A SIMPLE MODEL ESTIMATOR FOR MULTIPLE MODEL CONTROL. BUCK DC-DC CONVERTER APPLICATION

Dominique Alejo, Pascal Maussion, Jean Faucher

Abstract-- ***This paper describes a simple model estimator for a new control method based upon algorithms commutation between two linear control laws. The multiple model control (MMC) defined is based upon the fusion of only two traditional IP controllers outputs. The influence of the digital integration methods and of the noise are pointed out. This new strategy improves the performances of the step input responses for different loads on a buck dc/dc converter.***

Index Terms-- ***Industrial power system control, Multiple Model Control, Fusion, dc/dc converter, estimator***

I. INTRODUCTION

The object of this article is not the development of a new method for Buck chopper control because fast, appropriate but analog control circuits already exists. We would rather focus on a special indicator principle and performances, used for an original multiple model control : how to improve the global performances by a progressive mixture of two very simple controllers, when the system turns from one state to another ? Very few works deal with this problem [1], [2], while fuzzy logic certainly gives the opportunity to combine various laws for the same system [3], [4], [5]. So, based upon the fuzzy logic principles (membership functions), this work presents, a very simple fusion of two traditional control laws with supervision, in order to improve the dynamic performances.

II. CONTROL PRINCIPLE

A. The basic idea

Controller tuning is easy when the system parameters and structure remain constant but it becomes rather difficult for non stationary systems. So, the basic idea is to mix two simple controllers, both tuned for a specific set point. Then, the resulting controller will provide soft fusion between two linear control laws and increase the performances.

Laboratoire d'Electrotechnique et d'Electronique Industrielle de Toulouse
Unité Mixte de Recherche INPT-ENSEEIHT/CNRS n°5828
BP 7122- 2, rue Camichel – 31071 Toulouse Cedex 7 – France
maussion@leei.enseeiht.fr, alejo@leei.enseeiht.fr, faucher@leei.enseeiht.fr
http://www.leei.enseeiht.fr

B. Buck model example

Depending on the load, the non reversible buck dc to dc converter could have different equivalent average models during its operation [6]. As the converter is used in current mode control, the current mode loop is implemented on an analog board and then could be considered as a very "fast" system with respect to the voltage loop. The following equations (1) to (4) describe the continuous current mode (with maximum load) and the discontinuous current mode (no load).

$$\frac{Vs(p)}{Il(p)} = \frac{R}{(R.C.p+1)} \quad (1) \qquad \frac{Vs(p)}{Il(p)} = \frac{\sqrt{R}.A}{(R.C.B.p+1)} \quad (2)$$

$$\text{with : } B = \frac{1-\dfrac{Vs}{E}}{2-3.\dfrac{Vs}{E}} \quad (3) \qquad \text{and } A = \frac{\sqrt{2.L.f.\left(1-\dfrac{Vs}{E}\right)}}{2-3.\dfrac{Vs}{E}} \quad (4)$$

It can be seen that although the load is a simple but time varying resistance, the problem is not so simple because system model and parameters are not constant and simultaneously change. A measurement filter makes the system become a 2° order.

C. Classical control

In industrial applications, classical controllers are PI, IP or PID. In our case we use an IP controller, first based upon PI (5) and (6) with a reference filter (7) :

$$u(t) = k_p e(t) + \frac{k_p}{k_i}\int e(t)dt \quad (5)$$

The IP controller is tuned for 3 ms response time and 0.7 for damping factor.

$$\frac{Ilref\ (p)}{e(p)} = \frac{Kp.(Ki.p+1)}{Ki.p} \quad (6) \qquad \frac{Vs_f(p)}{Vs_{ref}(p)} = \frac{1}{Ki.p+1} \quad (7)$$

Because gain and time constant of the model both change with the resistive load, the set of parameters obtained for a specific resistor value is not appropriate for another and the desired features are not respected. Then, for a single IP controller with fixed parameters, robustness will be poor, mainly because the load resistor have significant influence on the output behaviour.

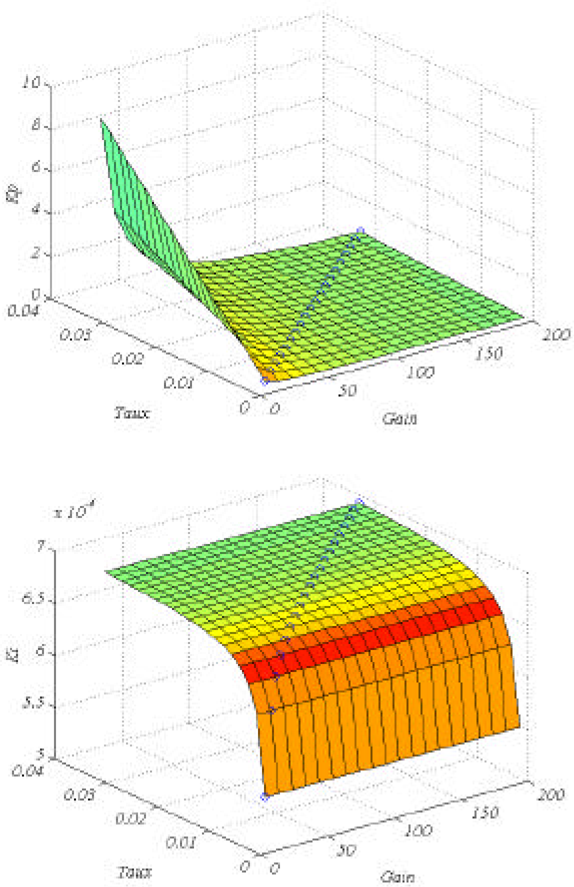

Fig. 2 and 3. Control parameters variations versus gain and tim e constant

To illustrate these control parameters dependence versus the system parameters, figures 2 and 3 show the appropriate parameters K_p and K_i for IP control if the gain and time constant of the system model separately change. But, a special attention should be paid to the particular case of load resistor variation on the buck converter. In this particular type of system, the gain and time constant have non linear and coupled variations. The surfaces for K_p (and K_i) becomes non linear curves, marked by the "o" symbols on figure 2 and 3.

D. *Multiple model control*

1) *Multiple Model Control (MMC) principle*

The MMC principle is shown on figure 4. Two controllers C_1 and C_2 have to cooperate to provide the best control action u for improved performances.

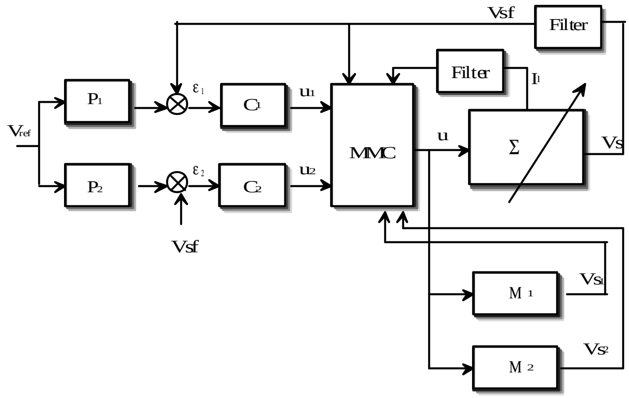

Fig. 4. Bloc diagram of the Multiple Model Control

The controller C_1 is tuned for maximum load conditions (R_2 // R_1) and C_2 is tuned for no load conditions (R_2 disconnected). Two models have the same control signal than that of the system, in order to generate Vs_1 and Vs_2, models outputs. One of the aims is simplicity, so only two system models are taken into account in this control law. It will be shown that despite this raw information on the system, performances are rather good.

2) *A specific integral action*

A specific integral action is used in this multimodel controller to avoid control signal strong discontinuity, that is to say the reference current. This principle is based on anti-windup method. Thus integral action is calculated not according to the reference current delivered by the regulator to which it belongs, but from the two fusion regulators current reference, Fig.5. We already used this principle in another type of controllers fusion between a bang-bang and a PI controller to avoid chattering between the two regulators.

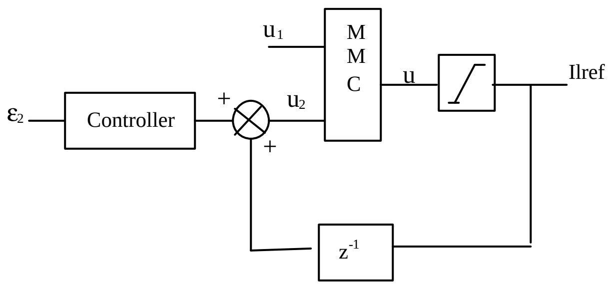

Fig. 5. Specific integral action

3) *Fusion control*

The principle of fusion control is very simple. At each sampling instant, C_1 and C_2 controllers give a control action u_1 and respectively u_2 that are mixed to compute the right and optimal value u. The following equations explain the fusion control principle, how to get the control voltage u, from the distances between the actual output voltage of the system V_S and the output of model 1, namely V_{S1} and the output of model 2, V_{S2}.

$$d_i = |Vs - Vs_i| \quad (8)$$

$$Fa_1 = 1 - \frac{d_1}{d_1 + d_2} = \frac{d_2}{d_1 + d_2} \quad (9)$$

$$Fa_2 = 1 - \frac{d_2}{d_1 + d_2} = \frac{d_1}{d_1 + d_2} \quad (10)$$

$$u = \frac{u_1.Fa_1 + u_2.Fa_2}{Fa_1 + Fa_2} = \frac{u_1.d_2 + u_2.d_1}{d_1 + d_2} \quad (11)$$

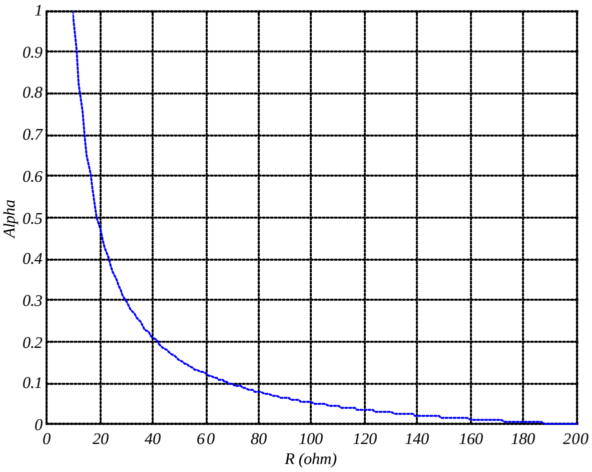

Fig. 6. Theoretical weighting factor between controllers C_1 and C_2

The theoretical weighting factor (alpha) between the two controllers C_1 and C_2 could be calculated, in order to give an equivalent optimal IP controller. The corresponding relationship between alpha and the resistor value is plotted on figure 6. It can be seen that for R=10 Ω, alpha is "1" that is to say that the system is completely model 1. For R=20 Ω, alpha is 0,5, because the system is half model 1 and half model 2.

For the choice of the two models, a special attention should be paid to the behaviour during the transients. When the load is disconnected, the inductor current remains different from zero for quite a long time and the discontinuous current mode and model, should not be used. Then, the continuous current model is still active but with the no-load parameters. When the inductor current finally reaches the discontinuous mode :

- the time response is almost over, so the unadapted time constant is no longer a problem,
- there is no steady state error due to the integral action althought the wrong gain value.

4) First simulation results

Simulation results are obtained from Matlab-Simulink™ softwares, using S-functions to generate control signals, experimental results are given in part 5. A triple test benchmark is used for each of the 3 control laws :

- nominal load step start, no-load regulation (at t_1=35 ms), nominal load regulation (at t_2=70 ms),
- half nominal load, no-load regulation (at t_1=35 ms), nominal load regulation (at t_2=70 ms),
- no-load regulation.

A special study case is presented hereafter. Fig 7 shows a very theoretical behaviour, assuming that load value and load commutation instants are perfectly known, which is impossible. This study case put in evidence the theoretical very best performances for this strategy.

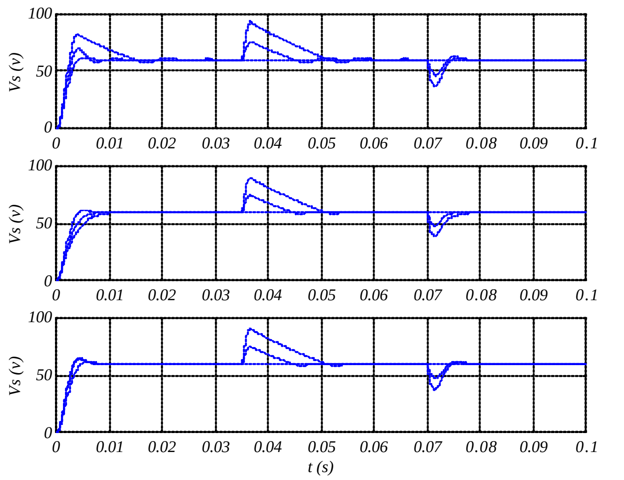

Fig. 7. Output voltage for Vs_{ref} = 60 v with IP_1 controller alone (upper), with IP_2 controller alone (middle), theoretical MMC (lower)

The advantages of this control strategy appear on figure 7, where the output voltage behaviour is almost the same for different loads.

This behaviour can also be red in table 1, where the time response and overshoot values are improved from IP_1 or IP_2 correctors with respect to MMC. But the main advantage lies in the fact that these performances remain constant despite the load variations.

TABLE 1 : PERFORMANCE MEASUREMENTS WITH STEP INPUT FOR DIFFERENT LOADS DURING STEP INPUTS

60 v set point	Type of controller	Step input for different loads 10 Ω	20 Ω	200 Ω
Response time 5% (ms)	IP1	3.35	5.35	8.7
	IP2	7.8	6.5	3.1
	MMC	**3.5**	**3.2**	**3.1**
Overshoot (%)	IP1	2.5	11.33	24.17
	IP2	0	0	1.67
	MMC	**1.67**	**1.8**	**1.33**

But this study case is only theoretical and there is a need for a special indicator able to estimate how much the system looks like one model or another. The principles for this model membership degree estimation are presented hereafter.

III. Model Estimator

A. *Model detection*

A special procedure is defined to compute the model membership function degree, to check if the system looks like model 1, model 2 or none. At each sampling period, the four previous points (V_s, Il_{ref}) are kept in memory and compared to the results of model 1 and model 2 simulated behaviours. The result is the distances between the system and the two models, that is to say the membership function activation degree, d_1 and d_2 at k sampling instant and at k+1 sampling instant, cf figure 8.

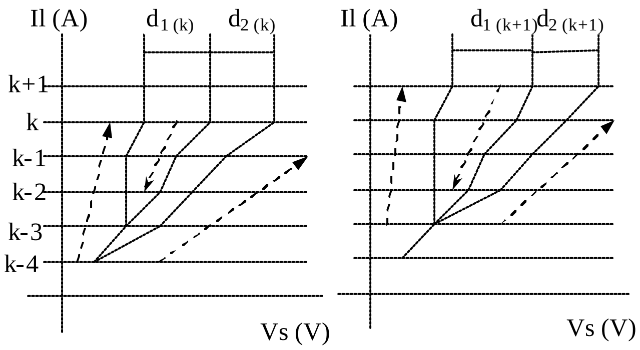

Fig. 8. Model detection principle.

Figure 8 shows the model on line detection principle with the 4 last points, but a reduced number of points could be sufficient under special conditions as it will be shown hereafter. The influence of the number of points, depending on the circumstances will be checked in the experimental results section.

This method looks like an internal model control or behaviour model control [7], but is rather different because there are 2 different models and 2 different controllers, mixed from the model membership function degrees. There is no need for adaptive gains, always difficult to set.

Simulation results are given on figure 9. They are worse than that of the theoretical study case on figure 7, but they put in evidence some performances improvement with respect to IP controllers, under the same conditions. It could also be seen on figure 10 that the membership function activation degree, how much the system looks like one model or the other, is correct. For example with 10 Ω, model 1 degree is almost 1 and model 2 degree is almost 0.

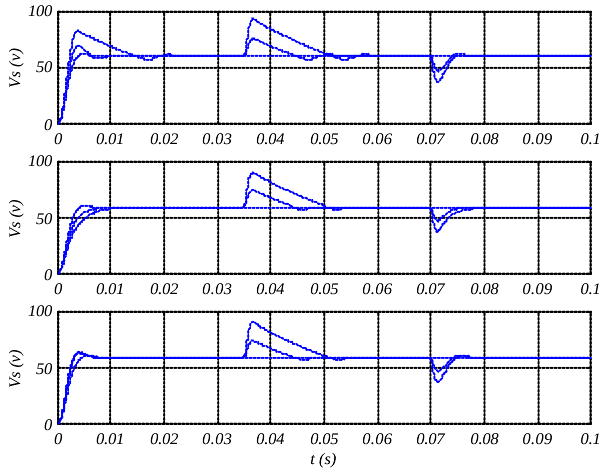

Fig. 9. Output voltage for Vs_{ref} 60 v with IP_1 controller alone (upper), IP_2 controller alone (middle), MMC (lower) with estimator

The differences between the theoretical value (1 for model n°1) and the actual value are due to the difference between the average model and the real system operating with an internal current mode control.

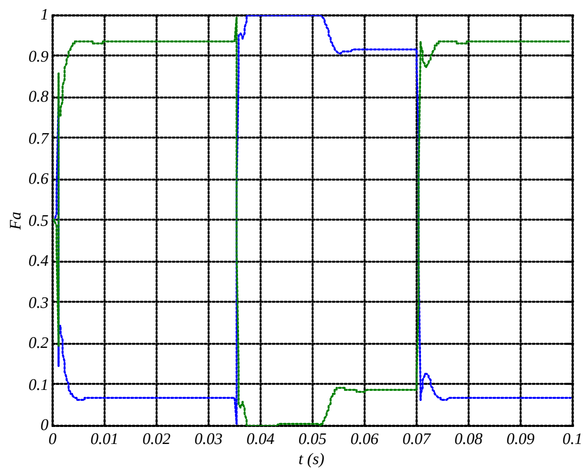

Fig. 10. Corresponding membership function activation degrees for time varying load=10-200-10 Ω

IV. Experimental Results

A. *Influence of the digital integration method.*

A first test on the benchmark is run to put in evidence the global performances and the digital integration method influence.

The experimental behaviour on figure 11 is quite similar to simulations shown on figure 9 and no noticeable difference between the two digital integration methods could be pointed out. As the backward rule is simpler and faster to compute, this method will be used for the following experimentations. Our investigations will then focus in this last part, on the on-line estimator properties.

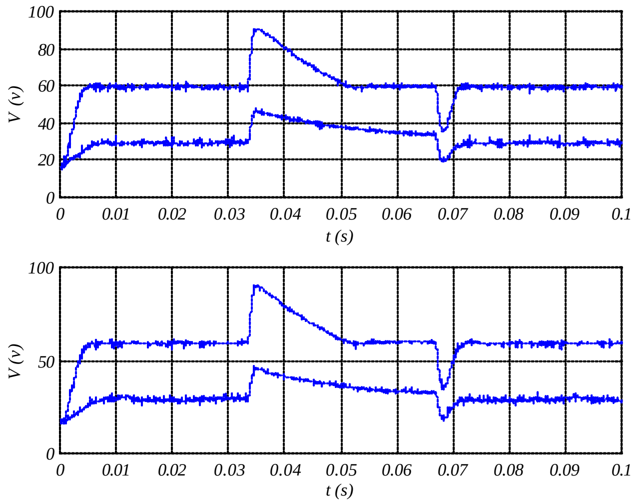

Fig. 11. Output voltage for Vs_{ref} = 30v and 60v through the MMC with model estimator for backward rule (upper curve) and zero order hold (lower curve)

B. *Influence of the number of points*

It was supposed that the estimator performances could depend on the number of points taken into account. At least, two points are necessary and sufficient to compute the model membership degree when noise level is not high.

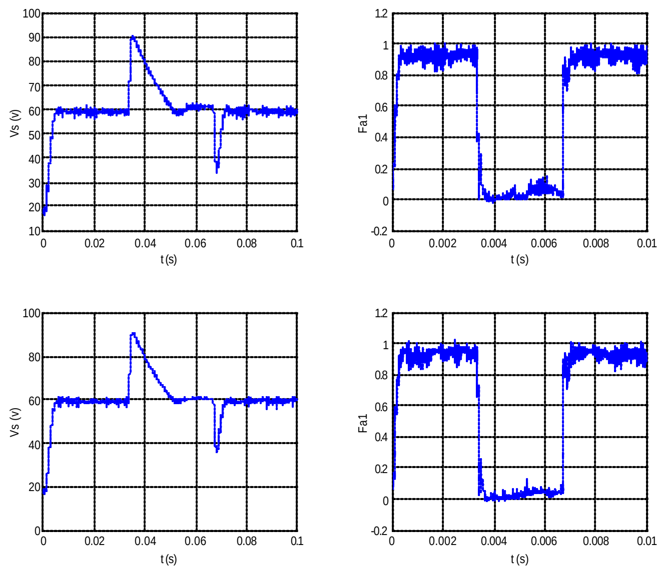

Fig. 12. Output voltage with 2 points (upper), and 3 points (lower) for model detection

In our experimental conditions, choosing two or three points do not make any difference on the global performance, figure 12. It could be different when the noise level increases, but using only two points instead of three or four, will allow a shorter computation time.

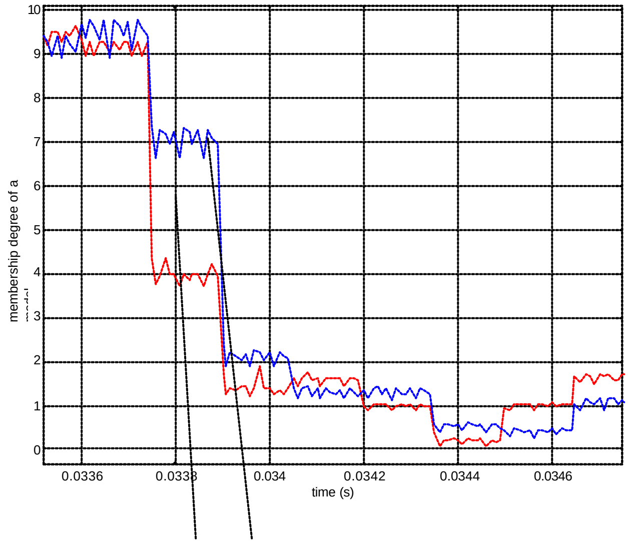

Fig. 13a. With only two or three points, zoom on the model estimator during load connection

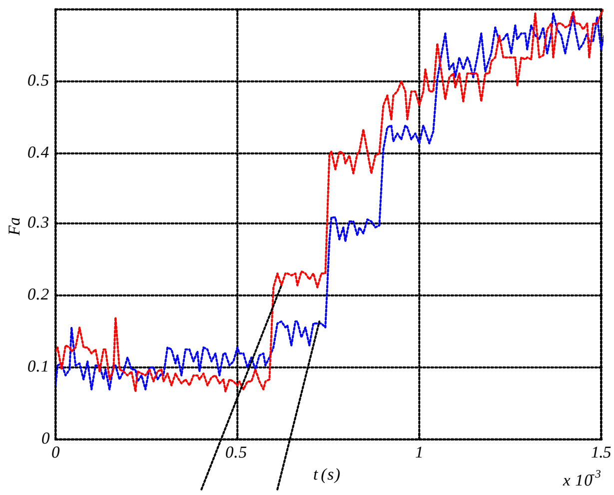

Fig. 13b. With only two or three points, zoom on the model estimator behaviour during step start.

It is necessary to zoom on transients to put in evidence the slight influence of the number of points on the model estimator, figure 13a (load connection) and figure 13b during start step. Finally, the minimum number of points will be used to compute the estimator because the improvement is not significant for a larger number of points.

C. *Influence of the noise*

Whatever the performances and the advantages of the MMC should be, the system has to be robust versus noise, that is to say, remain insensitive to noise level as far as possible.

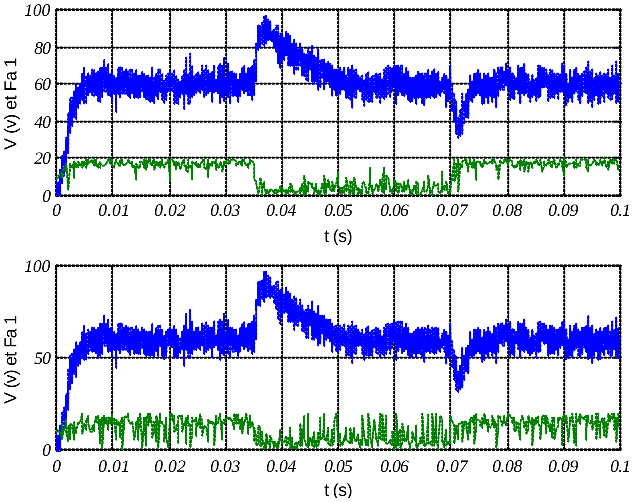

Fig. 14. Output voltage and model detection with 4 points (upper plots, and 2 points (lower plots)

A white noise 5.10^{-4} as noise power) is added on the measured signal. The results with 2 and 4 points are drawn on figure 14. At last, the maximum acceptable noise power depends on the number of points and reciprocally. With only two points to compute the model membership function degree, the behaviour is correct up to 10^{-5}. With four points, this upper limit is 10^{4}, that is to that the number of points must increase with the noise, to ensure a constant performances level.

V. CONCLUSION

This objective of this work was to propose a new and original method to mix two simple and linear controllers, in order to obtain a better control law and improve performances. The Multi Model Control strategy presented in this paper is efficient either on reference changes during step input or during load variations. But a specific procedure, the model estimator, is necessary for on line determination of what model the system looks like, without any adaptive gains. The membership function activation degree gives good performances with simple digital integration method and a reduced number of points, involving a reduced computation time. The whole system could increase its performances using a combined approach, between this work and the soft switching strategy given in [3].

VI. REFERENCES

[1] Bühler,H. (1986). "Réglage électronique de commande", Presses Polytechniques Romandes, Lausanne, Suitzerland

[2] L.Dubois, F.Delmotte, P.Borne (1996), « A general scheme for multi-model controller using trust », Mathematics and computers in simulation, volume 41, Issues 1-2, june 1996, pages 173-186

[3] Alejo, D., Maussion, P., Faucher, J. (2001). "Control laws soft switching for a dc/dc converter", presented at European Power Electronics, EPE'01, Graz, Austria

[4] Berthereau, F., Robyns, B., Hautier, J.P. (1999). "Orientation du flux par estimateur à structure variable avec superviseur à logique floue dans la commande vectorielle indirecte du moteur asynchrone", Electrotechnique du Futur Lille 1999, France

[5] Hissel, D., Maussion, P., Faucher, J. (1999). "Speed Ripples reduction of anon linear loaded synchronous motor trough fuzzy algorithm commutation", ISIE'99, Bled, Slovenie

[6] Ferrieux, J.P., Forest, F. (1996) "Alimentation à découpage, Convertisseurs à résonance", Editions Dunod, Paris, France,

[7] B. Vulturescu, A. Bouscayrol, J.P. Hautier, X. Guillaud, F. Ionescu, "Behaviour model control of a DC machine", *ICEM'2000*, Espoo, August 2000, vol. 1, pp 427-431, Finland.

APPENDIX

The system under control is a 1 kW non-reversible Buck dc to dc converter presented on figure 15.

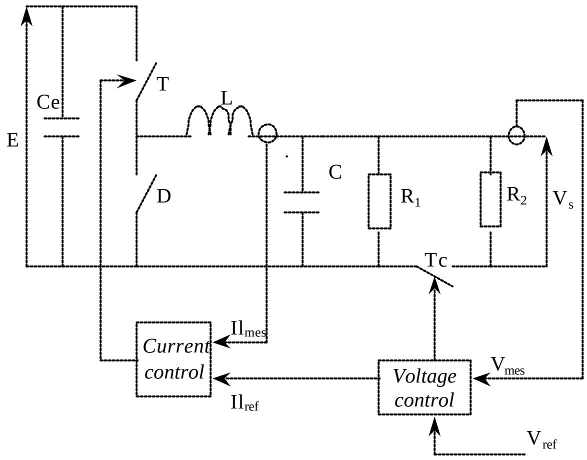

Fig. 15. DC to DC converter

Switching frequency = 20 kHz, t_{on} min = (2.5 µs)

Output filter : L=2.23 mH, C=165 µF, R_1=200 Ω

Load is a variable resistor R_2=10 Ω

Power supply = 200v Input filter C_e=1 µF

Maximum inductor current = 10 A

The control algorithm is implemented in a DSP TMS320C31 on a DS1102 board from Dspace™

Sampling frequency = 6.6 kHz

Measure filter = 500 Hz.