Microcontroller-Based versus Mixed-Signal Progammable Chip Fuzzy Controller in A Soft-Start of DC Motor Application

Rafael Navas-González
Dto. de Electrónica
Complejo Tecnológico,
Campus de Teatinos
Universidad de Málaga
29071-Málaga
email:rnavas@ctima.uma.es

Fernando Vidal Verdú
Dto. de Electrónica
Complejo Tecnológico,
Campus de Teatinos
Universidad de Málaga
29071-Málaga
email:vidal@ctima.uma.es

Angel Rodríguez Vázquez
Dto. de Diseño de Circuitos
Analógicos y de Señal Mixta
C N M-Universidad de Sevilla
Edificio CICA, C/Tarfia s/n,
41012-Sevilla
email:angel@cnm.us.es

Abstract

In this paper we present and compare results obtained from two examples of soft-start of DC motors, for a mixed-signal programmable chip or a microcontroller based system implementing a fuzzy control-loop. In the presented application, the controller determines the proper duty cycle of a PWM control circuit for the DC-DC switching converter that powers the motor drive. The main goal is getting a safe and fast start of the motor at constant starting torque. Experimental results show that a very efficient control is only possible in the mixed-signal chip case.

Keywords: Fuzzy Control, DC-Motors, Soft Start, Mixed-Signal, Fuzzy Hardware, ASIC, Microcontrollers, Switching Converters.

1 INTRODUCTION

Power systems and motion control are fields where fuzzy systems and fuzzy controllers are widely applied in recent years [2][3][8][9][11][13]. Many of these applications are related to real-time control of non-linear systems, where complex control laws, which include plant modelling and parameter estimation tasks, are often required to cope with non linearity, parameter variation, and system disturbance effects [1][4][5][6][7][10][14][16][17][18][19].

In [14] we presented an application to soft-start of a DC motor to illustrate the performance of a new proposed mixed-signal programmable fuzzy controller chip which increases the complexity while preserves most of the advantages of pure analog monolithic fuzzy controllers against their digital counterpart: small input-output delay time and good performance in terms of area and power consumption. The controller chip is based on a multiplexed strategy where a very simple programmable analog core, which implements the *simplest fuzzy system*, performs the fuzzy computations, while a digital shell allows to program dynamically this core to increase the complexity [15]. Then, instead of having the analog circuitry around a digital heart that makes the computations, we use an analog core which is programmed by digital circuitry around it. This provides easy programming access to and from other digital systems, at the same time that the processing and interface with the outer world is carried out by the analog core.

On the other hand, because of the spreading of the microprocessor technology in the industry, most of the reported fuzzy controllers are usually implemented with microcontroller or DSP based systems, which usually include real time control resources on chip, like complex timer unit, A/D, D/A interfaces, and complex interrupt controllers, and they feature complex computing capabilities, flexibility and low cost. In many of these applications the fuzzy processing is the main task that the microcontrollers must execute [7][10][17], while it is only one among others in the global control system in other cases [1][16][19].

Thus, despite the good performance of the reported fuzzy chip, it could be argued that a similar one is achieved by this general purpose processors. In this paper we try to answer this question by comparing both approaches in the same application example. Specifically, we present the results obtained when a microcontroller replaces the fuzzy controller chip in the closed-loop control example in [14]. In the application example the controller determines the proper duty cycle to a PWM control circuit for the DC-DC switching converter that powers the motor drive, from the sensed motor speed, the armature current and the programmed control law. This example was chosen in order to force high speed in the control action.

From comparison we conclude that, although the microcontroller based control seems to works properly, and performs the control strategy, it cannot tight the current close to a safe value at the very beginning of the start, and the starting torque is not kept as stable as the fuzzy controller chip does. In others words, fuzzy chip is able to respond to changes in the armature current that the microcontroller based system cannot, and a very efficient control is only possible in the former case.

Finally, although the enhanced computation speed of new microcontrollers can be exploited to implement complex control algorithms with very high sampling rate, some times high performance control systems require the partition of the control task into modules that are executed concurrently in several processors. Then, the derived improvements will not be only in CPU computing but in the integration level that will permit the incorporation of more complex devices on the same chip to work in parallel [12]. For this kind of control systems, an approach with semi-custom ASIC, PLD's or system compatible macro-cells will be privileged [4][5][6][14][18]. In this context, the circuitry implemented in [14] in an ASIC could be adapted to build a macro-cell in this more powerful processors, to perform low-level, high-speed control tasks in parallel with the other high-level control algorithms. Hence, the research in mixed signal complex fuzzy cells is justified, not just to build ASICs, but to be parts of more complex chips.

In Section 2, we will briefly explain the control strategy and describe the experimental system used in both control examples. In Section 3, the microcontroller based realization results are presented and compared with the reported fuzzy controller chip realization results. Finally, section 4 collects the conclusions.

2 APPLICATION EXAMPLE: SOFT-START OF DC MOTORS.

2.1 CONTROL STRATEGY

As said above, the control consists in providing a proper duty cycle to the switching converter that powers a DC electrical motor. In [14] it was discussed in more detail the closed-loop control strategy adopted, which mainly tries to get a safe and fast start of the motor.

In brief, for the closed-loop control scheme in Fig.1(a), if we consider the motor is a time invariant plant, we can write the following set of equations for the motor dynamic and control law respectively,

$$\begin{aligned} \dot{\omega}(t) &= \Phi_{\omega}(\omega(t), I_m(t), D) \\ \dot{I}_m(t) &= \Phi_{I_m}(\omega(t), I_m(t), D) \\ D &= g(\omega(t), I_m(t)) \end{aligned} \quad (1)$$

The latter equation should be chosen to force the plant state $(\omega(t), I_m(t))$ to follow a given target trajectory $(\omega_d(t), I_{md}(t))$. In the examples, the target trajectory is determined by two conditions: first, the starting must be safe; second, it should be as fast as possible.

In order to reach these goals, the control function $D = g(\omega(t), I_m(t))$ is built with the fuzzy approach as follows

IF $I_m(t)$ **is below** I_{mmax} ***THEN*** $D = D_T$ (2)

IF $I_m(t)$ **is above** I_{mmax} ***THEN*** $D = D_{min}$ (3)

where D_T and D_{min} are respectively the target and the minimum duty cycle. The previous rules force the current $I_m(t)$ to keep close to I_{mmax}, the maximum safe armature current value. Simultaneously, the target speed trajectory is forced by providing the duty cycle determined by the DC motor steady state equations, in a way that the starting trajectory could be figured out as a sequence of steady states

IF $I_m(t)$ **is** I_{mmax} ***THEN*** $D = \frac{K_\phi}{V_{cc}}\omega(t) + \frac{R_m}{V_{cc}} I_m(t)$, (4)

where K_ϕ and R_m are motor constant parameters, and V_{cc} the power supply voltage.

Note that, although expressed as IF-THEN rules, the previous sentences are not the final fuzzy rules, which are obtained by interpolating the ramp in (4) as well as forcing (2) and (3) for every value of ω along this ramp and taking into account that the control finishes once the duty cycle reaches the value it has in the target steady state.

2.2 EXPERIMENTAL SYSTEM DESCRIPTION

Fig.1(b) illustrates the experimental system building blocks used in the control examples. The motor drive used in both examples is the same. The armature current and speed are sensed by means of a resistor and a tachometer respectively, and the corresponding sensed signal are used as the controller input variables.

In the example in [14] the fuzzy controller is a mixed-signal programmable chip, while a microcontroller based system is used in the present work. Thus, in the former some interface circuitry is needed at input and output of the controller to adapt the ranges as well as to translate the output into a PWM circuitry control signal, as Fig.1(b) shows. In the second case, the chosen microcontroller incorporates A/D converter on chip, as well as the PWM circuitry, so it provides the switch control signal S_C in Fig.1(b), although some interface circuitry is yet needed to adapt the input signals to the A/D input ranges. Thus, because of the different interface requirements, the interface circuitry blocks in Fig.1(b) have little differences in both examples. In addition, the power supply V_{cc} value and the frequency of the PWM signal S_C are a little bit

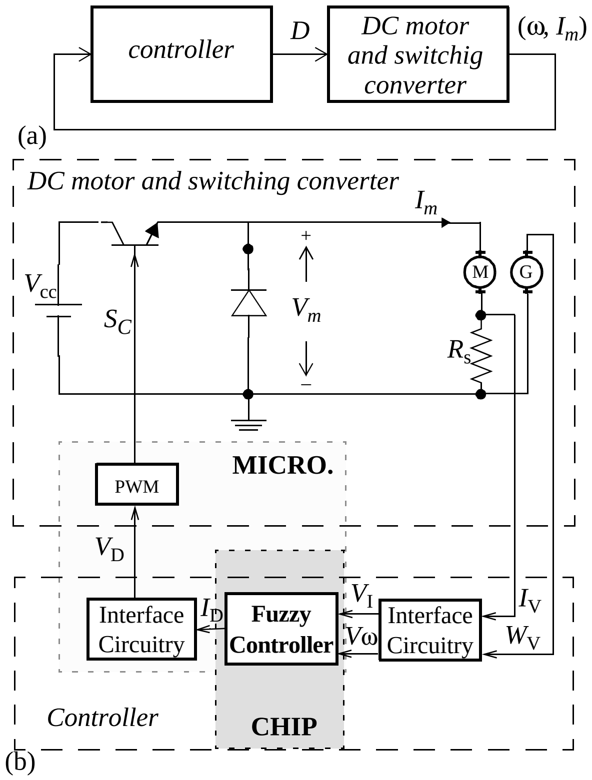


Fig. 1: Closed loop soft-start of a DC motor by a fuzzy controller: a) Concept; b) microcontroller and ASIC implementations.

different in both examples, but the differences do not have much effect on the comparison items, because the difference in the supply voltage is roughly compensated by different final duty-cycle targets, while the frequencies of S_C are in the same order of magnitude (100Khz and 62.7Khz. for the chip and microcontroller example respectively).

The fuzzy controller chip is widely described in [14] and [15], thus we only highlight its main features here; specifically, the fuzzy controller has two inputs, implements 64 rules and the measured input-output delay is around 500ns.

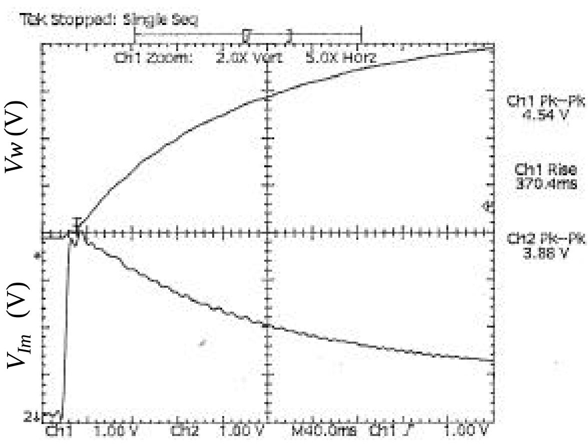
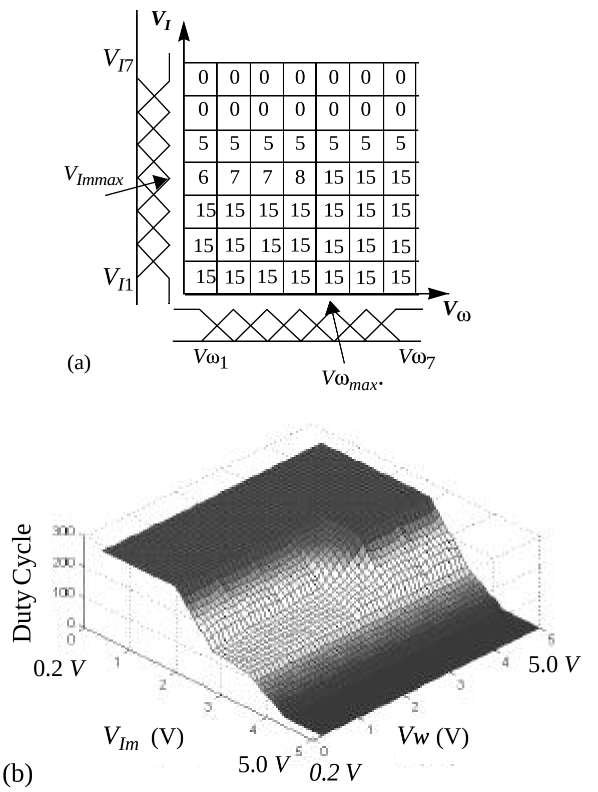


Fig. 2: Direct connection starting of a DC motor: Speed curve (top); Armature Current curve (bottom)

The microcontroller based system includes a 16 bits CMOS M30624FGFP microcontroller from the M16C/62 family, and the development board MSA0654-G02, both from Mitsubishi. This microcontroller has been selected because it is very suitable to high speed control applications. The fuzzy controller in this case has also two inputs, one output and implements 49 rules. The fuzzy algorithm has been optimized and written in assembly language in order to get minimum program execution time. The execution time, taking into account A/D time conversion of the controller inputs is around 500 microsecond.

3 EXPERIMENTAL RESULTS AND COMPARISON

Fig.2 shows the starting curves for a direct-start experiment, which means that the motor is powered by the switching converter controlled by the signal S_C whose duty-cycle is kept constant at its maximum value $D_T = 99\%$. The sensed input V_ω and V_{Im} are shown at the top and bottom of Fig.2 respectively. From this values the current peak measured value is 1.61A, 4.88 times larger than the steady-state motor current after starting, whose value is 0.33 A. On the other hand the measured rise time was 370.4ms.



0	0	0	0	0	0	0
0	0	0	0	0	0	0
5	5	5	5	5	5	5
6	7	7	8	15	15	15
15	15	15	15	15	15	15
15	15	15	15	15	15	15
15	15	15	15	15	15	15

Fig. 3: Fuzzy rule set (a); and Control surface (b) for the microcontroller based application example

The curves in Fig.4 correspond to a soft-start experiment with the control strategy described above executed by the microcontroller based system. The fuzzy rule set and control surface implemented by the controller are shown in Fig.3. The sensed input V_ω and V_{Im} are shown at the top and bottom of Fig.4 respectively. Note that V_{Im} rises when the motor is powered, although the control action forces it to reach a value close to I_{mmax}. This control action is kept until the motor speed is close to its final value. The measured rise time was 395.2ms, only 1.07 times larger than that obtained with the direct connection, and the measured current peak value is 0.96 Amp., 2.91 times larger than the final steady-state motor current, and close to the current peak target (1A).

From these data we could conclude that the soft-start control seems possible and work properly, providing almost the same rise time with an important reduction in the current peak value. However, if we compare the curves in Fig.4 with the curves in Fig.5, which correspond to the experiment with the chip in [14], the main difference we can note is that the current ripple during the control action in Fig.4 is larger than the current ripple in Fig.5.

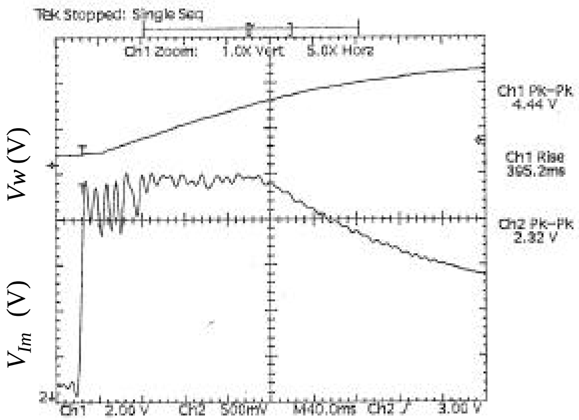


Fig. 4: Results from the soft-start procedure for the microcontoller based example: Speed V_ω ; Armature Current V_{Im} .

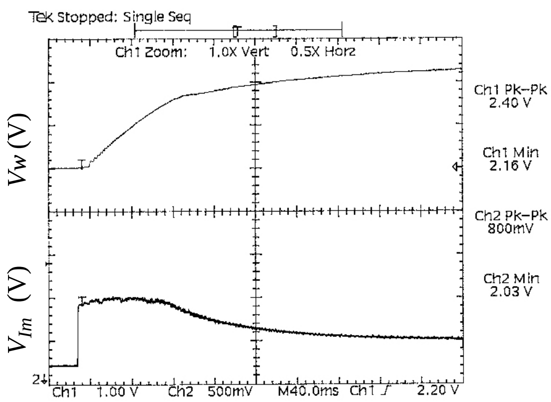


Fig. 5: Results from the soft-start procedure in [14]: Speed V_ω ; Armature Current V_{Im}

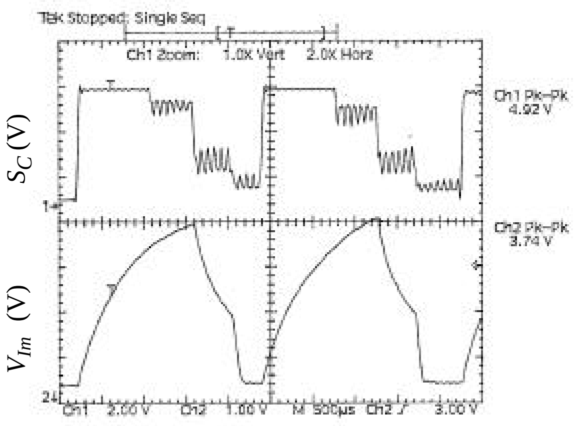


Fig. 6: Starting zoom : PWM signal S_C (top); Armature Current V_{Im} (bottom).

To highlight the observed current ripple differences, Fig.6 and Fig.7 show views of the first starting milliseconds in both control actions. Fig.6 depicts a zoom in the microcontroller based system example, where the current variable (V_{Im}) and the PWM output signal (S_C) are shown. In this figure the duty-cycle changes correspond to different voltage levels in S_C, and illustrate the discrete-time fuzzy controller action. From this graphic is clear that the current responds to these changes, but it cannot be kept close to the target value. Moreover, it presents a large ripple.

On the other hand, Fig.7 is a view for the example in [14]. In this figure, the armature current variable (V_{Im}) and the fuzzy controller output (V_D) are shown. The figure illustrates the smoothness of the continuous-time chip control action and how the current is kept close to the target value, 0.8A in that case, in response to the control action.

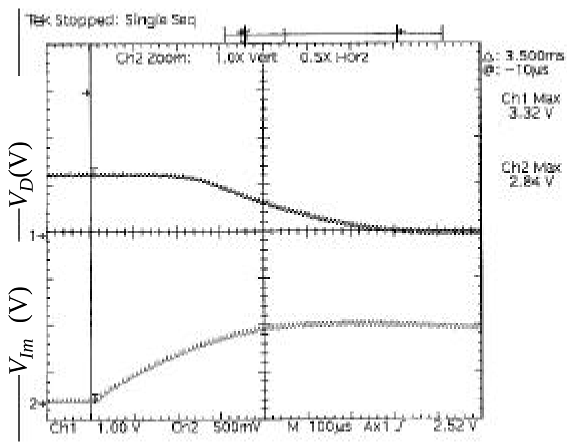


Fig. 7: Starting zoom in [14] example: Controller output V_D (top); Armature Current V_{Im} (bottom).

4 CONCLUSIONS

This paper compares results from two examples of closed-loop soft-start of a DC motor. In the first example a general purpose programmable fuzzy controller chip is included in the control-loop, while a microcontroller based system replaces it in the second. The fuzzy control strategy is the same in both examples, and the fuzzy rule matrix is also similar. From the point of view of the results in Fig.2 and Fig.4, we could conclude that the microcontroller based control seems to perform the control strategy according to the proposed target if a precise control of current and torque is not needed. On the contrary, a more detailed view in Fig.6 clearly shows that the microcontroller system cannot always keep the current close to the safe value and it neither can keep the starting torque constant.

On the other hand, with the use of a fast mixed-signal fuzzy controller a very efficient control is possible as Fig.5 and Fig.7 illustrate.

Finally, this paper does not intend to suggest that the microcontrollers should be replaced by ASIC in motor control tasks. It is not possible, specially in the case of induction motors or a more general motion control system, because some powerful computing resources are needed. Instead, we propose the use of external ASICs to implement low-level high-speed tasks in parallel with the microcontrollers operation. This could be implemented ideally by integrating the dedicated fuzzy control circuitry in [14] as a macro-cell inside a microcontroller or DSP.

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