A Digital Flatness-based Control System of a DC Motor

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Abstract: In this paper, an approach to design and implement a real-time system based on a RISC microcontroller dedicated to a DC motor speed control, is proposed. A polynomial RST controller based on the flatness property of linear systems is implemented in C/C++ embedded programming language. The flatness property is used in order to design a robust controller with high performance in terms of tracking. The proposed controller is then applied to control a DC motor. The simulation and experimental results underline the efficiency of the flatness-based polynomial controller in a real-time control framework.

Keywords: Flatness control, RST polynomial controller, robustness, trajectory planning and tracking, microcontroller, AC-DC power converter.

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1. Introduction

The possibility of varying or reversing the rotation speed of motors constitutes a necessity in industrial domain and in process automation. In this framework, the use of a DC motor can be a good solution. However, the speed control presents some delicate problems, particularly in terms of robustness, of perturbation rejection and especially when tracking trajectory. In this case, it is interesting to consider adequate control laws for the drive. Several techniques of control theory systems using conventional and non conventional methods have been applied on such type of motor [16][22][24][28].

The flatness property, introduced in 1992, presents a new point of view in the control theory domain [1-10]. This property, developed initially in the nonlinear continuous-time case, defines a class of systems well known as flat systems. The existence of a variable called flat or linearizing output allows to define all other system variables. In the linear case [3][4], it is sufficient to consider the Brunovsky's outputs of the canonical controllability form like the flat outputs [30][31]. Thus, the dynamic of such a process can be deduced without solving differential equations. Therefore, it is possible to express the state, as well as the input system, as differential functions of the flat output. The main contribution of the flatness that will be exploited in this paper is the effective trajectory planning and tracking solutions with high performances specification.

The flatness property of DC motor model will be used to obtain of a closed-loop system with high performances by designing a robust polynomial RST controller with an argued choice for its design. The tracking of a reference trajectory, function of the flat output system, as well as the rejection of disturbances and noises of measure, will be the goal of this controller.

On the other hand, the evolutions in the micro-electronics field, especially in the domain of digital signals processors are at the origin of many progresses in power electronics. Many works in the control theory domain have shown the performances of DSP (Digital Signal Processor) integration, microcontrollers (PIC, AVR...) or as digital components like FPGA or ASIC. The development of built-in digital controller on programmable target PIC 16F876 presents an advantage of fast real-time implementation of the control algorithms as well as the reduction in terms of components number and bulk [12-14].

In this paper, an approach to design such a control system as well as its hardware architecture is presented. A software integration of the developed RST algorithm, relative to the computer tools bound to this type of built-in circuits in embedded programming C/C++ language is implemented in a real-time environment.

2. Central Algorithm

2.1. Flatness-based control

The dynamic linear discrete system can be represented by equation (1) where the signals u_k and y_k represent the discrete systems input and output, respectively:

$$A(q)\,y_k = B(q)\,u_k \tag{1}$$

In this equation, the polynomials $A(q)$ and $B(q)$ are the denominator and the numerator of

the transfer function respectively:

$$\begin{aligned} A(q) &= q^n + a_{n-1}q^{n-1} + \ldots + a_1 q + a_0 \\ B(q) &= b_{n-1}q^{n-1} + \ldots + b_1 q + b_0 \end{aligned} \tag{2}$$

where q is the forward operator.

Applied in a real-time framework on industrial processes [5-10], the flatness property consists in designing a control signal u_k that allows to the flat output system z_k to track asymptotically a desired trajectory z_k^d. The discrete flat output z_k is related to the control signal u_k and to the output system y_k by the following relations:

$$\begin{aligned} u_k &= A(q)\,z_k \\ y_k &= B(q)\,z_k \end{aligned} \tag{3}$$

The flatness-based control law can be then given by the following expression:

$$u_k = z_{k+n}^d + \sum_{i=0}^{n-1} k_i\left(z_{k+i}^d - z_{k+i}\right) + \sum_{i=0}^{n-1} a_i z_{k+i} \tag{4}$$

which can be rewritten in the following polynomial expression:

$$u_k = K(q)\,z_k^d + \left(A(q) - K(q)\right)z_k \tag{5}$$

The tracking error dynamics is defined by the choice of the k_i coefficients of the $K(q)$ polynomial given by:

$$K(q) = q^n + k_{n-1}q^{n-1} + \ldots + k_1 q + k_0 \tag{6}$$

which must be Hurwitz [7].

2.2. Flatness-based RST controller

To design a polynomial controller in a linear case, we are going to follow the method given in [5] [6]. The proposed method is based on the design of a direct observer of the flat output and its forward values.

By considering the state vector $Z_k = \begin{pmatrix} z_k & z_{k+1} & \ldots & z_{k+n-1}\end{pmatrix}^T$ of the controllable LUENBERGER realization of system (3), the system of the equations (3), in which the variable z_k is the partial state [30], is considered in a canonical state space representation of the controllable LUENBERGER realization:

$$\begin{aligned} Z_{k+1} &= \mathrm{A} Z_k + \mathrm{B} u_k \\ y_k &= \mathrm{C} Z_k \end{aligned} \quad (7)$$

where the matrix A , B and C are given by:

$$\mathrm{A} = \begin{pmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \ddots & \vdots \\ \vdots & \ddots & \ddots & \ddots & 0 \\ 0 & \dots & 0 & 0 & 1 \\ -a_0 & -a_1 & \dots & -a_{n-2} & -a_{n-1} \end{pmatrix}, \ \mathrm{B} = \begin{pmatrix} 0 & \dots & 0 & 1 \end{pmatrix}^T, \ \mathrm{C} = \begin{pmatrix} b_0 & b_1 & \dots & b_{n-1} \end{pmatrix}$$

By using the flatness property, the control law u_k , given by the equation (5) can be expressed as:

$$u_k = K(q) z_k^d + (a - k) Z_k \quad (8)$$

where a and k are two constant vectors constituted by the a_i and k_i coefficients of the $A(q)$ and $K(q)$ polynomials given by:

$$a = \begin{pmatrix} a_0 & a_1 & \dots & a_{n-1} \end{pmatrix}, \ k = \begin{pmatrix} k_0 & k_1 & \dots & k_{n-1} \end{pmatrix}$$

The realisable structure of the RST controller in terms of the q^{-1} operator can be obtained by:

$$S(q^{-1}) u_k = K(q) z_k^d - R(q^{-1}) y_k \quad (9)$$

with

$$S(q^{-1}) = 1 + (a - k)\left(\mathrm{A}^{n-1} \mathrm{O}^{-1} \mathrm{M} - \begin{pmatrix} \mathrm{A}^{n-2}\mathrm{B} & \dots & \mathrm{AB} & \mathrm{B} \end{pmatrix}\right) Q^* \quad (10)$$

$$R(q^{-1}) = -(a - k) \mathrm{A}^{n-1} \mathrm{O}^{-1} Q \quad (11)$$

and

$$\begin{aligned} Q^* &= \begin{pmatrix} q^{-(n-1)} & q^{-(n-2)} & \dots & q^{-1} \end{pmatrix}^T \\ Q &= \begin{pmatrix} q^{-(n-1)} & q^{-(n-2)} & \dots & 1 \end{pmatrix}^T \end{aligned} \quad (12)$$

where M and O are the controllability and the observability matrices respectively.

Thus, the closed loop dynamics is defined by the tracking polynomial $K(q)$ of the desired flat trajectory z_k^d .

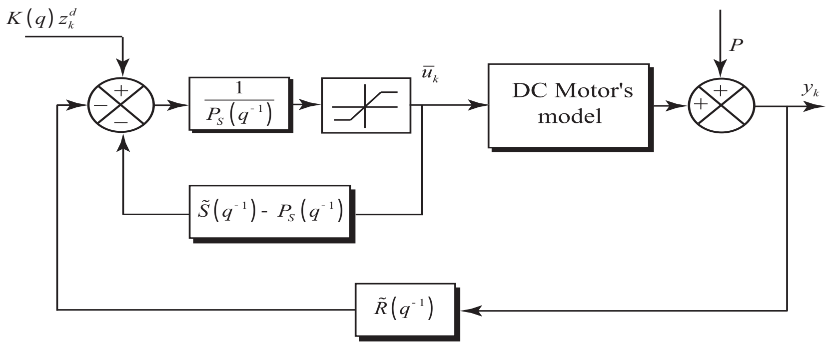

Figure 1. Flatness-based RST Polynomial Controller for DC Motor Model

In order to obtain a robust controller, we must introduce in the model equation (3), the pre-specified parts $\mathrm{H_S}$ and $\mathrm{H_R}$, given by equation (13). In [32], it is shown that the polynomial $\mathrm{H_R}$ is used to eliminate the high frequency noises on the input signal and the $\mathrm{H_S}$ polynomial to allow the rejection of static disturbance present on the output signal.

$$\begin{aligned} H_S\left(q^{-1}\right) &= 1-q^{-1} \\ H_R\left(q^{-1}\right) &= 1+q^{-1} \end{aligned} \tag{13}$$

While taking into account the pre-specified parts $\mathrm{H_S}$ and $\mathrm{H_R}$, the polynomials of the re-calculated RST controller can be seen as in equation (14).

$$\begin{aligned} \tilde{S}\left(q^{-1}\right) &= H_S\left(q^{-1}\right)S\left(q^{-1}\right) \\ \tilde{R}\left(q^{-1}\right) &= H_R\left(q^{-1}\right)R\left(q^{-1}\right) \end{aligned} \tag{14}$$

The additive static disturbances lead generally to the increase of the control signal magnitude applied to the system exceeding admissible values. The actuator saturation can have an adverse effect upon the behaviour of the control signal and, in particular, when the controller contains an integrator [32]. Thus, the use of an anti-windup technique is mandatory.

Let's note by $u_{\mathrm{sat}}^{\mathrm{inf}}$ and $u_{\mathrm{sat}}^{\mathrm{sup}}$ the lower and higher limits of the control saturation, respectively. The effective control law applied to the plant becomes:

$$\bar{u}_k = \begin{cases} u_k & \text{if} \quad u_{sat}^{\inf} \le u_k \le u_{sat}^{\sup} \\ u_{sat}^{\inf} & \text{if} \quad u_k > u_{sat}^{\sup} \\ u_{sat}^{\sup} & \text{if} \quad u_k < u_{sat}^{\inf} \end{cases} \tag{15}$$

It is also possible to impose a specified dynamics when the system leaves the saturation. The desired dynamics is defined by the polynomial $\mathrm{P_S}\left(q^{-1}\right)$ given by equation:

$$P_S\left(q^{-1}\right) = 1-\exp\left(-\frac{T_e}{\tau_{sat}}\right)q^{-1} \tag{16}$$

where $\mathrm{T_e}$ and τ_{sat} represent respectively the sampling period and the time constant of a first order system both chosen equal to 10 ms in the DC motor's case.

The new control law of the flatness-based polynomial controller in presence of saturation will be given by the following complete algorithm:

$$P_S\left(q^{-1}\right)u_k = K\left(q\right)z_k^d - \tilde{R}\left(q^{-1}\right)y_k - \left(\bar{S}\left(q^{-1}\right)+\exp\left(-\frac{T_e}{\tau_{sat}}\right)\right)\bar{u}_{k-1} \tag{17}$$

The polynomial $\bar{\mathrm{S}}\left(q^{-1}\right)$ which introduces delays into the control signal, is given by:

$$\tilde{S}\left(q^{-1}\right) = 1+q^{-1}\bar{S}\left(q^{-1}\right) \tag{18}$$

Thus, this digital control algorithm takes into account the presence of a disturbance due to the load as well as to effects of saturation.

As in [32], the sensitivity functions which used to study the robustness of the designed RST controller are given by:

$$S_{yp}\left(q^{-1}\right) = \frac{A\left(q^{-1}\right)\tilde{S}\left(q^{-1}\right)}{K\left(q^{-1}\right)} \tag{19}$$

$$S_{up}\left(q^{-1}\right)=-\frac{A\left(q^{-1}\right)\tilde{R}\left(q^{-1}\right)}{K\left(q^{-1}\right)} \tag{20}$$

The designed control law is then applied to drive the DC motor shown on figure 2, which is a separated excitation motor with the following nominal features $U_n = 180\,V$, $I_n = 2.1\,A$ and $\Omega_n = 3000\,rpm$.

2.3. Process identification

The studied plant, constituted by the DC motor, the AC-DC power converter and the tachometer can be considered as a second order system given by the following continuous-time transfer function:

$$H(s)=\frac{G}{(1+\tau_m s)(1+\tau_e s)} \tag{21}$$

where G is the static gain of the global plant, τ_m and τ_e are the mechanical and electrical constant times respectively, and s is the LAPLACE operator.

Figure 2. The DC Motor Benchmark

In order to identify these characteristic parameters, experimental measures have been achieved. The obtained numerical values are given in Table 1.

Table 1. Model's Parameters

Parameters	Measured Numeric Values
G	$0.05(V/V)$
τ_m	$300\,ms$
τ_e	$14\,ms$

The discrete-time transfer function $H(q)$, given by the equations (22), is obtained by sampling the continuous-time model (21). The sample period $T_e = 1/f_e$ is chosen equal to $10\,ms$ as mentioned previously.

$$H(q)=\frac{y_k}{u_k}=\frac{B(q)}{A(q)} \tag{22}$$

where $A(q)$ and $B(q)$ are co-prime polynomials.

3. Simulation Results

As in [32], the robustness of the designed RST controller can be guaranteed while observing figures 3 and 4. Indeed, the module of the output sensitivity functions S_{yp} remains inside the predefined template and the one of the input sensitivity function S_{up} presents attenuation in high frequencies.

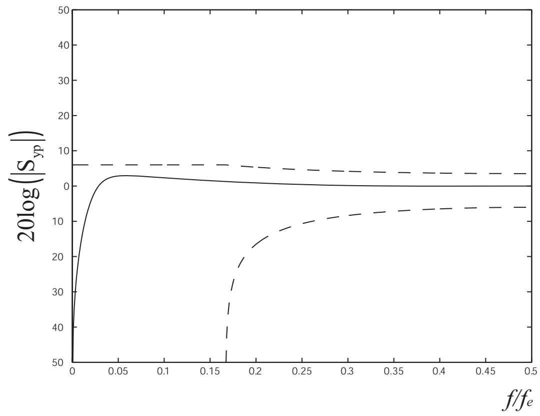

Figure 3. Output sensitivity function: case of static disturbance rejection

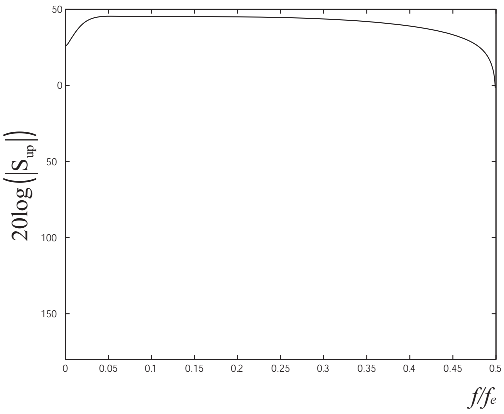

Figure 4. Input sensitivity function: case of high frequency noises elimination

The implementation of the flatness-based RST controller is illustrated by simulation results shown in figure 5. In this application, the speed's DC motor varies from 0 rpm to 1000 rpm. The desired continuous-time flat trajectory $z^d(t)$ can be computed following the method described in [6]. One obtains:

$$z^d(t) = \begin{cases} 0 & \text{if} \quad 0 \le t \le \mathrm{t}_0 \\ P_1(t) & \text{if} \quad t_0 \le t \le t_1 \\ \dfrac{1}{B(1)} & \text{if} \quad t_1 \le t \le t_2 \\ P_2(t) & \text{if} \quad t_2 \le t \le t_3 \\ 0 & \text{if} \quad t \ge t_3 \end{cases} \tag{23}$$

where $\mathrm{t}_0 = 10\,\mathrm{s}$, $\mathrm{t}_1 = 20\,\mathrm{s}$, $\mathrm{t}_2 = 50\,\mathrm{s}$ and $\mathrm{t}_3 = 60\,\mathrm{s}$ are the instants of transitions, $B(1)$ the static gain between the flat output z_k and the output signal y_k, and $\mathrm{P}_1(t)$ and $\mathrm{P}_2(t)$ are polynomials given by equation (24).

$$\begin{aligned} P_1(t) &= 5.6844(t-t_0)^3 - 0.8526(t-t_0)^4 + 0.0341(t-t_0)^5 \\ P_2(t) &= -5.6844(t-t_2)^3 + 0.8526(t-t_2)^4 - 0.0341(t-t_2)^5 + 568.413 \end{aligned} \tag{24}$$

From these equations, the desired discrete-time trajectory z_k^d can be obtained easily by sampling $z^d(t)$.

The obtained polynomials of RST controller are numerically given by:

$$\begin{aligned} \tilde{S}(q^{-1}) &= 1 - 0.7102q^{-1} - 0.2025q^{-2} - 0.0873q^{-3} \\ \tilde{R}(q^{-1}) &= 242.3 - 83.72q^{-1} - 223.5q^{-2} + 102.6q^{-3} \\ P_S(q^{-1}) &= 1 - 0.1353q^{-1} \end{aligned} \tag{25}$$

where the k_i coefficients of the tracking $K(q)$ polynomial are chosen as:

$$K(q) = q^3 - 2.02q^2 + 1.313q - 0.259 \tag{26}$$

The simulation results in figure 5, show that the effective speed of DC motor tracks a desired trajectory with high performance. The tracking error is very small in the transient regime and equal to zero in steady-state.

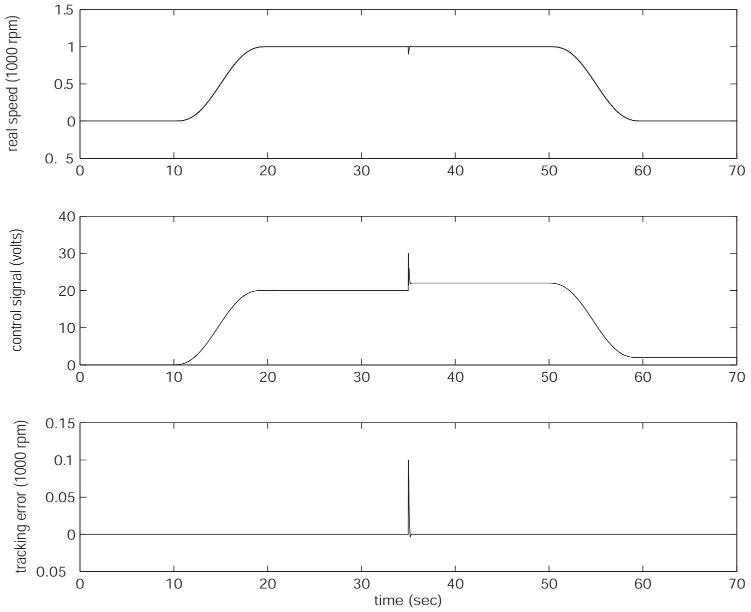

Figure 5. Simulation results in the case of flatness-based RST polynomial controller

The controller robustness is guaranteed when observing simulations of the Fig. 3, Fig. 4 and Fig. 6. Indeed, the robustness with respect to the static additive disturbances and high frequency noises can be shown in Fig. 3 and Fig. 4. As in [32], the modulus of the output sensitivity function satisfies the desired template which defines the desired robustness margins (modulus margin and delay margin). Furthermore, the input sensitivity function presents attenuation in the high frequencies region, which will guarantees noise cancellation on the input signal. The robustness is also guaranteed with respect to the model uncertainties. To show this property, the a_i coefficients of the $A(q)$ polynomial's model, have been varied with 50% of their nominal values. The simulation results are given in Fig. 6.

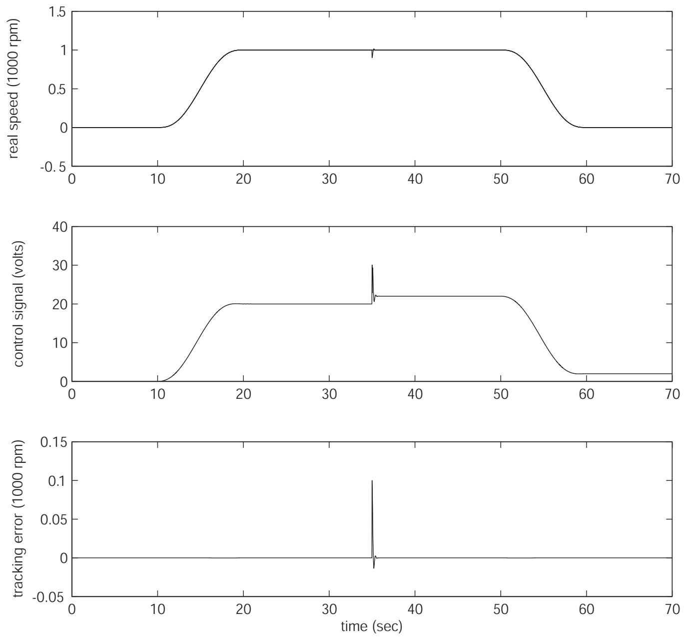

Figure 6. Simulation results in the case of flatness-based RST polynomial controller. Variation with 50% of the a_i parameters model

After the simulation phase, the proposed digital control algorithm will be applied in the real-time framework.

4. Design Aspects

4.1. Digital control system hardware

Starting from the idea consisting in varying the supply voltage of the motor, several arguments led us to choose a structure of hardware control system based on an AC-DC one phase asymmetric rectifier [17][22][23][24][26][27][29].

Presently, the choice of such a converter rather than another solution, as DC-DC converter for example, is based essentially on the possibility to vary the supply motor voltage from 0V to 250V while directly using the one phase distribution network as alternative voltage source. Such an interval of variation is very sufficient to satisfy our needs since the machine to drive requires 180V as nominal supply voltage.

The present AC-DC converter, based on thyristors, represents only the power circuit of the developed hardware control system. For the thyristors's gate control circuit, a digital control based on a RISC microcontroller PIC16F876 produced by MICROCHIP, is used [12].

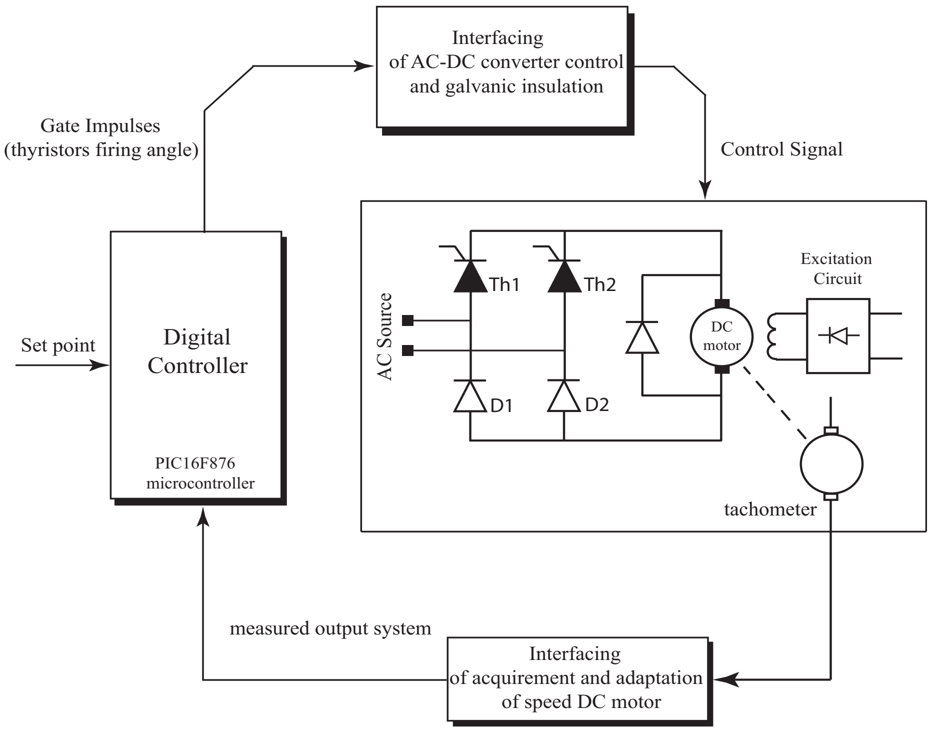

Figure 7. Hardware Architecture of the Digital Control System

This microcontroller will be the framework for the implantation of the designed control algorithm in order to generate gate impulses control signal for the thyristors. The choice of the PIC microcontroller is justified by the simplicity of implementation, using a flexible embedded programming language such C/C++, in addition to a material architecture of peripherals allowing to satisfy integration constrains of control for an electrical system.

In order to complete the structure of the hardware control system of the separated excitation DC drive, two other hardware modules are designed: a circuit of acquisition and conditioning of the speed measurement, and a circuit providing the excitation of the DC motor. Thus, the complete architecture of the proposed hardware control system is given in Fig. 7.

4.2. AC-DC power converter control

This electronic control interface is designed and developed around an impulse transformer [16][18][20][21][23][25][26][27] which allows to control by gate impulses, the BT152 thyristors used in the bridge rectifier, while ensuring a galvanic insulation between the control circuit, based on the PIC microcontroller, and the power circuit. The use of the impulse transformer in this application, instead of optocouplers for example, is due to the possibility of working in the high frequencies and possibility to provide an important current able to fire the considered thyristors, as well as the good behaviour with high voltage and the simplicity of the use. The principle of the control circuit is given in Fig. 8.

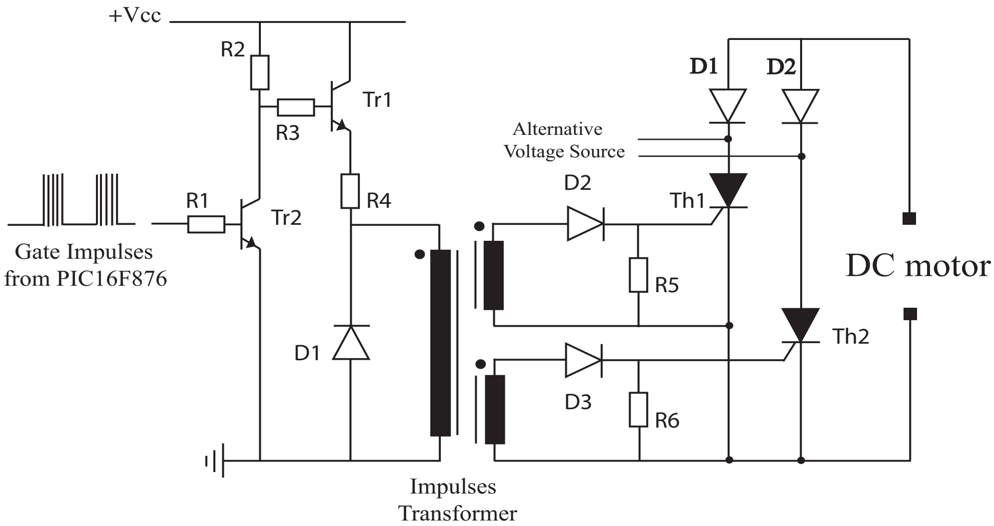

Figure 8. AC-DC Power Converter Control

4.3. The microcontroller

In order to fire the BT152 thyristors, the used microcontroller PIC16F876 must provide the control signal as gate impulses [12-14].

The PIC microcontroller includes several variants. Indeed, the PIC16F876 is chosen because it has the necessary peripherals to implement the control algorithm. In addition, this type of microcontroller can operate with clock frequencies up to 20 MHz, improving performances of the digital controller in terms of speed signal processing.

The various peripherals considered in our application are given in the following section.

4.3.1. Timer1

Through registers T1CON, INTCON, PIE1 and TMR1 [12], the timer1 is configured to operate as a 16-bit counter which can increment from 0x0000 to 0xFFFF. With 4 MHz quartz and 1:8 prescale value, a $8\mu s$ clock signal is obtained.

The content of the timer1, which is the value of registers TMR1H and TMR1L, represents the value of the thyristors firing angle. As the timer 1 will be launched at each occurrence of the external interrupt that finished when the AC supply voltage crosses the zero, every 10 ms, this time can count until 1250, corresponding to angle variation from 0° to 180°. Then, one must load the content of registers TMR1H and TMR1L by the value (64285+*Alpha*) where *Alpha* takes a numerical value between 0 and 1250. Thus, the timer1 will count from the value (64285+*Alpha)* to 65536 to represent the angle α of thyristor firing. An interruption, flag TMR1IF, will be set when timer1 overflows, in order to start the timer0.

4.3.2. Timer0

The role of the timer0 is to generate the gate impulses used for firing SCR after the delay given by the timer1. It is an 8-bit peripheral configured in a mode through the associated registers [12]. With the same 4 MHz quartz and with 1:2 prescale value, a 500 KHz count frequency is obtained.

After loadeding the content of the register TMR0 by the value 246 obtained by a simple calculation to have one square signal of $40\,\mu s$ period as typical value, the timer0 generates the impulses after the firing delay, until the occurrence of the next external interrupt.

As RB4 pin is chosen to generate this control signal, initially forced to zero, the operation consists simply in an *exclusive-OR* with logic "**1**" of this PIC output signal every overflow of the timer0, in order to generate the gate-impulses.

4.3.3. Analog-to-digital converter

The Analog-to-Digital Converter (ADC) of PIC16F876 microcontroller has 5 inputs (AN0 ... AN4). The conversion of an analog input signal results in a corresponding 10-bit digital number. This peripheral is used to acquire the speed measurement of DC motor through tachometer. As all other peripherals, the initialization of the ADC is made by configuring the associated registers [12].

The developed electronic circuit is shown in Fig. 9.

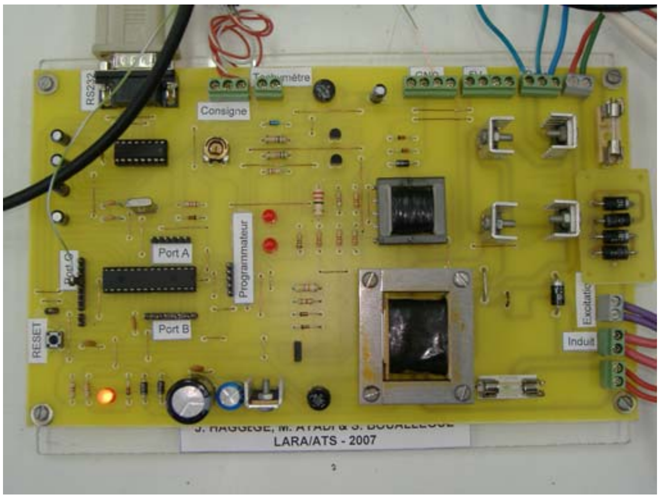

Figure 9. Developed Electronic Circuit

5. Software Implementation

After the configuration of the PIC peripherals (timers, ADC converter, I/O interfaces) as well as the general validation of interrupts (GIE=1), the setting of a bit *flag-Te* relative to the sampling time, triggers the execution the following subroutines, in this order:

1) Subroutine of the set point acquirement
2) Subroutine of acquirement and treatment of the measure
3) Subroutine of the control computation
4) Subroutine of adaptation of the obtained control
5) Subroutine of application of the control signal

Indeed, the setting of this flag is made at each occurrence of the external interruption INT/RB0 (flag INTF=1), chosen as time basis for the whole application.

A graphic and normalized representation of such a built-in system of control is given by the flow chart in Fig. 10.

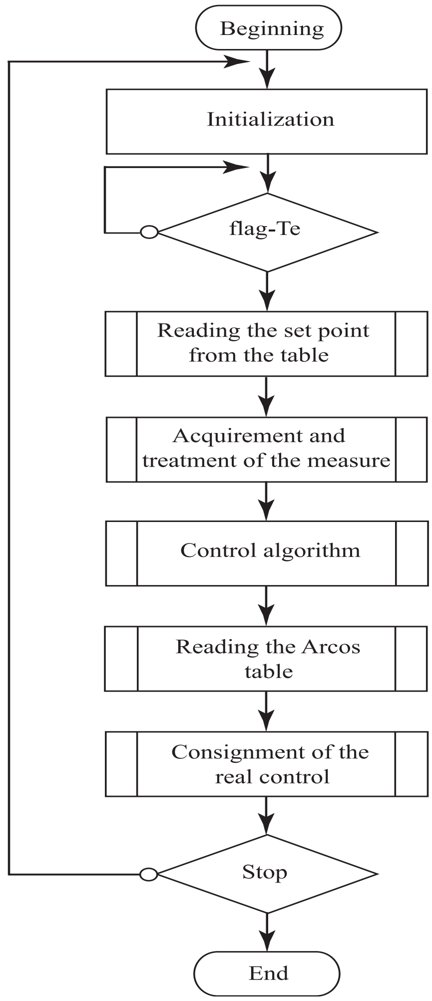

Figure 10. Flow Chart of the Control algorithm

6. Experimental Results

The real-time implementation with C/C++ embedded programming language of the flatness-based RST polynomial controller in PIC 16F876 target, led to the experimental results shown in figures 11, 12, 13 and 14. Here, it can be notice that experimental results given by figure 11 are comparable with those obtain by simulations, in figure 6, which valid the designed control system.

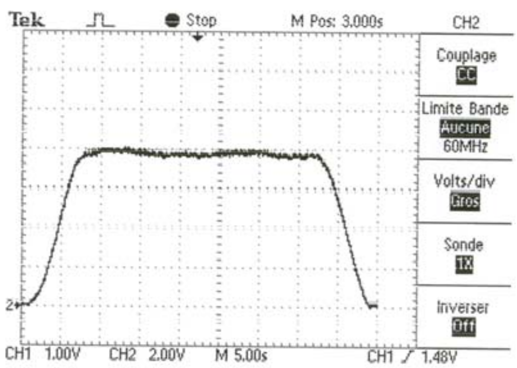

Figure 11. Experimental Response-DC Motor Speed

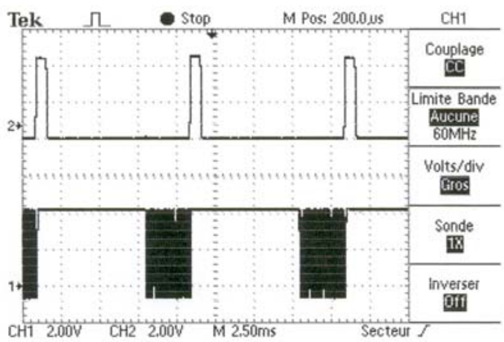

Figure 12. Synchronization and Control Signals

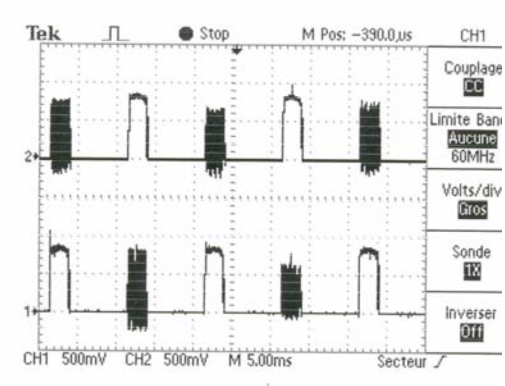

Figure 13. State of Thyristors Conduction

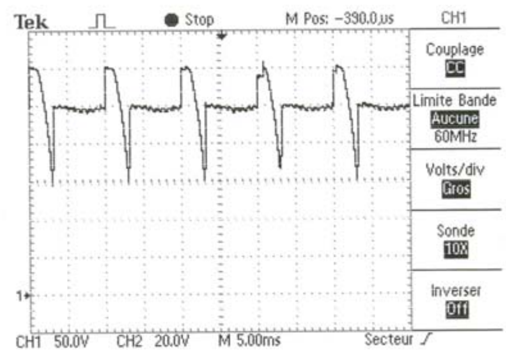

Figure 14. Control Voltage of DC Motor

As we will essentially be interested by the tracking trajectory in the transient regime, it is sufficient to consider solely the part of the response illustrated by figure 15.

While observing the figure 15, the superposition of the experimental response with the one simulated show the high performance in terms of tracking. Indeed, the tacking error is small in the transient regime and it is nearly equal to zero in the permanent regime.

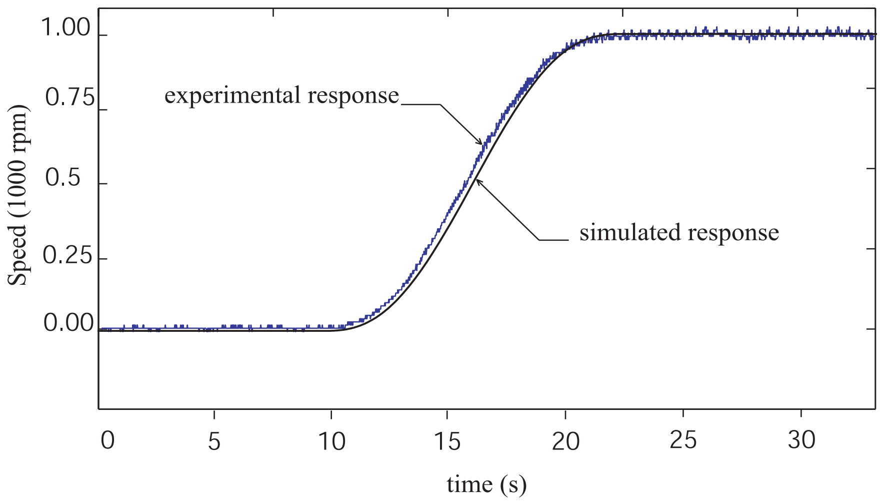

Figure 15. Comparison of Experimental and Simulated Responses

7. Conclusions

An application of concepts, methods and specific tools to the design and the implementation of real-time systems to control processes has been considered in this paper. The feasibility of the real-time controller with a high performance in terms of tracking, is the principal contribution.

While basing on analytic procedures, the flatness control of the DC drive has led to a robust polynomial controller. However, the exploitation of performances in tracking a reference trajectory and in rejection of additive load disturbances as well as the simplicity of implementation represent arguments that justify the choice of a such technique of advanced automatic control. The design of the RST polynomial controller using the flatness property of the plant, is guided by the choice of the tracking dynamics. The robustness of the developed controller with regards to modelling uncertainties as well as the intervention of disturbance and noises in the control, is guaranteed.

The implemented control algorithm led to satisfactory experimental results close to those obtained by simulation. It remains to illustrate effects of additive disturbance using validation experiment in real-time framework.

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