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# Associative methods for dc/dc power electronics control

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**Keywords** : Controller combination, Fuzzy control, Converter control, Multiple Model Control, Fusion, dc/dc converter,

**Summary** : *This paper describes two different control principles using simple combinations between basic control laws. The objective is to improve the performance (time response, overshoot, robustness...), without strongly increasing the complexity. These principles are tested on a dc-dc power converter. Linear and/or non linear controllers are mixed depending on the optimisation objective and on the decision data. The basic idea is that in the world of control, as elsewhere, “unity is strength”, i.e. complex functions could be carried out through basic object combinations.*

*The first principle is based on the combination of two linear controllers. Only two models of the system are taken into account in this Multi Model Control (MMC) method. A new and specific procedure for model validity is put forward. It is based on the distance between two extreme models of the controlled system, with unknown severe disturbances. The second principle suggests the combination of a linear controller and a non-linear controller (a Bang Bang and an Integral and Proportional controller). This combination is created through the fuzzy fusion of state variables. The tuning of the fuzzy logic parameters is made through Hooke and Jeeves optimisation procedure.*

*The performance is verified through experimental results on a dc/dc converter application. They are significantly improved with respect to standard controllers, with only one voltage sensor and without any adaptive gains.*

## Introduction

As many systems have variation parameters, robust controllers are often necessary to achieve good performance. To improve robustness, many different approaches have already been presented such as adaptive control or non linear control. Our contribution lies in the field of non linear control, but with a highly specific approach that combines basic controllers.

We often have to face a dilemma with regard to control. On the one hand, PI controllers are simple but not very robust and on the other hand, robust controllers could achieve better dynamic performance, but they are often much more complex. Therefore, the objective of this paper deals with basic controller combination in order to take advantage of their simplicity and at the same time, increase robustness. Simplicity will remain one of our guidelines, in order to allow the implementation in basic microcontrollers such as in [1]. The object of this paper is not specifically the development of new methods for dc/dc converter control, but rather the presentation of original a control principle: how can the dynamic performance and the robustness be improved by a progressive combination of two controllers ? Few papers deal with this idea, but some elements can be found in [2] and [3]. Previous contributions in this field will be explained in detail hereafter, with respect to this work.

## The principles for control algorithm combination

A schematic presentation of the different functions involved in the complete control system, is shown in Fig. 1, where several functions and objects are clearly identified. Their combination and classification is the subject of this first introductive part.

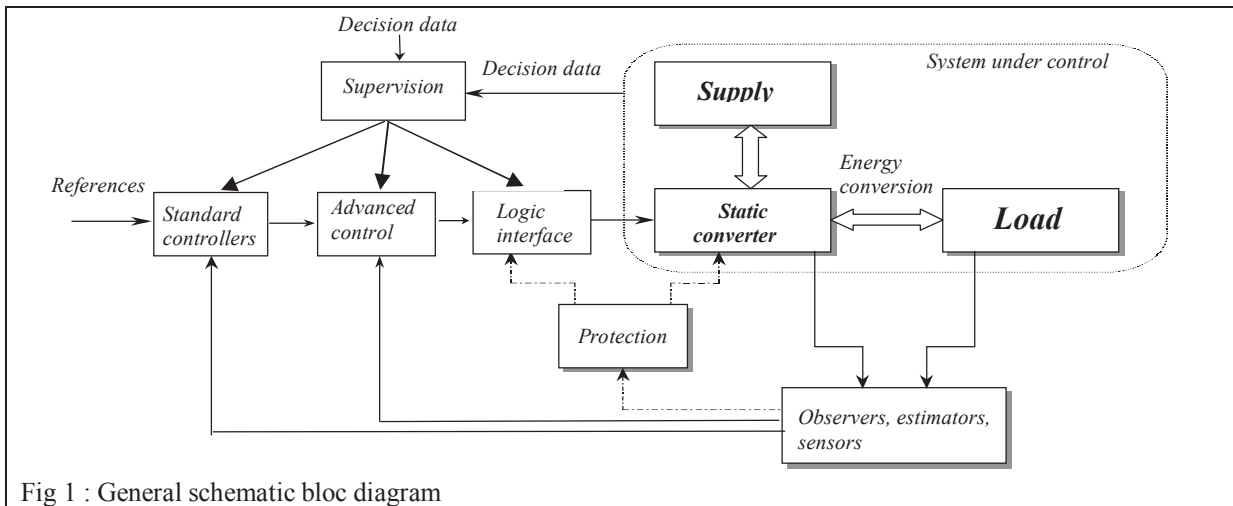


Fig 1 : General schematic bloc diagram

For all the objects involved in Fig. 1, Table 1 suggests a classification as to it is a desired combination or a forced combination :

- In railway systems, the change from one PWM pattern to another is absolutely necessary because of the maximum switching frequency [4], this is an example of a forced combination,
- Estimators and observers can be associated, in order to improve the flux estimation in an induction machine control [5], [6], this is an example of a desired combination,
- Advanced control laws (DTC, FOC...) could be combined to improve performance (desired combination) or because it is absolutely necessary, (forced combination), for example when data comes close to 0 in a decoupling control law that takes the inverse of this data into account.

	desired combination	forced combination
<b>Standard controllers ( PI, PID...)</b>	x	
Advanced controllers (DTC, Vector control...)	x	x
Logic interface (PWM patterns, dead times...)		x
Observers, estimators	x	

Table 1 : Object classification versus combination type

Our work will especially deal with controller combination, linear and/or non linear controller desired combination. A specific supervision will combine basic controllers, with a performance increase and/or a robustness objective. Whatever the controller or the decision data, the principle for two controller combination is illustrated on Fig. 2.

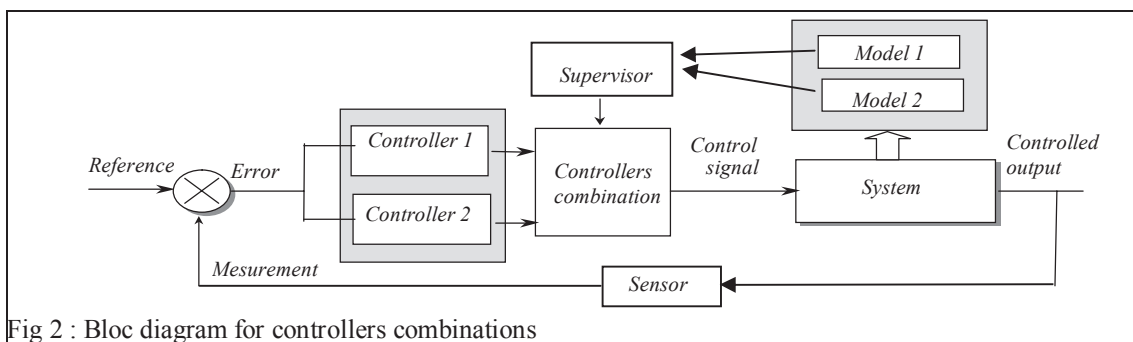


Fig 2 : Bloc diagram for controllers combinations

Among the different control strategies for drives, fuzzy logic is an interesting solution [7], [8]. It could particularly be used to achieve interesting performance with several dc/dc converters such as buck, boost... with low computation time [1] or with dedicated look-up tables [9]. Many fuzzy controllers had already been proposed but fuzzy logic also gives the opportunity to combine various control laws for the same system. One long-standing solution consist of two separate fuzzy rule tables, one coarse and one fine [7] but this solution is rather complex. On the other hand, [10] combines two different fuzzy controllers through a supervisory layer, for the control of power networks, but with five rule tables. Furthermore, [11] deals with the fusion of 2 controllers such as sliding mode and state feedback controller while [12] combines a sliding mode and PI controller but with 7 parameters to tune. At least [13], [5] combine two different flux observers for an induction machine. We assume that for systems

where a basic controller is generally used, a suitable combination of two simple controllers increases dynamic performance and robustness versus parameter variations. Two types of basic controller combination will be set out:

- First, a linear controller combination is a Multi Model Control system [13], [14]. Its principle is based on model validity as decision data, i.e. how much the system resembles one of its models or the other. We will take only 2 extreme models into account, corresponding to the limits of the parameter variations. Linear controller 1 corresponds to model 1 and linear controller 2 is associated to model 2. Details are given on the special indicator principle, i.e. the special procedure which is defined to compute the activation of the model membership function.
- The second controller combination is set out on the system's behaviour. The decision data is state variables used to combine a non linear and a linear controller.

In part 3 and 4, this work presents two simple fusions of two simple controllers under supervision, in order to improve the dynamic performance. Our paper put in evidence interesting experimental results on a dc/dc converter with only one voltage sensor, for both associative principles with time variation parameters.

### Application to a dc/dc power converter control

The system under control for the validity test of the first and the second controller combinations is a 1 kW dc/dc Buck converter with time variation parameters, Fig. 3. Classical controllers (PI, IP or PID) are often used for such power electronic converters. Most of the time, the set of controller parameters obtained for a specific load resistor value is not appropriate for another load and the requirements are not respected. Thus, the control is not very robust, as the equivalent resistor has significant influence on the output voltage. Moreover, depending on the load variations in Fig. 4, ( $R_1=200\ \Omega$  down to  $R_2=10\ \Omega$ ), the non reversible buck dc/dc converter has different equivalent average models during operations. Equations for the continuous current mode (1) and for the discontinuous current mode (2)(3) and (4), with A and B parameters depending on the output voltage  $V_s$  are listed hereafter, with  $R = R_1$  (light load) or  $R = R_1//R_2$  (nominal load).

$$\frac{V_s(s)}{I(s)} = \frac{R}{(R.C.s + 1)} \tag{1}$$

$$\frac{V_s(s)}{I(s)} = \frac{\sqrt{R}.A}{(R.C.B.s + 1)} \tag{2}$$

$$\text{with : } B = \frac{1 - \frac{V_s}{E}}{2 - 3 \cdot \frac{V_s}{E}} \tag{3}$$

$$\text{and } A = \frac{\sqrt{2.L.f. \left(1 - \frac{V_s}{E}\right)}}{2 - 3 \cdot \frac{V_s}{E}} \tag{4}$$

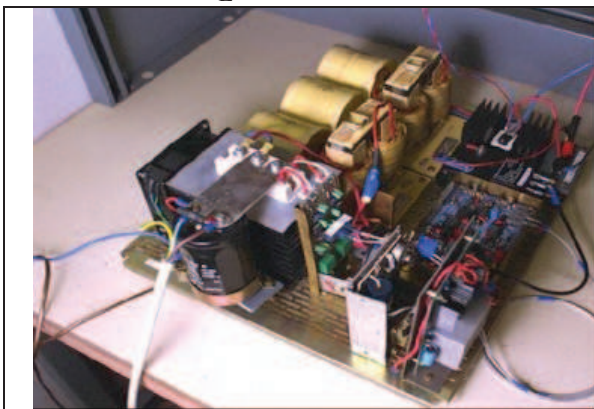


Fig. 3 : Photo of the DC/DC converter  
 Power supply = 200v; Input filter  $C_e=1\ \mu\text{F}$   
 Maximum inductor current = 10 A  
 Sampling frequency = 6.6 kHz

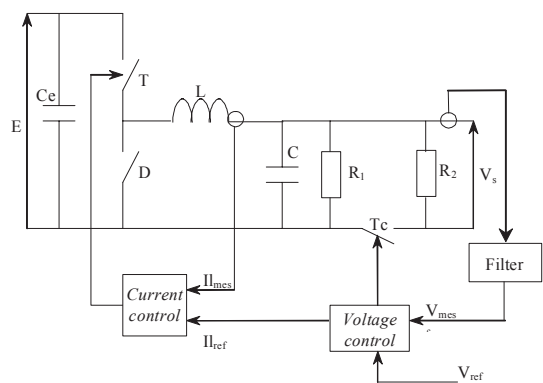


Fig. 4 : DC/DC converter  
 Switching frequency = 20 kHz,  $t_{on\ min} = (2.5\ \mu\text{s})$   
 Output filter :  $L=2.23\ \text{mH}$ ,  $C=165\ \mu\text{F}$ ,  
 $R_1=200\ \Omega$ ; The load is a variable resistor  $R_2=10\ \Omega$

As a measurement filter is added to avoid noise, the system becomes second order with a sampling period time delay. The load is a simple but also a time variation resistor. However, the problem is not so simple because the system model and parameters simultaneously change, particularly during discontinuous mode. For example, when the load resistance switches from  $R = R_1 = 200 \Omega$  to  $R = R_1 // R_2 \neq 10 \Omega$ , the gain in (1) suddenly becomes 20 times higher and the time constant in (1) changes from 1.65 ms to 33 ms. It is important to notice that these important parameter variations are due to the power converter itself, that they cannot be anticipated and occur very rapidly.

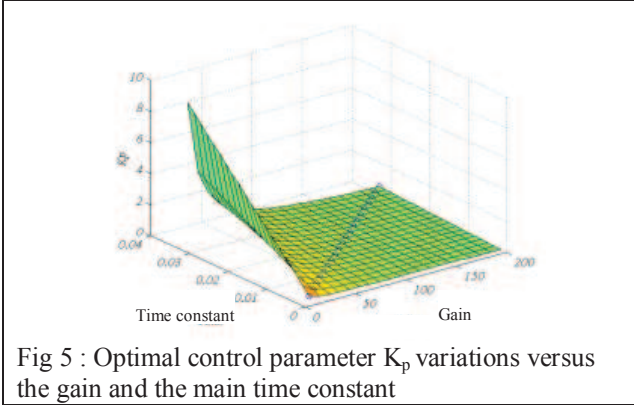


Fig 5 : Optimal control parameter  $K_p$  variations versus the gain and the main time constant

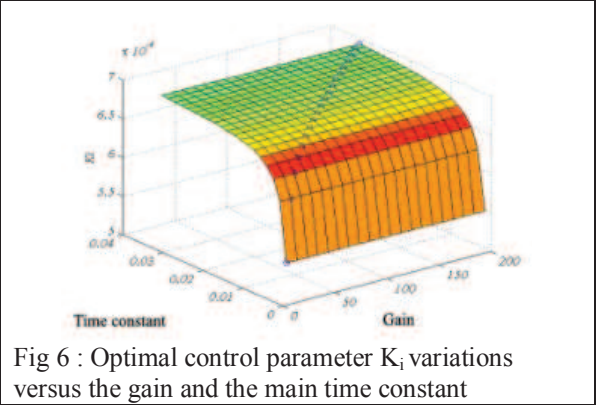


Fig 6 : Optimal control parameter  $K_i$  variations versus the gain and the main time constant

To illustrate this control parameter dependence versus the system parameters, Fig. 5 and 6 show the appropriate parameters  $K_p$  and  $K_i$  for an IP controller tuned by pole placement. When the gain and the time constant of the system model such as in (1) both change during the load resistor variation, optimal controller parameters have to be tuned according to Fig. 5 and 6.

**Linear controller combination through Multi Model Control on the dc/dc converter**

**Multiple Model Control (MMC) principle**

Our first solution is based on the Multi Model Control as shown in Fig. 7, where two basic and linear PI controllers  $C_1$  and  $C_2$  have to cooperate for the optimal performance. In this example, both controllers are IP controllers, implemented as PI inside the loop and reference filters for zero cancellation, tuned for 3 ms response time and 0.7 = damping factor.  $C_1$  is for maximum load and  $C_2$  is for no load, [16].

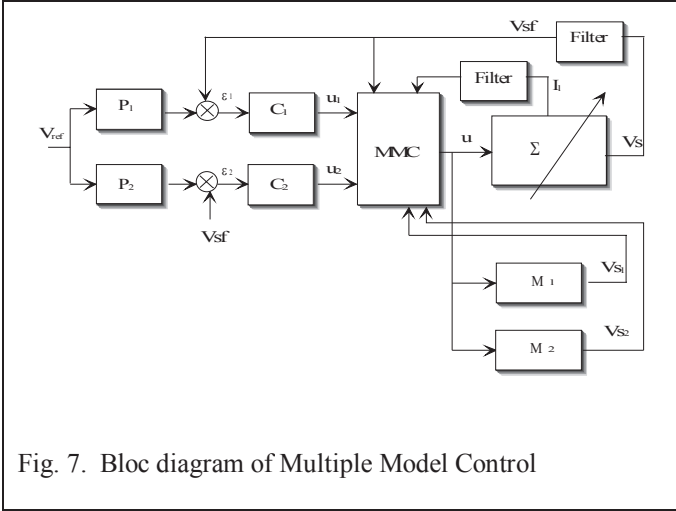


Fig. 7. Bloc diagram of Multiple Model Control

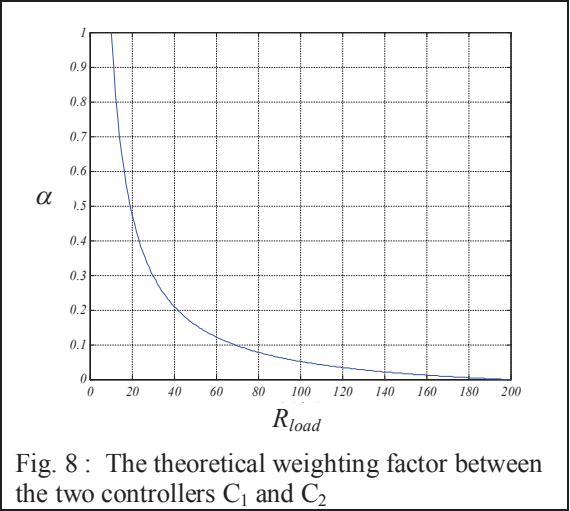


Fig. 8 : The theoretical weighting factor between the two controllers  $C_1$  and  $C_2$

The associative principle lies in a suitable balance between two basic controllers, each of them optimized for a set of system parameters, that is to say for a system model. Hence, one has to know how much the system resembles one model or the other, in order to balance the two basic controller actions. This balance between the two controller outputs  $u_1$  and  $u_2$  is given by (8), where  $\alpha$  is a weighting factor that depends on the system model validity between model 1 and model 2:

$$u = \alpha \cdot u_1 + (1 - \alpha) \cdot u_2 \tag{8}$$

The theoretical weighting factor ( $\alpha$ ) between the controllers  $C_1$  (with  $T_1=R_1.C$ ) and  $C_2$  (with  $T_2 = R_1/R_2.C$ ) could be calculated, in order to give an equivalent optimal PI controller (9), replacing in (8)  $u_1$  and  $u_2$  by expression :

$$u = PI(s) = \frac{\alpha.K_1.(T_1s + 1)}{T_1s} + \frac{(1-\alpha).K_2.(T_2s + 1)}{T_2s} \quad (9)$$

resulting in :

$$PI(s) = \frac{K(\alpha).(T(\alpha).s + 1)}{T(\alpha).s} = (\alpha.K_1 + (1-\alpha).K_2) \cdot \frac{\left[ s \cdot \frac{T_1.T_2.(\alpha.K_1 + (1-\alpha).K_2)}{(\alpha.K_1.T_2 + (1-\alpha).K_2.T_1)} + 1 \right]}{s \cdot \frac{T_1.T_2.(\alpha.K_1 + (1-\alpha).K_2)}{(\alpha.K_1.T_2 + (1-\alpha).K_2.T_1)}} \quad (10)$$

where  $K(\alpha)$  is the equivalent gain (11) and  $T(\alpha)$  is the equivalent time constant given by (12)

$$\text{With : } K(\alpha) = (\alpha.K_1 + (1-\alpha).K_2) \quad (11)$$

$$\text{And : } T(\alpha) = \frac{T_1.T_2.(\alpha.K_1 + (1-\alpha).K_2)}{(\alpha.K_1.T_2 + (1-\alpha).K_2.T_1)} \quad (12)$$

Consequently, the theoretical calculation of the mixing factor  $\alpha$  versus load resistor (where  $T=R.C$ , with  $R$  varying from  $R_2$  to  $R_1//R_2$ ) is given by (13). Then, the corresponding relationship between  $\alpha$  and the resistor value is plotted on Fig. 8.

$$\alpha(T) = \frac{(K_2.T_1.(T_2 - T))}{(T.K_1.T_2 - T.K_2.T_1 - T_1.T_2.K_1 + K_2.T_1.T_2)} \quad (13)$$

It is important to notice that the load resistor is unknown between a maximum and a minimum value. Its variations are sudden and cannot be anticipated because the disconnection and the connection instants are quite unknown. A particular and new procedure is necessary to extract the system model validity with respect to model 1 and model 2, in order to compute the mixing factor  $\alpha$  from the system behaviour.

### Model detection

Thus, a special procedure [17] is defined to compute the activation degree of model membership function, to check if the system is like model 1, model 2 or none of them. At each sampling period, the four previous points ( $V_s, I_{ref}$ ) are memorized and compared to the results of model 1 and model 2 simulations. The result is the distances  $d_1(k)$ , equation (14) and  $d_2(k)$ , equation (15) between the system and the two models, i.e. the activation degree of the membership function, see Fig. 9.

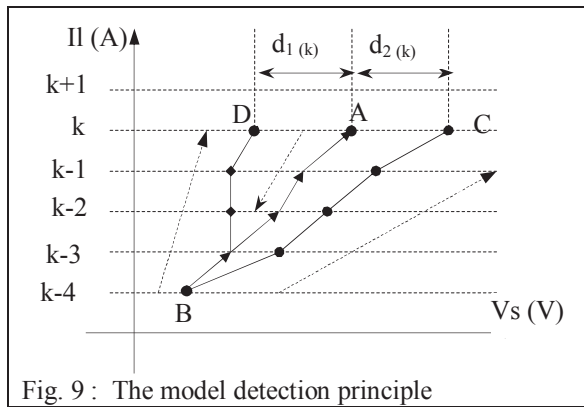


Fig. 9 : The model detection principle

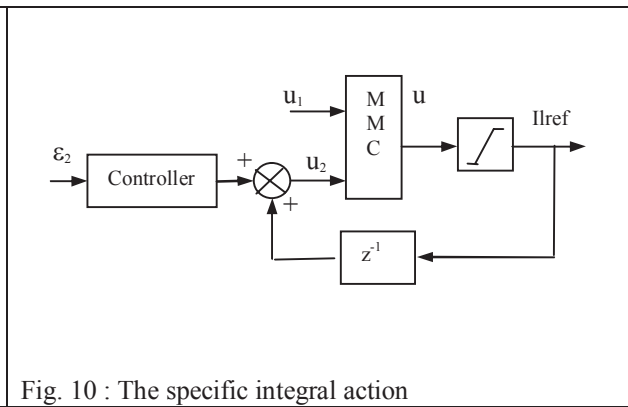


Fig. 10 : The specific integral action

$$d_1 = \sqrt{(V_s)^2 - (V_{s_1})^2} \quad (14)$$

$$\text{and } d_2 = \sqrt{(V_s)^2 - (V_{s_2})^2} \quad (15)$$

At each sampling time  $k$ , the actual state ( $V_s(k), I_{ref}(k)$ ), point A for example is kept in memory with the four previous samples ( $V_s(k-4), I_{ref}(k-4)$ ), point B. From this point, point C is computed with model 1 and point D with model 2. Consequently, the distance between point A and point C is distance  $d_1(k)$  and the distance between point A and point D is distance  $d_2(k)$ . This method resembles an internal model control or a behaviour model control [18]. In fact, it is quite different because 2 different models and 2 different controllers are combined from the

function degrees of the model memberships. This method does not need adaptive gains which are always difficult to set.

### The specific integral action in the MMC

A specific integral action is used in this multimodel controller to avoid strong control signal ( $I_{Iref}$ ) variations. The principle is based on an anti-windup method. The integral action is computed from the fusion of the two controller outputs  $u_1$  and  $u_2$ , as shown on Fig. 10, in order to get the appropriate reference current. This way, the integrator is forced to follow the actual controller output, even when it is not selected and there is no discontinuity due to the initial conditions.

### The fusion control principle

The principle of control fusion 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 (16), (17) and (18) explain the fusion control principle.

$$Fa_1 = 1 - \frac{d_1}{d_1 + d_2} = \frac{d_2}{d_1 + d_2} \quad (16)$$

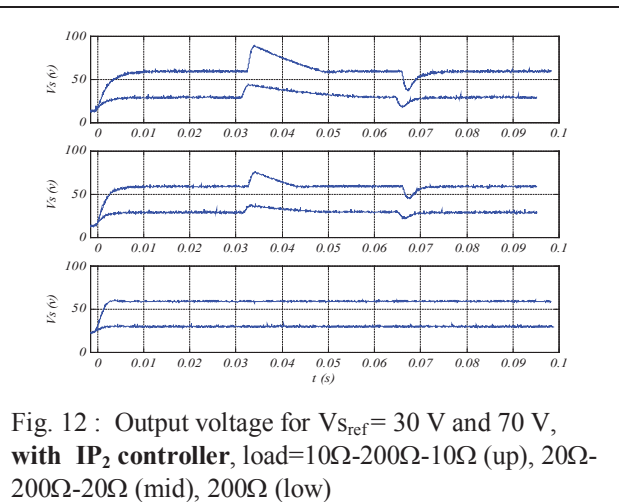
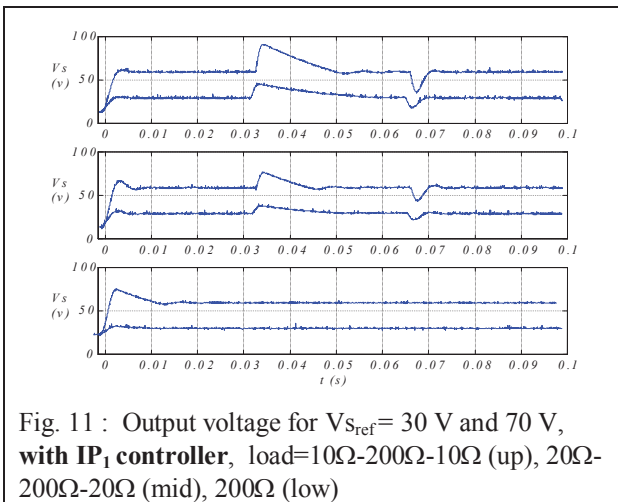
$$Fa_2 = 1 - \frac{d_2}{d_1 + d_2} = \frac{d_1}{d_1 + d_2} \quad (17)$$

$$\text{and } u = \frac{u_1 \cdot Fa_1 + u_2 \cdot Fa_2}{Fa_1 + Fa_2} = \frac{u_1 \cdot d_2 + u_2 \cdot d_1}{d_1 + d_2} \quad (18)$$

### Experimental results

Fig. 11 to 14 put in evidence that the MMC has better performance than both of the IP controllers, mainly during step input responses and more slightly during load transients. This behaviour can be explained by the discontinuous current mode and by the type (linear) of controllers itself. Consequently, our investigations will focus in this part, only on step input, keeping the performance constant despite the load variations. A triple experimental test benchmark for the control law is used :

- nominal load step start,
- light load regulation (at  $t=t_1=33$  ms),
- nominal load regulation (at  $t=t_2=66$  ms).



#### Step inputs for IP<sub>1</sub> controller (tuned for $R=10\Omega$ )

On Fig. 11, the best response is obviously reached when the system runs with 10 Ω, with IP1 controller tuned for that particular load. Upper curves are acceptable while the mid and lower curves are not, because of overshoot.

#### Step inputs for IP<sub>2</sub> controller (tuned for $R=200\Omega$ )

On Fig. 12, the best response is once again reached when the system runs with the specific value it was designed for, that is to say 200Ω. Performance on the upper and mid curves are bad, (too slow response) and performance on the lower curves are quite good.

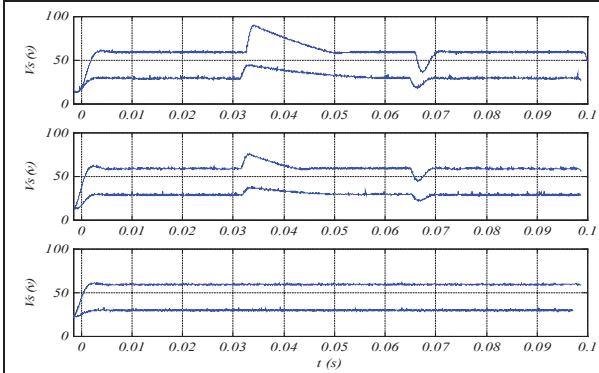


Fig. 13 : Output voltage for  $V_{S_{ref}}= 30 \text{ V}$  and  $60 \text{ V}$  with MMC, load= $10\Omega$ - $200\Omega$ - $10\Omega$  (up) and load= $20\Omega$ - $200\Omega$ - $20\Omega$  (mid) and load =  $20 \Omega$  (low)

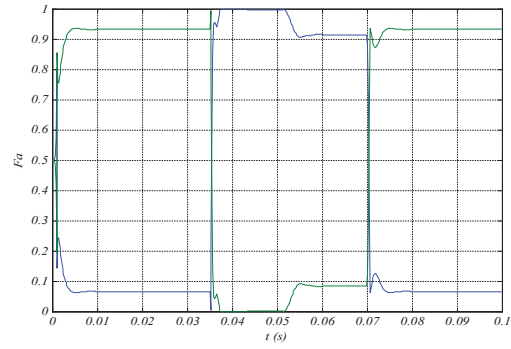


Fig. 14 : Corresponding membership function activation degrees for time varying load= $10$ - $200$ - $10 \Omega$

MMC controller = mix of  $IP_1$  and  $IP_2$

Comparing Fig. 11, 12 and 13, the performance and robustness improvement due to the MMC clearly appears. It could be seen on Fig. 13 that the results are quite good for all the plots. In another way, the output waveform and performance (overshoot, time response...) with the MMC do not depend any longer on the load. The best controller is always automatically chosen between C1 and C2, but the performance could not be better than those obtained with the best controller in each case. The activation degree of the membership function could also be seen on Fig. 14. For example with load= $10 \Omega$ , model 1 degree is almost 1 and model 2 degree is almost 0. The differences between the theoretical value (1 for model  $n^{\circ}1$ ) and the actual value are due to the difference between the average model and the real system operating with a maximum current-mode control.

$V_{ref}=60 \text{ V}$	Type of controller	Load		
		$10 \Omega$	$20 \Omega$	$200 \Omega$
Tr 5% Response time (ms) during step input	IP1	3.35	5.35	8.7
	IP2	7.8	6.5	3.1
	MMC	3.5	3.2	3.1
Overshoot (%) during step input	IP1	2.5	11.33	24.17
	IP2	0	0	1.67
	MMC	1.67	1.8	1.33

Table 2 : Parameters comparison between IP and MMC control

Table 2 summarizes the performance. The overshoot and time response with the MMC remain constant whatever the reference level and the load resistance. The advantage is that performance remains constant despite the load variations, providing a certain robustness.

## Control algorithm combination for the dc/dc converter “state” control

### Principle

This second principle gives another original answer to the associative problem, Fig. 15 : a combination between a simple linear controller (IP), equation and a simple non linear controller (bang-bang), equation 20. Let us recall that the aim of this paper is the test of control laws combination principle, i.e. how can we enhance the control performance by a progressive mix of two very basic controllers, a bang-bang and an IP [19]. When the system is close to its reference, the linear controller is activated. The non linear controller is activated when the output is far from its reference. The required data to associate these two control laws must include information on the system behaviour, i.e. the error and its variation with only one voltage sensor.

$$\text{IP controller} \quad u(t) = k_p e(t) + \frac{k_p}{k_i} \int e(t) dt \quad (19) \quad \text{Bang-Bang} \quad u(t) = \begin{cases} I_{ref \max} & \text{if } e(t) > 0 \\ I_{ref \min} & \text{if } e(t) \leq 0 \end{cases} \quad (20)$$



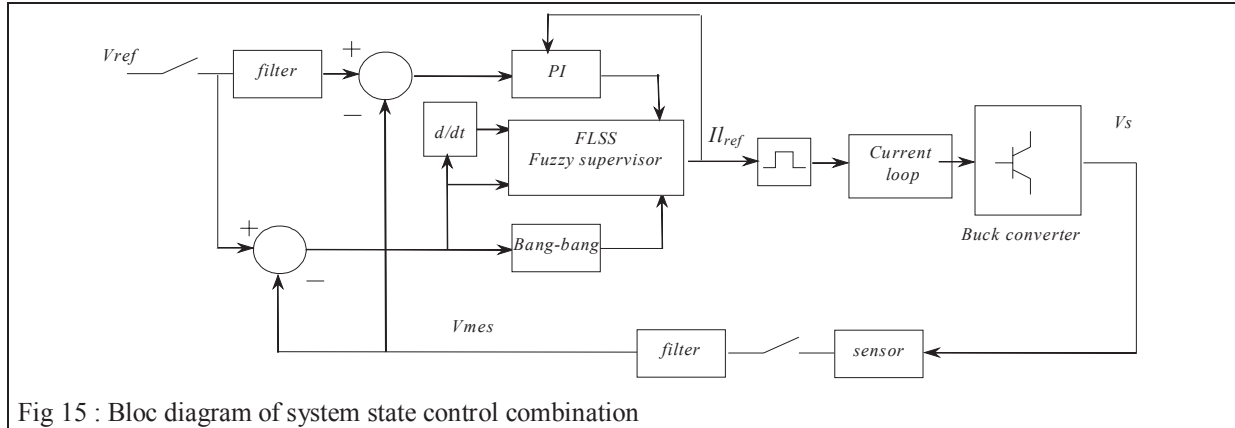


Fig 15 : Bloc diagram of system state control combination

In case of basic controller parameter tuning with respect to only one mode (continuous or discontinuous) the performance could not be optimised for all set points and operation modes. In our system, from error and its variation on Fig. 15, a FLSS (Fuzzy Logic Soft Switch) will mix the two controller outputs. The whole controller could be seen as a Bang-Bang-Integral-Proportional controller, named BBIP controller. The classical IP control loop is based on the current continuous model of the dc/dc converter with nominal load in order to obtain a 3 ms response time and a 60° phase margin. A linear combination is used to mix the two controllers according to (21), but the weighting factor  $\alpha$  itself is non linear while delivered by a fuzzy logic supervisor.

$$\text{FLSS} \quad u(t) = \left( k_p e(t) + \frac{k_p}{k_i} \int e(t) dt \right) \cdot \alpha + \begin{cases} I_{ref \max} & \text{if } e(t) > 0 \\ I_{ref \min} & \text{if } e(t) \leq 0 \end{cases} \cdot (1 - \alpha) \quad (21)$$

### Fuzzy logic supervisor

The fuzzy logic supervisor generates a weighting factor  $\alpha$  that combines the two controllers. We use a Sugeno fuzzy logic controller [20]. In our case the normalisation factor for error is  $1/V_{ref \max}$  and for error variation  $10/C$ . The input membership functions are triangular with 50 % overlap, see Fig. 16.

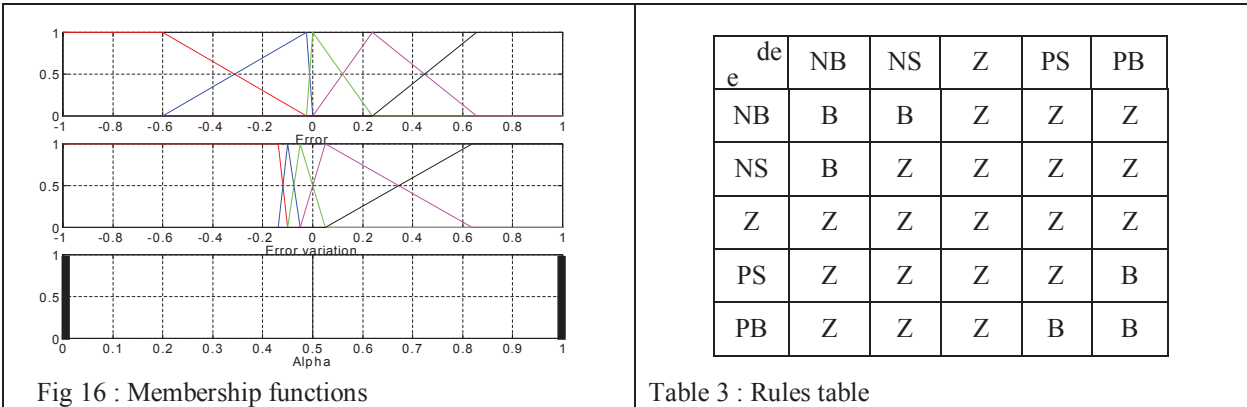


Fig 16 : Membership functions

Table 3 : Rules table

The inference is som-prod with two singletons Z and B for the output and center of gravity method improve time calculation. Denormalisation factor is equal to 1. In order to establish the rule table (Table 3), we follow this kind of idea :

$$\begin{aligned} \text{if } e \cdot de > 0 &\Rightarrow V_s \text{ moves away from } V_{ref} \Rightarrow \text{a strong control action is necessary} && \Rightarrow \text{Bang Bang} && \Rightarrow \alpha = 0 \\ \text{if } e \cdot de < 0 &\Rightarrow V_s \text{ moves towards } V_{ref} && \Rightarrow \text{damping is necessary} && \Rightarrow \text{IP} && \Rightarrow \alpha = 1 \end{aligned}$$

Thus, we determine when it is necessary to use bang-bang controller ( $V_s$  moves away from  $V_{ref}$ ) and derive the rule table (Table 3). Fig. 16 shows the membership functions for input ( $e, de$ ) and for  $\alpha$ , the weighting factor. They are different from those of a classical fuzzy logic controller. The MF positions are off line optimised according to the Hook and Jeaves non-linear procedure, [19].

### A specific integral action for the BBIP controller

It is necessary to take into account the real control output to avoid chattering between IP and bang-bang controller,

Fig. 17. The integrator is forced to follow the actual controller output, even when it is not selected and there is no discontinuity due to the initial conditions. After optimization, the fuzzy logic soft switching has the following non linear control surface, plotted on Fig. 18.

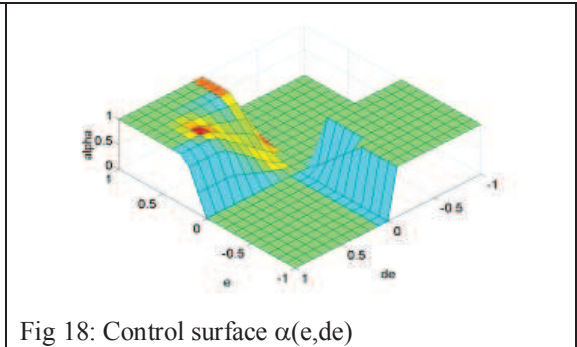
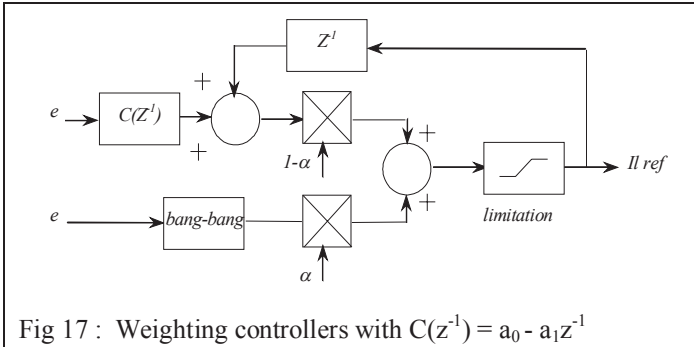


Fig 17 : Weighting controllers with  $C(z^{-1}) = a_0 - a_1z^{-1}$

Fig 18: Control surface  $\alpha(e,de)$

**Experimental results**

The test benchmark for the control law remains the same :

- nominal load step start,  $R = R_1//R_2$
- load disconnection (at  $t=t_1=33\text{ ms}$ ),  $R = R_2$
- nominal load connection (at  $t=t_2=66\text{ ms}$ ),  $R = R_1//R_2$

The optimisation criterion, is still the Integral of Absolute Error (IAE) between the reference and the measured output voltage. The FLSS between the IP and bang-bang controllers achieves good dynamic performance. Robustness with respect to the reference level is also tested on Fig. 19, where the shape is almost the same between 30V and 80V. The IP results are plotted on Fig. 20 with the same axis for comparison and the improvement is obvious

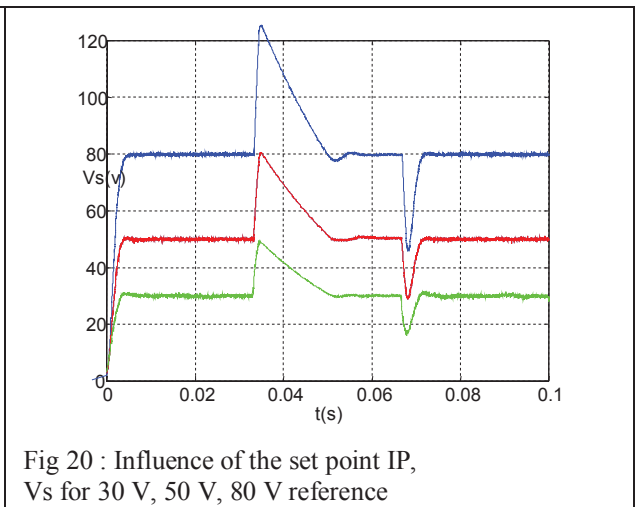
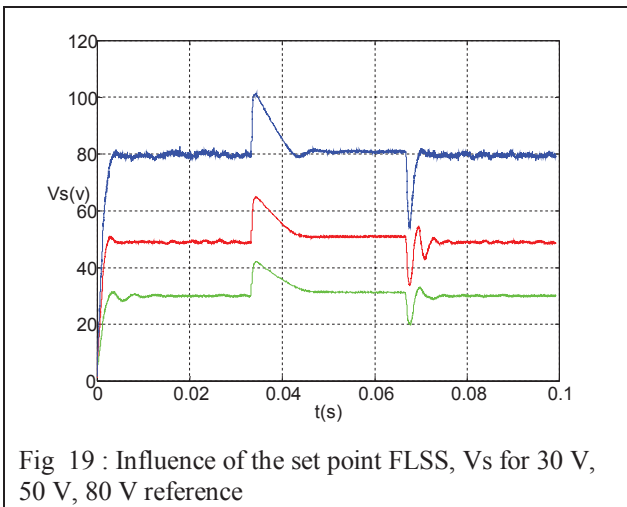


Fig 19 : Influence of the set point FLSS, Vs for 30 V, 50 V, 80 V reference

Fig 20 : Influence of the set point IP, Vs for 30 V, 50 V, 80 V reference

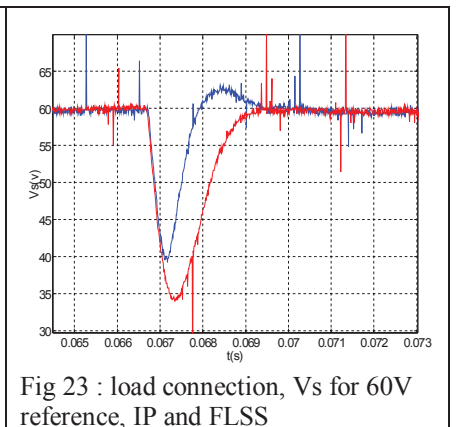
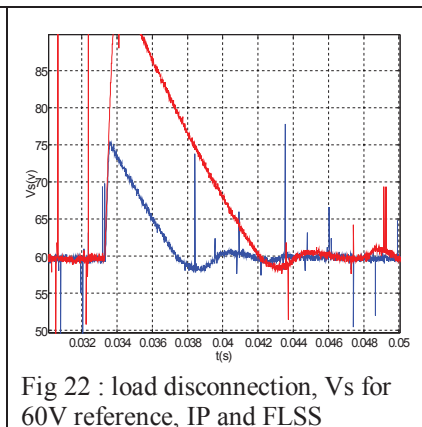
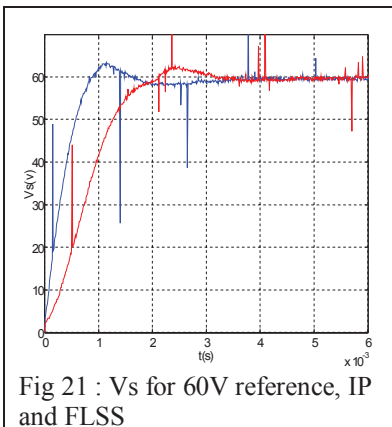


Fig 21 : Vs for 60V reference, IP and FLSS

Fig 22 : load disconnection, Vs for 60V reference, IP and FLSS

Fig 23 : load connection, Vs for 60V reference, IP and FLSS

The improvement due to the FLSS for 60V reference is put in evidence, with zoom on start, Fig. 21, load connection on Fig. 22 and load disconnection on Fig. 23.

It could be seen also in Table 3, that whatever the set point could be, the soft switching between IP and bang-bang controllers (BBIP control) improves performance (IAE, time response and overshoot) except on a limited number of cases. In these particular cases (italic numbers in Table 3), the damage is very limited (Overshoot <5% for example). The controller combination takes the advantages of both Bang Bang and IP controllers : dynamic performance, load robustness and good damping ratio. This kind of basic controller combination from the state variables of the system, achieves good results and could be a useful design solution.

	Set point (V)	80		50		30	
		with IP only Fig.19	with IP and Bang Bang Fig.20	with IP only Fig.19	with IP and Bang Bang Fig.20	with IP only Fig.19	with IP and Bang Bang Fig.20
	IAE criterion (V) / complete cycle	0.625	0.354	0.419	0.293	0.306	0.259
	Improvement (%)		43.4		30		15.4
from t = 0	Tr 5% (ms) for start with 10Ω	3.5	2.7	3.75	1.925	3	2.15
	Improvement (%)		22.86		48.67		28.33
	D (%) for start with 10Ω	0	0	0.6	3	2.6	4.2
	Improvement (%)		0.00		-400		-61.54
from t = 33 ms	Tr 5% (ms) for load disconnection	15.2	5.5	16.2	7.2	16.1	11.5
	Improvement (%)		63.82		55.56		28.57
	D (%) for load disconnection	56.5	26.4	61	29.6	63.3	40.3
	Improvement (%)		53.27		51.48		36.33
from t = 66 ms	Tr 5% (ms) for load connection	4.1	2.4	4.5	5.2	4.4	2
	Improvement (%)		41.46		-15.56		54.55
	D (%) for load connection	42.4	31.9	42	32.4	44.3	34.2
	Improvement (%)		24.76		22.86		22.80

Table 3: Parameters values and variation ratios for different references (experimental results) with Tr 5% = 5% Time response in ms and D% = Overshoot in %

## Conclusion

In the first associative method, the MMC is based on two extreme system models. It combines two linear controllers with only one voltage sensor. The MMC increases performance and has better robustness than that of classical controllers. In any case, a progressive fusion of basic controllers highly improves the global system performance, while the overall complexity slightly increases. Unity is strength ! The specific procedure for model validity computation achieves a good performance with a simple digital integration method and a reduced number of points for low computation time, without any adaptive gains. It is possible with fuzzy logic to take more than 2 models into account through fuzzy fusion. Hence, 4 models and controllers will be the objective of a future work for systems where gains and time constants simultaneously or separately change.

In the second associative method, a Bang Bang and an IP controller are mixed in a Multi Model Control strategy. This strategy achieves good results with the help of fuzzy logic for the controller combination. Consequently, some parameters have to be tuned, but a simple optimisation algorithm is sufficient in this case.

The objective of this work was to put forward new and original methods to combine two controllers, linear and/or non-linear, in order to improve performance. Both associative methods are efficient with regard to reference changes during step input. The performance on parameters variations are increased or at least remain constant whatever the load, even in the case of high variations. It was shown that performance versus hard load variations, depends on the type of information which is taken into account to compute the control action. In relation to the decision data, it has been seen that state variables with the BBIP controller are much more efficient than model validity with the MMC. Nevertheless, the MMC is simpler to compute and to implement.

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*IUFM : Institut Universitaire de Formation des Maîtres,*

*INPT : Institut National Polytechnique de Toulouse*

*LEEI : Laboratoire d'Electrotechnique et d'Electronique Industrielle.*