Fuzzy Control of PWM Converters

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Abstract— **The paper develops a Fuzzy Control of Dc-to-Dc Converters using T-S Fuzzy Modeling Approach. These systems have a nonlinear dynamic behavior, as they work in switch-mode. First a methodology for developing the Takagi-Sugeno Model (TSM) for a PWM Dc-to-Dc Converter is derived. Second, a nonlinear fuzzy controller is designed accordingly via the Parallel Distributed Compensation (PDC) method, the gain feedback coefficients for local models are chosen by means of a Linear matrix Inequalities (LMIs).**

Simulations results on the regulation of the buck-boost DC-DC converter subject to input voltage and load disturbances, using the proposed fuzzy controller are provided to illustrate the effectiveness of the proposed approach.

Keywords: DC-DC Converter, Takagi-Sugeno, PDC, LMI.

I. INTRODUCTION

DC-to-DC switching converters exhibit a nonlinear dynamic behaviour and the control to output transfer function of their linearised models is in many cases of no minimum phase type.

Based on approximated linear models, the converters have been successfully developed for many years using linear system design techniques [1]; nevertheless the nonlinear nature of switching converters has prompted some authors to use nonlinear control for regulation purposes: Feedback linearization [2], sliding-mode control [3] and passivity-based control [4] are some of the nonlinear strategies that have been used in recent years in the field of switching converters. In the field of fuzzy logic, many researches have been investigating the application of Mamdani-type fuzzy controllers to the converters [5], [10]. These works are generally based on a small signals model using state-space averaging methods; the model obtained by these methods is only useful for small signals.

Recently the Takagi–Sugeno fuzzy model has generated a good deal of interest for dc-dc converters, due to its efficiency to represents a nonlinear system with a set of linear subsystems [6], based on this approach, several fuzzy controls have been designed [13], [14], [15], however in all these fuzzy controls, the nonlinearity feature of the transfer function relating the output voltage to the duty ratio, mainly when the parasitic resistances are considered, is not directly taken into account as a premise variable.

In this paper, the problem is tackled from the nonlinear control viewpoint with consideration to the system stability, to deal with dc-dc converters control problems, we propose a fuzzy control technique as well as the T–S fuzzy model with the duty ratio as premise variable; the DC-DC converter is to be modelled using the Tagaki-Sugeno (T-S) fuzzy modelling approach [8], in this type fuzzy model, local dynamics in different state space regions are represented by a set of linear sub-models. The overall model of the system is then a fuzzy ‘‘blending’’ of these linear sub-models. In the design procedure of controller, parallel-distributed compensation (PDC) scheme was utilized to construct a global fuzzy logic controller by blending all local state feedback controllers, the gain feedback coefficients for local models are chosen in the LMI framework.

Stability conditions in the form of linear matrix inequalities (LMIs) can be derived based on Lyapunov stability theory [11]. As the solution to the LMI-based stability conditions can be solved numerically using the convex programming technique, the fuzzy-model-based control approach provides a systematic and effective way to realize the design of fuzzy controllers for nonlinear plants.

The paper is organized as follows. First, the state-space model of converter, in both static and dynamic regime, is constructed and the T–S type fuzzy model is briefly presented to model the converter. Furthermore, the control design is carried out via the PDC scheme, then, based on Lyapunov’s approach, a stability criterion is derived to guarantee the stability of fuzzy systems via the linear matrix inequality (LMI) technique.

Finally, a numerical example of buck-boost converter with simulations is given to demonstrate the results, and the conclusions are drawn.

II. THE CONVERTER MODELING

In this section, we describe and model a buck-boost converter in continuous conduction mode. This circuit is a constituted of power electronics components connected as shown in Fig.1. It is switched periodically with a switching period of T_s. The switch remains closed for a period of $\bar{d}\,T_s$ and open for $(1-\bar{d})Ts=\bar{d}'\,Ts$ in each cycle, where $\bar{d}$ ($0 \leq \bar{d} \leq 1$) is called the duty ratio of the switch. R_L and R_c are the parasitic resistances of the inductor and the capacitor respectively. V_{in}, R , $\bar{y}$ and i_L, denote supply voltage, current

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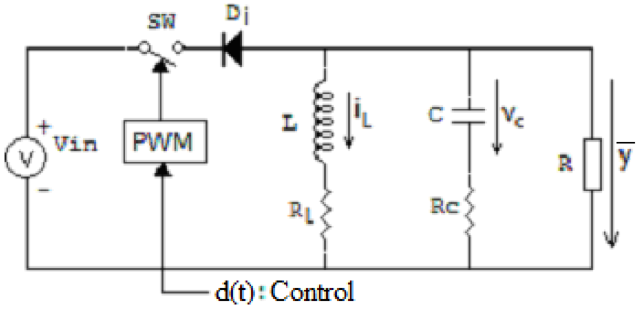


Figure 1. Buck-boost converter schema

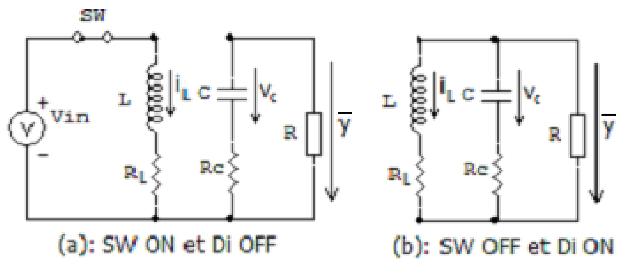


Figure 2. Buck-Boost converter configurations

in inductance, load resistor and output voltage respectively. Let $x = [i_L, v_c]^T$ the instantaneous state vector of converter. In continuous conduction mode there exist two configurations following the state of switch sw as shown in fig.2.

The first configuration can be described by the following equations:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{v_{in}}{L} - \dfrac{R_L}{L} i_L & (1.1) \\ \dfrac{dv_C}{dt} = -\dfrac{1}{(R_C+R)C} v_C & (1.2) \\ \bar{y} = \dfrac{R}{R+R_C} & (1.3) \end{cases}$$

And the second configuration can be represented by the following equations:

$$\begin{cases} \dfrac{di_L}{dt} = \dfrac{(R_L + R//R_c)}{L} i_L - \dfrac{R}{L(R+R_c)} v_c & (1.4) \\ \dfrac{dv_c}{dt} = \dfrac{R}{(R+R_c)C} i_L - \dfrac{1}{(R+R_c)C} v_c & (1.5) \\ \bar{y} = \dfrac{RR_c}{(R+R_c)} i_L + \dfrac{R}{(R+R_c)} v_c & (1.6) \end{cases}$$

In the state space representation the two configurations take the following form:

$$\begin{cases} \dot{\bar{x}} = \bar{A}_i\ \bar{x} + \bar{B}_i\ V_{in} \\ \bar{y} = \bar{C}_i\ \bar{x} \end{cases} \qquad (1.7)$$

Where: i=1 for fig.2.(a); i=2 for fig.2.(b)

and: $A_1 = \begin{bmatrix} \dfrac{-R_L}{L} & 0 \\ 0 & \dfrac{-1}{(R+R_c)C} \end{bmatrix}$, $B_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}$, $C_1 = [0 \quad \frac{R}{R+R_c}]$

$A_2 = \begin{bmatrix} \dfrac{-R_L + R_c // R}{L} & \dfrac{-R}{L(R+R_c)} \\ \dfrac{R}{(R+R_c)C} & \dfrac{-1}{(R+R_c)C} \end{bmatrix}$, $B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$, $C_2 = [R//R_C \quad \frac{R}{R+R_c}]$.

During each switching period Ts, the state space system becomes:

$$\begin{cases} \dot{\bar{x}} = \bar{A}\,\bar{x} + \bar{B}\,V_{in} \\ \bar{y} = \bar{C}\,\bar{x} \end{cases} \qquad (2)$$

Where:

$\bar{A} = \bar{d}\,A_1 + (1-\bar{d})A_2$; $\bar{B} = \bar{d}\,B_1 + (1-\bar{d})B_2 = \bar{d}\,B_1$;

$\bar{C} = \bar{d}\,.C_1 + (1-\bar{d})C_2$.

$$\bar{A} = \begin{bmatrix} \dfrac{-R_L + (1-\bar{d})R//R_c}{L} & \dfrac{-R(1-\bar{d})}{L(R+R_c)} \\ \dfrac{R(1-\bar{d})}{(R+R_c)C} & \dfrac{-1}{(R+R_c)C} \end{bmatrix}, \quad \bar{B} = B_1 = \begin{bmatrix} \frac{\bar{d}}{L} \\ 0 \end{bmatrix},$$

$$\bar{C} = \begin{bmatrix} (1-\bar{d})R//R_c & \dfrac{R}{R+R_c} \end{bmatrix}; \quad R//R_c = RR_c/(R+R_c)$$

In steady state: $\dot{\bar{x}} = 0 \Rightarrow \bar{x} = -\bar{A}^{-1}\bar{B}V_{in}$ and $\bar{y} = -\bar{C}\bar{A}^{-1}\bar{B}V_{in}$ for every chosen duty ratio $\bar{d}$ and line voltage V_{in}, one can get the transfer function relating the output voltage to the input voltage:

$$\bar{y}(\bar{d}) = V_{in}\,\frac{\bar{d}}{1-\bar{d}} \times \frac{(1-\bar{d})^2 R}{R_L + \bar{d}(1-\bar{d})R // R_c + R(1-\bar{d})^2} \qquad (3)$$

Using the parameters of the converter given in section.V, and for R_c=0.12Ω, we can clearly remark in fig.3 the effect of the parasitic especially for $\bar{d}$ >0.86 where the converter change

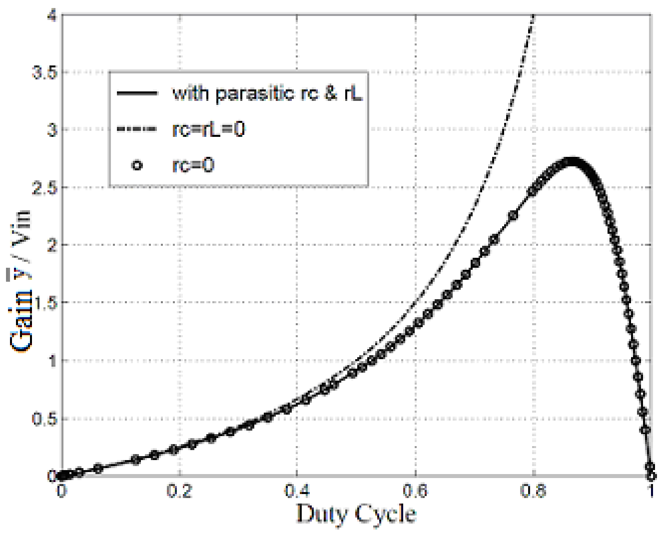


Figure 3. Transfer Function

completely its feature (the output voltage decrease when the duty ratio increase); one can also remark that this decrease in the gain $\bar{y}/V_{in}$ is caused by inductor resistance and that the capacitor resistance changes it nothing; Consequently, during the paper, we suppose that $R_c=0$, what can be justified as well by the fact as R_c is generally very weak in front of the load resistance. We obtain:

$$\bar{C}_1=\bar{C}_2=\bar{C}=\begin{bmatrix}0 & 1\end{bmatrix}$$

Assume that each variable can be written as the sum of a constant component (static: $\bar{d}$, $\bar{x}$ and $\bar{y}$) and a small varying one (dynamic: noted in hat lower-case letter). Hence:

$$d(t)=\bar{d}+\hat{d}(t)\ ;\ x(t)=\bar{x}+\hat{x}(t)\ ,\ y(t)=\bar{y}+\hat{y}(t)\ ,$$

Let $x_m(t)$ and $y_m(t)$ represent respectively the mean state vector and the mean output voltage:

$$x_m(t)=\frac{1}{Ts}\int_t^{t+Ts}x(\tau)d\tau=\bar{x}+\hat{x}_m(t)$$

$$y_m(t)=\frac{1}{Ts}\int_t^{t+Ts}y(\tau)d\tau=\bar{y}+\hat{y}_m(t)$$

System in transient state is governed by the state space system according to:

$$\begin{cases}\dot{x}_m=\left[\bar{d}A_1+\bar{d}'A_2\right]x_m(t)+\left[\bar{d}B_1+\bar{d}'B_2\right]v_{in}\\ y_m=\left[\bar{d}.C_1+\bar{d}'C_2\right]x_m\\ \bar{d}'=1-\bar{d}\end{cases}\tag{4}$$

For a load variation, one replaces respectively A_i,B_i,C_i, by $A_i+\hat{A}_i, B_i+\hat{B}_i, C_i+\hat{C}_i$ in the model (4) (i=1,2), thus the transient state space becomes so:

$$\begin{cases}\dot{\hat{x}}_m(t)=[\bar{A}+(\bar{d}\hat{A}_1+\bar{d}'\hat{A}_2)]\hat{x}_m(t)+[\bar{A}_1+\hat{A}_1-\bar{A}_2-\hat{A}_2]\hat{x}_m(t)\hat{d}(t)\\ \qquad+(\bar{B}_1+\hat{B}_1-\bar{B}_2-\hat{B}_2)\hat{v}_{in}(t)\hat{d}(t)+[\bar{A}_1+\hat{A}_1-\bar{A}_2-\hat{A}_2]\bar{x}\\ \qquad+(\bar{B}_1+\hat{B}_1-\bar{B}_2-\hat{B}_2)\hat{v}_{in}]\hat{d}(t)+(\bar{d}\bar{B}_1+\bar{d}'\bar{B}_2)\hat{v}_{in}(t)\\ \qquad+(\bar{d}\hat{A}_1+\bar{d}'\hat{A}_2)\bar{x}+(\bar{d}\hat{B}_1+\bar{d}'\hat{B}_2)V_{in}\\ \hat{y}_m(t)=[\bar{C}+(\bar{d}\hat{C}_1+\bar{d}'\hat{C}_2)]\hat{x}_m(t)+[\bar{C}_1+\hat{C}_1-\bar{C}_2-\hat{C}_2]\hat{x}_m(t)\hat{d}(t)\\ \qquad+(C_1+\hat{C}_1-C_2-\hat{C}_2)\bar{x}\hat{d}(t)+(\bar{d}\hat{C}_1+\bar{d}'\hat{C}_2)\bar{x}\end{cases}\tag{5}$$

Between nTs and (n+1)Ts, we suppose that $\hat{v}_{in}(t)=0$ and $\hat{r}=0$ then $\hat{A}_i=0, \hat{B}_i=0, \hat{C}_i=0$; after some manipulations, and by neglecting the second order terms in equations set (5), the dynamic state space system around a specified operating point becomes:

$$\begin{cases}\dot{\hat{x}}_m(t)=\bar{A}\hat{x}_m(t)+\bar{E}\hat{d}(t)\\ \hat{y}_m(t)=\bar{C}\hat{x}_m(t)\end{cases}\tag{6}$$

Where:

$$\bar{E}=(\bar{A}_1-\bar{A}_2)\bar{x}+\bar{B}_1V_{in}$$

As shown in Fig.3, the gain of the converter presents a clear nonlinearity, so we will adopt in the next section the TS fuzzy modeling approach to choice local models so that one can determine the local state space (6) in every range of duty ratio.

III. TS FUZZY MODEL OF THE CONVERTER

The Takagi–Sugeno (T–S) fuzzy system provides a general framework to represent a nonlinear plant by using a set of local linear models which are smoothly connected through nonlinear fuzzy membership functions [12];

The fuzzy IF-THEN rules are used to represent the relations in the same manner as given by Takagi and Sugeno for linear relations [8]. The fuzzy system is then of the following form for a nominal value $\bar{d}$ of duty ratio:

$$\text{Rule } i : \text{IF } \bar{d}\in F_i \text{ THEN } \dot{\hat{x}}_m(t)=\bar{A}_i\hat{x}_m(t)+\bar{E}_i\,\hat{d}_i(t)$$

where $i = 1,..,r$ and F_i, is the ith fuzzy set, r is the number of fuzzy rules; and A_i and E_i are system matrices with appropriate dimensions. The final output of the fuzzy system is then given by:

$$\dot{\hat{x}}_m(t)=\sum_{i=1}^{r}\mu_i(\bar{d})\left[\bar{A}_i\hat{x}_m(t)+\bar{E}_i\hat{d}(t)\right]\tag{7}$$

Where $\bar{d}$ is the premise variable; and μ_i is the grade of membership of $\bar{d}$ in F_i. It is assumed in this paper that

$$\mu_i(\bar{d})=\omega_i(\bar{d})\Big/\textstyle\sum_{i=1}^{r}\omega_i(\bar{d})\ ,\ \ \omega_i=\prod_{i=1}^{r}F_i(\bar{d}) \text{ is the number of fuzzy.}$$

Note that $\omega_i=\sum_{i=1}^{r}\mu_i(\bar{d})=1$ for all t,

Where $\mu_i(\bar{d})\geq 0$ are regarded as the normalized weights.

In this type of fuzzy model, local dynamics in different state-space regions are represented by linear models. The overall model of the system is achieved by fuzzy ‘‘blending’’ of these linear models through nonlinear fuzzy membership functions.

In the next section the control design is carried out on the basis of the fuzzy model via the so-called PDC scheme.

IV. CONTROL DESIGN AND STABILITY ANALYSIS

In order to design a global controller for the T–S fuzzy model (7), the PDC technique is adopted in this paper.

The idea of PDC is to derive each control rule so as to compensate each rule of a fuzzy system. The resulting overall controller, which is nonlinear in general, is again a fuzzy ‘‘blending’’ of each individual linear controller. Fig. 4 shows the concept of PDC design. Using the same premise as (7), the ith rule of the fuzzy logic controller (FLC) can be obtained as follows:

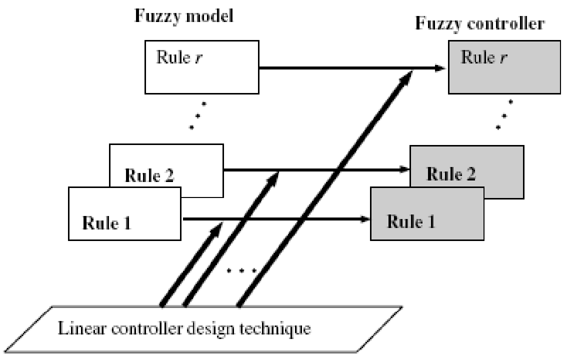


Figure 4. Parallel-distributed-compensation (PDC) design.

Controller Rule i: IF $\bar{d} \in F_i$ THEN $\hat{d}_i(t) = -k_i \hat{x}_m(t)$ (8)

Where k_i is the local feedback gain vector in the ith subspace.

The final model-based fuzzy controller is analytically represented by:

$$\hat{d}(t) = -\sum_{i=1}^{r} \mu_i(\bar{d}) k_i \hat{x}_m(t)$$

The overall closed-loop fuzzy system obtained by combining (7) and (8) as follow:

$$\dot{\hat{x}}_m(t) = \sum_{i=1}^{r}\sum_{j=1}^{r} \mu_i(\bar{d}(t))\mu_j(\bar{d}(t))\left[(\bar{A}_i - \bar{E}_i k_i)\hat{x}_m(t)\right] \quad (9)$$

A sufficient condition that guarantees the stability of the fuzzy system; obtained in terms of Lyapunov's direct method; is given as follows:

Theorem 1 [9]: The equilibrium of fuzzy control system (9) is asymptotically stable in the large if there exits a common positive definite matrix P such that the following two inequalities are satisfied:

$$G_{ii}^T P + P G_{ii} < 0 \qquad \text{for } i=1,..,r; \quad (10)$$

and $$G_{ij}^T P + P G_{ji} < 0 \qquad \text{for } i<j\le r \quad (11)$$

Where: $G_{ii} = (\bar{A}_i - \bar{E}_i k_i)/2$ and $G_{ij} = \left[(\bar{A}_i - \bar{E}_j k_i) + (\bar{A}_j - \bar{E}_i k_j)\right] / 2$

Lemma 1 ([11, 17]): Schur complements). The LMI

$$\begin{bmatrix} Q(x) & S(x) \\ S(x) & R(x) \end{bmatrix} > 0 \quad (12)$$

Where $Q(x) = Q^T(x)$, $R(x) = R^T(x)$ and $S(x)$ depends on x, is equivalent to: $R(x) > 0$;

$$Q(x) - S(x)R^{-1}(x)S^T(x) > 0. \quad (13)$$

In other words, the set of nonlinear inequalities (13) can be represented as the LMI (12).

Remark 1. Theorem 1 can be rewritten into the LMI problem and efficient interior-point algorithms are available in Matlab toolbox to solve this problem. Therefore, equations (10) and (11) are transformed to the LMI by the following procedure.

By introducing new variables, $N = P^{-1}$, $Y_i = G_{ii}N$, and $Y_{ij} = G_{ij}N$. Equations (10) and (11) can be rewritten as follows:

$$Y_i + Y_i^T < 0 \quad (14)$$

and $$Y_{ij} + Y_{ij}^T < 0 \quad (15)$$

Remark 2. By pre- and post-multiplying the set of inequalities (14) and (15) by $N = P^{-1}$, we can obtain the following LMIs which are equivalent to *Theorem 1*.

$$NA_i^T + A_i N - B_i Y_i - Y_i^T B_i^T < 0, \ i=1,2,...,r \quad (16)$$

$$A_i N + NA_j^T + A_j N + NA_j^T - B_i Y_j - Y_j^T B_i^T - B_j Y_i - Y_i^T B_j^T < 0, \ i<j \quad (17)$$

The sate feedback gains have the following expression:

$$k_i = Y_i P^{-1}.$$

V. SIMULATION RESULTS :

This section shows efficiency of designed control system and our design approach through computer simulations, the parameters of the buck-boost converter employed are shown in Table 1; The universe of discourse is chosen as the duty ratio space. It is divided into four subspaces as shown in Figure.5.

$F_1=[0 \ \ 0.25]$; $F_2=[0.25 \ \ 0.4]$; $F_3=[0.4 \ \ 0.65]$; $F_4=[0.65 \ \ 0.85]$.

The converter is characterised by the following parameters:

$V_{in}=15V$, $L=20mH$, $C=47\mu F$, $R=50\Omega$, $R_L=1.23\Omega$, $F_s=1/T_s=10Khz$.

Here, we approximate the converter by the following four-rule fuzzy model:

Rule 1: IF $\bar{d}$ is F_1 THEN $\dot{\hat{x}}_m(t) = \bar{A}_1 \hat{x}_m(t) + \bar{E}_1 \hat{d}_1(t)$;

Rule 2: IF $\bar{d}$ is F_2 THEN $\dot{\hat{x}}_m(t) = \bar{A}_2 \hat{x}_m(t) + \bar{E}_2 \hat{d}_2(t)$;

Rule 3: IF $\bar{d}$ is F_3 THEN $\dot{\hat{x}}_m(t) = \bar{A}_3 \hat{x}_m(t) + \bar{E}_3 \hat{d}_3(t)$;

Rule 4: IF $\bar{d}$ is F_4 THEN $\dot{\hat{x}}_m(t) = \bar{A}_4 \hat{x}_m(t) + \bar{E}_4 \hat{d}_4(t)$;

Where:

$$\bar{A}_1 = \begin{bmatrix} -66.7374301676 & -43.6452513966 \\ 18572.4474028290 & -424.5130834932 \end{bmatrix}; \bar{E}_1 = [6.25 \ \ 0]^T;$$

$$\bar{A}_2 = \begin{bmatrix} -65.5403032721 & -33.6691939346 \\ 14327.3165678966 & -424.5130834932 \end{bmatrix}; \bar{E}_2 = [16.25 \ \ 0]^T;$$

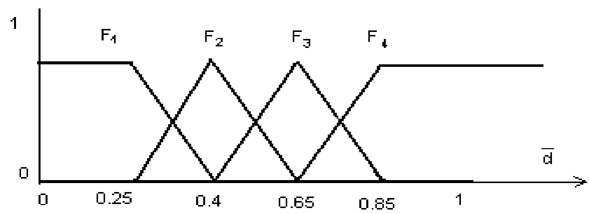


Figure 5. Membership functions

$$\bar{A}_3 = \begin{bmatrix} -64.3431763767 & -23.6931364725 \\ 10082.1857329643 & -424.5130834932 \end{bmatrix}; \bar{E}_3 = [26.25 \quad 0]^T ;$$

$$\bar{A}_4 = \begin{bmatrix} -629.9640861931 & -124.7007182761 \\ 53064.1354366542 & -4245.1308349323 \end{bmatrix}; \bar{E}_4 = [37{,}5 \quad 0]^T ;$$

It is able to test that the subsystem $(\bar{A}_i, \bar{E}_i)$ is controllable. i=1,2,3,4.

To validate our TS fuzzy model, we introduce in open loop, a duty-cycle step positive and negative changes (2%) around the following steady points:

- $\bar{d} = 0.4$ where $y_m = 9.34v < Vin$.
- $\bar{d} = 0.6$ where $y_m = 19.44v > Vin$.

Figure.6.a and Figure.6.b shows the response of both TS fuzzy model treated in section III, and detailed one presented in section II (from (1.1) to (1.6)); one can clearly notice the good precision of this model in both cases:

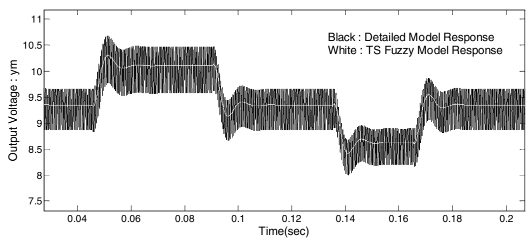
- When the converter works as buck ($\bar{d} = 0.4$).
- When the converter works as boost ($\bar{d} = 0.6$).

Now, a controller is constructed on the basis of the procedure in Section IV. Consequently, let us take an equilibrium points of the duty cycle and state $\bar{d} = 0.7$, $\bar{x}$ = [1.83A 27.48v], $\bar{y}$ = 27,48v.

Based on Theorem 1, the common positive definite matrix P and K_i gains (i=1..4) are obtained by LMI optimization algorithm in Matlab toolbox:

k_1=[1658.1042 -11.8959], k_2=[1191.3216 -10.4281], k_3=[921.848 -9.5056], k_4=[719.5195 -8.9509],

(a)



(b)

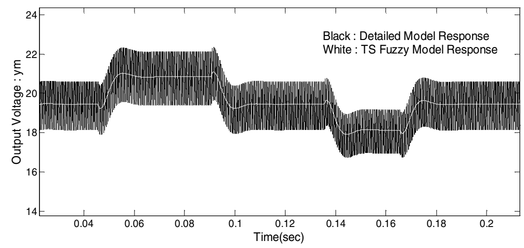


Figure 6. Output voltage response for a duty-cycle step positive and negative changes (2%) around : (a) $\bar{d} = 0.4$. (b) $\bar{d} = 0.6$

$$P = \begin{bmatrix} 1750.2947 & -22.7495 \\ -22.7495 & 0.0173581 \end{bmatrix}$$

Therefore the duty cycle is set to be:

$$u = \bar{d} - \left(\mu_1(\bar{d})k_1 + \mu_2(\bar{d})k_2 + \mu_3(\bar{d})k_3 + \mu_4(\bar{d})k_4\right)\hat{x}_m(t)$$

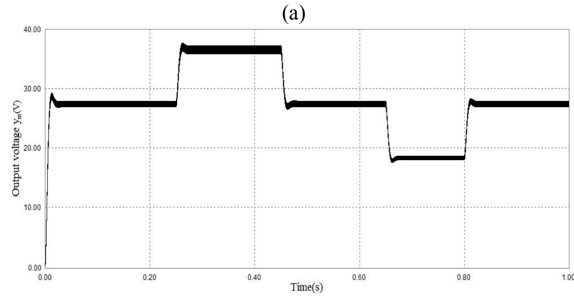
In order to test the performance of the buck-boost converter driven by the proposed controller, variations of line voltage and load are considered. The results simulated by MATLAB and PSIM are shown in Fig8. and where the load changes from 50 Ω to 100Ω at 0.25 s, and backs to 50Ω at 0.45s, then decreases to 25Ω at 0,65s and returns to 50 Ω at 0.8s. In Fig. 9, the line voltage changing from 15V → 20V → 15V → 10V → 15V at 0.25s, 0.45s, 0.65s, 0.8s respectively is considered.

Compared to Fig.7 where the same variations of input voltage and load were made in open loop, Fig.8 and Fig.9 illustrate that the proposed controller is able to regulate satisfactory the output voltage for different load or input voltage changes.

VI. CONCLUSION

In this paper, a Fuzzy Control of Dc-to-Dc Converters using T-S Fuzzy Modeling Approach is presented; in the design procedure, the converter is modeled by a family of local state space models with the duty cycle as premise variable, thus, a global fuzzy logic controller is constructed by aggregation of all local state feedback controllers according to the PDC approach. The local gains used for state feedback controllers are dimensioned via the LMI technique. A stability criterion in terms of Lyapunov's direct method is proposed to guarantee the stability of the fuzzy system.

(a)



(b)

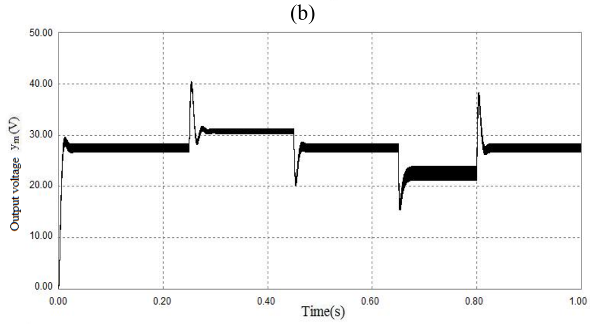


Figure 7. The opened loop response of the converter subject to (a) a load changing from 50Ω→100Ω→50Ω→25Ω→50Ω, and (b): a line voltage changing from 15v→20 v→15v→10v→15v

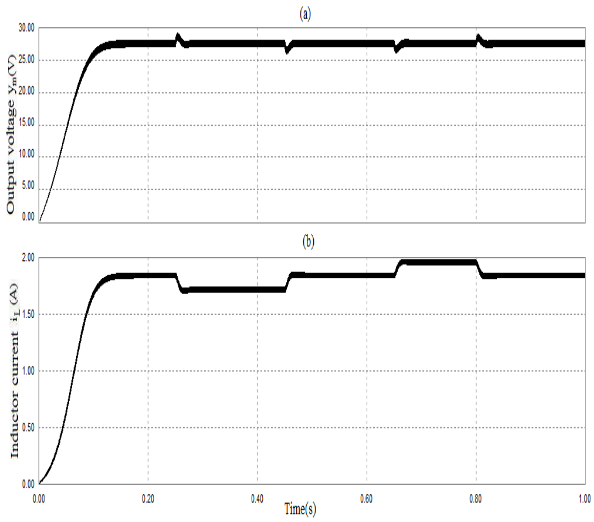


Figure 8. The closed loop response of the converter subject to a load changing from 50Ω→100Ω→50Ω→20Ω→50Ω (a): output voltage, (b): inductor current

The satisfactory simulation results further reveal the validity of the proposed approach.

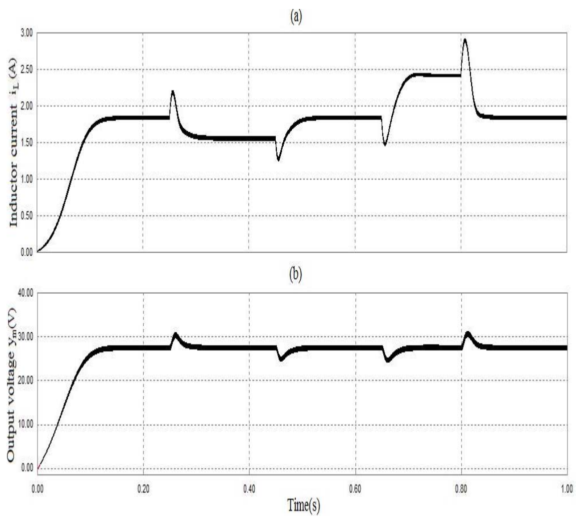


Figure 9. The closed loop response of the converter subject to a load changing from 15v→20v→15v→10→15v (a): inductor current, (b): output voltage

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