = 1300$ characterises the derivative action and allows the phase margin enhancement and $\omega_P = 40000$ is introduced to take into account the filtering aspect of real derivative action.

4.1 System without disturbances

Figures 7 and 8 give, respectively, the system response and the control signal for a reference step of *75v,* in the case when the system is certain and without disturbances.

These results show that the fuzzy controller gives a faster dynamic than the PID one. Indeed, as illustrated in figure 7, the time response decreases to *68%* (FLC: 5*ms,* PID: 16*ms*). Note that the fuzzy controller gives a zero steady state error comparing to the classical PID controller, which provides a steady state error of 0.18*v* at *t=0.1s* (Fig. 7). This improvement allows to enlarge the system bandwidth and consequently to maintain the closed loop performances.

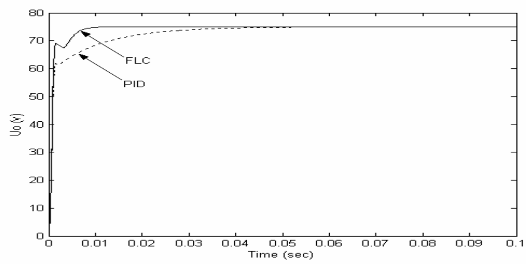

Fig. 7. The system response

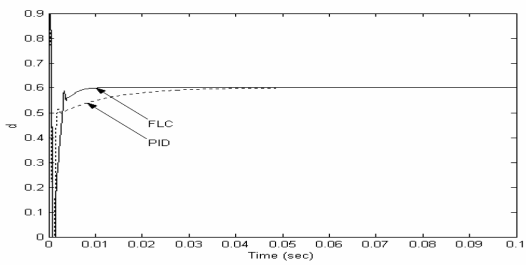

Fig. 8. The control action

4.2 Disturbed system

Our task now is to study the robustness of the proposed controller in presence of load variation, then supply voltage variation disturbances.

Load variation :Figure 9 presents the system output for a load variation from 1200Ω to 600Ω . Despite the important load variation (50%), the system response has been slightly modified (undershoot <0.5%). We can also note that the proposed fuzzy controller allows the system to return faster to its steady state.

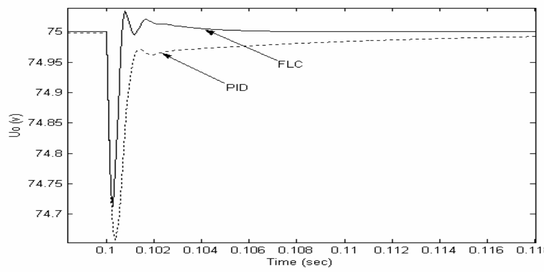

Fig. 9. The faster dynamic ensured by FLC

Supply voltage variation: Figures 10 and 11 summarise the results obtained when the system is subject to supply voltage variation which increases by *16v* of its nominal value during [0.1 0.2]*s.* In this case, the proposed controller is more robust than the PID one and due to its high control dynamics (Fig. 11), it is able to force the system to return quickly to its steady state. Indeed, using FLC the needed time to return to steady state is 0.7*ms*, while using PID controller gives 9.7*ms* (Fig. 10).

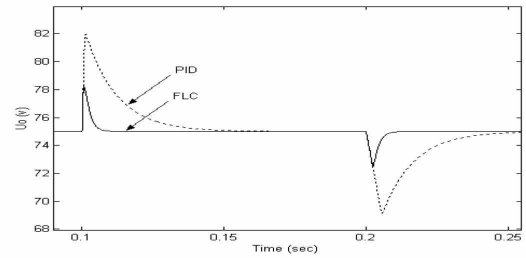

Fig. 10. The system response during the supply voltage variation

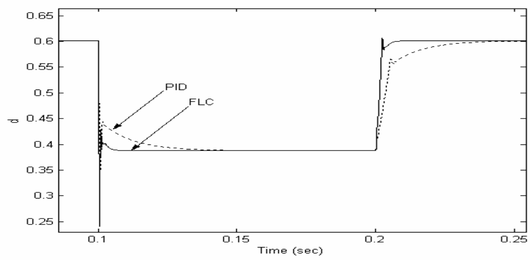

Fig. 11. The control signal during the supply voltage variation

4.3 System with time-varying operating point

To construct a suitable controller, the process mathematical model can be obtained around the operating point in the case where the system elements are well known. Otherwise, if the operating point, D, is time varying or unknown, we propose to initialise the fixed component of the operating point by an approached value and adjust it according to the control action $\hat{d}$ as follows:

$D(t) = D(t-1) + \hat{d}(t)$, with $0 \le D \le 0.9$.

For several initial values of D, the obtained results are depicted in table 2. These results show that the fuzzy controller is more adequate than the classical PID controller for situations where the system has time varying parameters. Indeed, using an initial value *D(0)=0.3*, the system response is presented in figure 12. We remark that while the operating point changes, the PID regulation performances are deteriorated. This is due to the fact that the classical PID controller parameters are designed for a fixed operating point. On the other hand, the FLC parameters are variables depending on the system state and this allows obtaining better performances.

Tab. 2. Characteristics of the regulated system

$D(0)$	Response time (ms)		Overshoot (v)	
	PID	FLC	PID	FLC
0	285	5.76	V.L.O	0.278
0.1	285	5.78	V.L.O	0.1793
0.3	285	5.77	V.L.O	0
0.5	285	5.77	V.L.O	0
0.7	285	5.77	V.L.O	0
0.9	285	5.77	V.L.O	0

V.L.O.: Very Large Overshoot

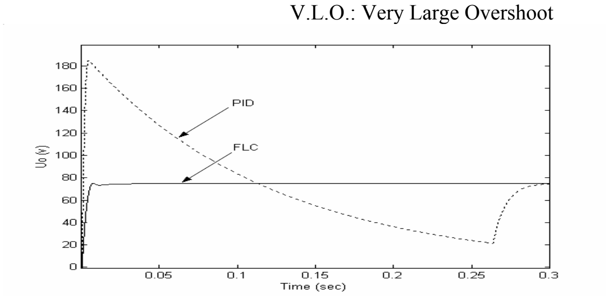

Fig. 12. The system response

5. CONCLUSION

In this paper we have presented an accurate small signals model for a Boost converter operating in CCM. This model was then used to design a fuzzy logic controller that ensures the output voltage regulation with good performances.

A comparative study, for regulation problem under load disturbances, supply voltage variation and time-varying operating point, showed the advantages of the proposed controller relatively to a classical PID control in terms of performances, robustness and flexibility.

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