Real-time flatness-based control of a DC motor

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***Abstract*— In this paper, an approach of design and develop a real-time system around RISC microcontroller dedicated to the DC motor speed control is proposed. A polynomial RST controller based on the flatness property of linear systems is implemented with 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 contribution of this paper is to present the feasibility of the proposed controller which can be implemented in target. The simulation and experimental results indicate the effectiveness of the flatness-based polynomial controller in a real-time control framework.**

***Keywords*— PIC16F876 microcontroller, AC-DC power converter, flatness control, RST polynomial controller, robustness.**

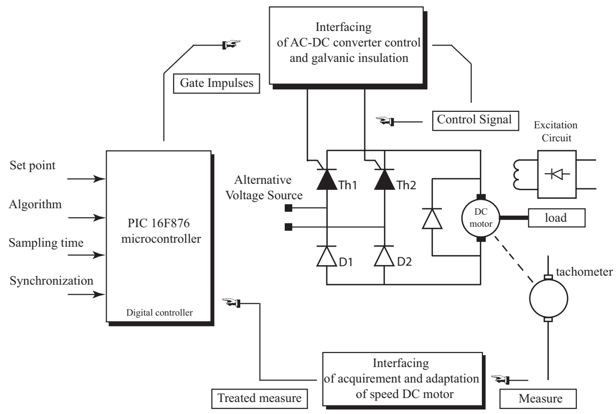

Fig. 1. Hardware architecture of control system

I. INTRODUCTION

The evolution of the micro-electronics in the domain of the digital signals processors are at the origin of many progress in power electronics. Many works in the control domain have shown the performances of processor integration DSP (Digital Signal Processor), of microcontroller (PIC, AVR) or as digital components of FPGA type and ASIC.

On the other hand, the development of built-in digital control on programmable target PIC 16F876 presents an advantage of fast real-time implementation of the control algorithm as well as reduction of the number of components and bulk.

The flatness property of DC motor model, very interesting in terms of planning and tracking trajectory, will be exploited for the development of a closed-loop system with high performances. To obtain a robust polynomial RST controller with an argued choice for its synthesis, while satisfying control objectives, 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 objective of this controller.

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 real-time framework.

II. DESIGN CONSIDERATION

A. Hardware desciption of the control system

Starting from the idea that consists 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 [12], [13], [14].

Actually, 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. As for the thyristors's gate control circuit, a digital control based on a RISC microcontroller PIC16F876 produced by MICROCHIP company is adopted [7].

This microcontroller target will be the seat of the implantation of the developed control algorithm which generates gate impulses control signal for the thyristors. The choice of the PIC microcontroller is argued by the simplicity offered at the level of a flexible programming with an embedded C/C++ language, in addition to a material architecture of peripherals allowing to confront constrains of integration control for an electric system.

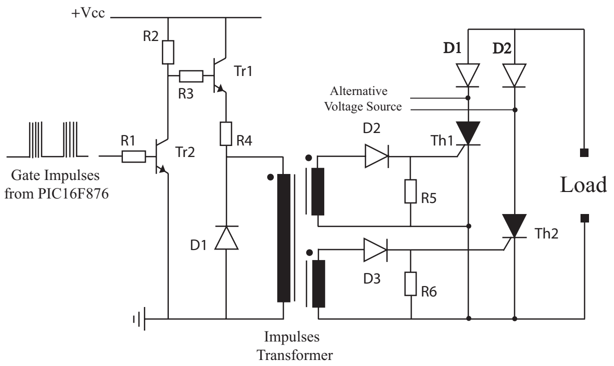

Fig. 2. The AC-DC power converter control

In order to complete the structure of the hardware control system of the separated excitation DC drive, we designed two other hardare blocs which are : a circuit of acquisition and conditionning of the speed measure and a circuit providing the excitation of the DC motor. Thus, the complete architecture of the proposed hardware control system is given by Fig 1.

B. AC-DC power converter control

This electronic control interface is designed and developed around an impulse transformer [8], [9], [10], [11].

This last one permits to control the BT152 thyristors used in control of the bridge rectifier by gate impulses, while insuring a galvanic insulation between the control circuit based on the PIC microcontroller and the power circuit. The the use of the impulse transformer in this type of application, instead of the opto-couplers 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 support in voltage and the simplicity of the use. The principle of the control circuit is given in Fig 2.

C. Microcontroller

In order to fire the BT152 SCR thyristor, the used microcontroller PIC16F876 must provide the control signal as gate impulses.

The PIC microcontroller includes several variants. Indeed, the PIC16F876 is chosen because it has the necessary peripherals to implement our 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 different peripherals considered in our application are as follows.

1) Timer 1: Through registers T1CON, INTCON, PIE1 and TMR1 [7], the timer 1 is configured to operate as a 16-bit counter which can increment from 0x0000 to 0xFFFF. Either with a 4MHz quartz and 1:8 prescale value, a 8 μs clock cycle is obtained.

The content of the timer 1, which is the value of registers TMR1H and TMR1L, denotes the value of the thyristors firing angle. As the timer 1 will be launched at every occurence of the external interrupt that occurs at every zero crossing of the AC supply voltage, every 10 ms, this one can count until 1250 corresponding to angle variation from $0°$ to $180°$. Then, it is sufficient to 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 timer 1 will count from the value $(64285 + Alpha)$ to 65536 to represent the angle α of SCR firing. An interruption, flag TMR1IF, will be then generated when timer 1 overflows, in order to start the timer 0.

2) Timer 0: The role of the timer 0 is to generate the gate impulses used for firing SCR after the delay given by the timer 1. It is a 8-bit peripheral configured in a counter mode through the associated registers [7]. With the same 4 MHz quartz and with 1:2 prescale value, we obtain a 500 KHz count frequency. After having loaded the content of the register TMR0 by the value 246 obtained by a simple calculation to have one square signal of 40 μs period as typical value, the timer 0 generates the impulses after the firing delay and until the occurence of the external interrupt.

As we choose to generate this control signal through pin RB4, initially stakes to zero, the operation consists simply in an *exclusive-OR* with '1' of this PIC output signal every overflow of the timer 0.

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 measure of DC motor through tachometer. As all other peripherals, the initialization of the ADC is made by configuring the associated registers [7].

III. DEVELOPEMENT OF THE CONTROL ALGORITHM

A. Flatness control

The dynamic linear discrete system can be represented by equation (1) in which the signals u_k and y_k represent respectively the system input and the output in a discrete-time framework:

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

In this equation, the polynomials $A(q)$ and $B(q)$ represent the denominator and the numerator of the transfer function respectively, and q is the forward operator.

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

Introduced recently, the flatness property consists in designing a control signal u_k that permits to the flat output system z_k to track asymptoticall a desired trajectory z_k^d, [1], [2], [3], [4], [5]. The discrete flat output z_k is related,to signal control u_k and

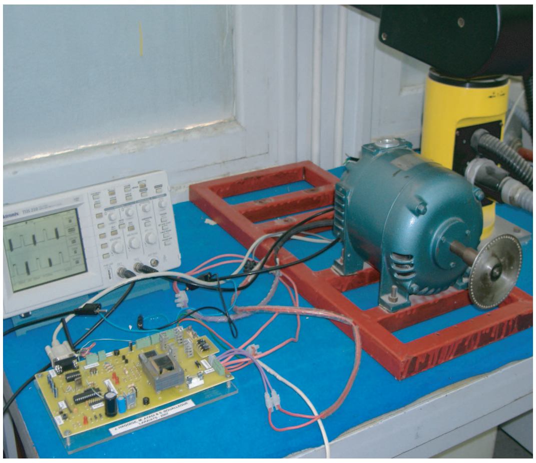

Fig. 3. DC motor with AC-DC power converter

to the output system y_k, respectively, by following relations:

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

Then, the flatness control law can be given by the following expression:

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

which can be rewritten in the following polynomial expression:

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

The tracking error dynamics is defined thus 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 Shur.

B. Flatness-based RST polynomial controller design

To design a polynomial controller in a linear case, we are going to follow the method given in [2], [3]. 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 $Z_k = \left(z_k \; z_{k+1} \ldots z_{k+n-1} \right)^{\mathrm{T}}$, the system of the equation (3) in which the variable z_k is the partial state [15] is considered in a canonical state space representation of the controllable Luenberger realization .

$$\begin{aligned} Z_{k+1} &= \mathcal{A} Z_k + \mathcal{B} u_k \\ y_k &= \mathcal{C} Z_k \end{aligned} \tag{7}$$

On the other hand, while using the property of flatness, the control law u_k, given by the equation (5) can expressed as:

$$u_k = K(q)\, z_k^d + (a - k)\, Z_k \tag{8}$$

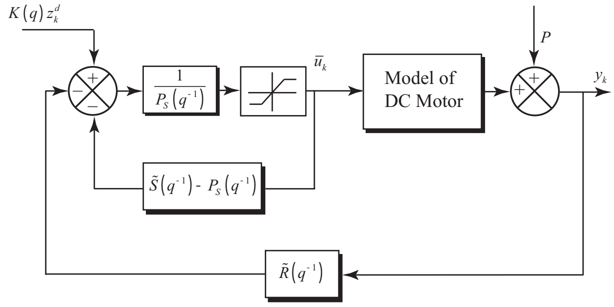

Fig. 4. Flatness-based RST polynomial controller for DC motor model

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

$$a = \left(a_0 \; a_1 \; \ldots \; a_{n-1} \right), k = \left(k_0 \; k_1 \; \ldots \; k_{n-1} \right)$$

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

$$S\left(q^{-1}\right) u_k = K(q)\, z_k^d - R\left(q^{-1}\right) y_k \tag{9}$$

with

$$S\left(q^{-1}\right) = 1 + (a - k)\left(\mathcal{A}^{n-1} \mathcal{O}^{-1} \mathcal{M} - \left(\mathcal{A}^{n-2} \mathcal{B} \ldots \mathcal{B} \right) \right) Q^* \tag{10}$$

$$R\left(q^{-1}\right) = -(a - k)\, \mathcal{A}^{n-1} \mathcal{O}^{-1} Q \tag{11}$$

and

$$\begin{aligned} Q &= \left(q^{-(n-1)} \; q^{-(n-2)} \; \ldots \; 1 \right)^{\mathrm{T}} \\ Q^* &= \left(q^{-(n-1)} \; q^{-(n-2)} \; \ldots \; q^{-1} \right)^{\mathrm{T}} \end{aligned} \tag{12}$$

where $\mathcal{M}$ and $\mathcal{O}$ are the controllability and the observability matrices respectively.
Thus, the closed loop dynamics is defined by the tracking polynomial $K(q^{-1})$ of the desired flat trajectory z_k^d. In order to obtain a robust controller, we must introduce in the model equation (3) the pre-specified parts H_S and H_R given by equation (13).
In [16], it is shown that the polynomial H_R is used to eliminate the high frequency noises on the input signal and the 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 H_S and H_R the polynomials of the new 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, causes generally the increase of the control signal magnitude applied to the system exceeding some values limits. The effect of actuator saturation can have an adverse effect upon the behaviour of the control signal and, in particular, when the controller contains an integrator [16]. Thus, the use of an anti-windup technique will be necessary.

Let's note by $u_{sat}^{\inf}$ and $u_{sat}^{\sup}$ the lower and higher limit of the control saturation, respectively, it becomes:

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

It is also possible to impose certain dynamics when the system leaves the saturation. This is illustrated in Fig 4. The desired dynamics is defined by the polynomial $P_S(q^{-1})$ given by equation (16).

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

as T_e and τ_{sat} represent the sampling time, fixed equal to 10 ms, and the time constant of a first order system chosen equal to 10 ms respectively.

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

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

The polynomial $\bar{S}(q^{-1})$ which makes appear terms of the delayed control signal, is given by:

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

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

IV. Simulation and Experimental Results

A. Simulation results

The robustness of the designed RST controller, in the relation to the static disturbance rejection and the high frequency noises rejection, is clearly guaranteed while observing Fig 5 and Fig 6. As in [16], the modulus of the output sensitivity function satisfies the desired template which defined the desired robustness margins (modulus margin and delay margin). Furthermore, the input sensitivity function presents an attenuation in the high frequency region which will define an elimination noises on the input signal. On the other hand, the implementation of flatness-based RST controller is illustrated by simulation results shown in figure 7.

Then, the developed polynomials of RST controller are given by:

$$\begin{aligned} &\tilde{S}\left(q^{-1}\right) = 1 - 0.7102q^{-1} - 0.2025q^{-2} - 0.0873q^{-3} \\ &\tilde{R}\left(q^{-1}\right) = 242.3 - 83.72q^{-1} - 223.5q^{-2} + 102.6q^{-3} \\ &P_S\left(q^{-1}\right) = 1 - 0.1353q^{-1} \end{aligned} \tag{19}$$

The simulation results of Fig 7 shows that the real speed of DC motor tracks a desired trajectory with high performance. The tracking error is too small in the transcient regime and tends to zero in steady-state.

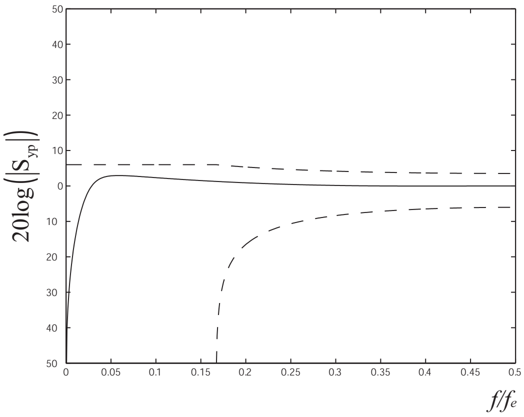

Fig. 5. Output sensitivity function: case of static disturbance rejection

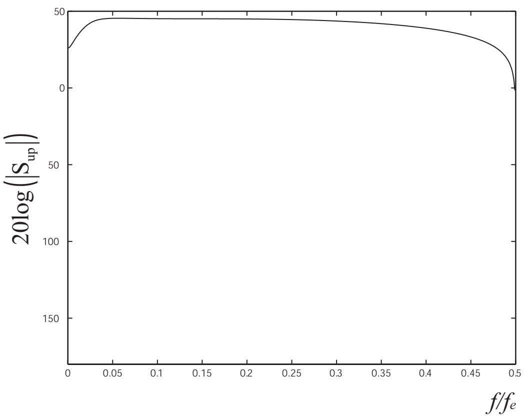

Fig. 6. Input sensitivity function: case of high frequency noises elimination

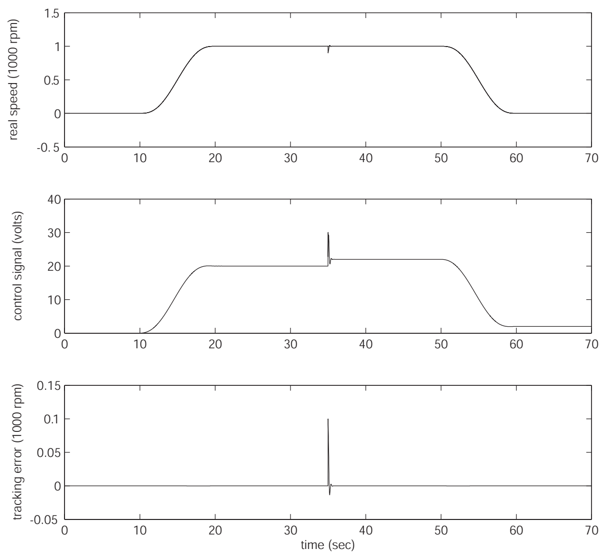

Fig. 7. Simulation results in the case of flatness-based RST polynomial controller

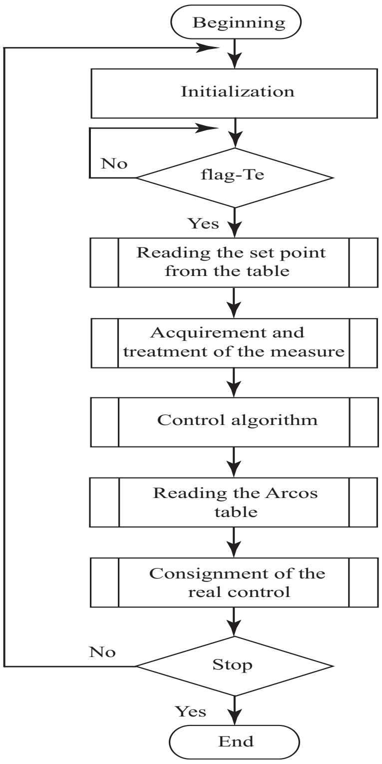

Fig. 8. Flow-chart of the control

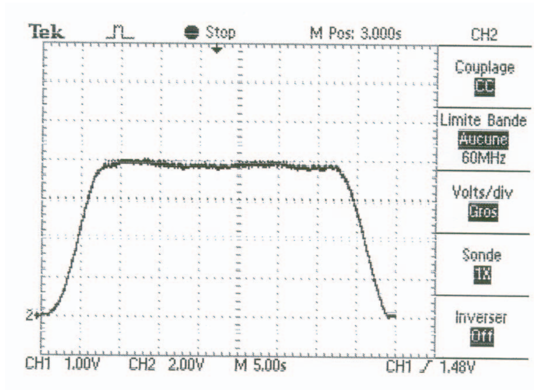

Fig. 9. Experimental response of DC motor speed

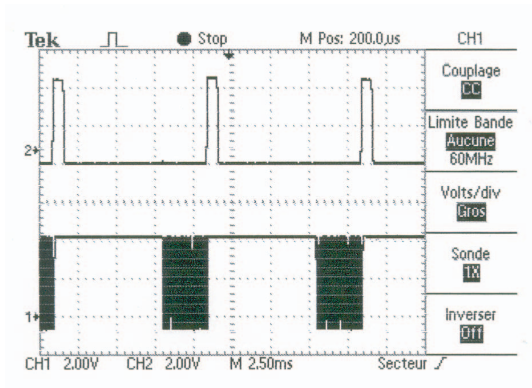

Fig. 10. Synchronization and control signals

B. *Experimental results*

After the configuration of the PIC peripherals (timers, analog-to-digital 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 :

- subroutine of acquirement of the setpoint;
- subroutine of acquirement and treatment of the measure;
- subroutine of the control calculation;
- subroutine of adaptation of the calculated control;
- subroutine of application of the control signal.

Indeed, the setting of this flag is made at every occurence of the external interruption INT/RB0 (flag INTF=1), chosen like time basis of the application. A graphic and normalized representation of such a built-in system of control is given by the flow-chart, a Fig 8.

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 9, 10, 11 and 12. The developed electronic circuit is shown by Fig 13.

In this work, we notice that experimental result given by Fig 9 is comparable with those obtain by simulations in Fig 7 which valid our developed control system.

V. Conclusion

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 the analytic manipulations, 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 the advanced automatic control.

The design of the RST polynomial controller using the flatness property of the system to control is guided by the choice of the tracking dynamics. The robustness of the developed controller with regards to modeling uncertainties as well as the intervention of disturbance and noises in the control, is guaranteed.

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

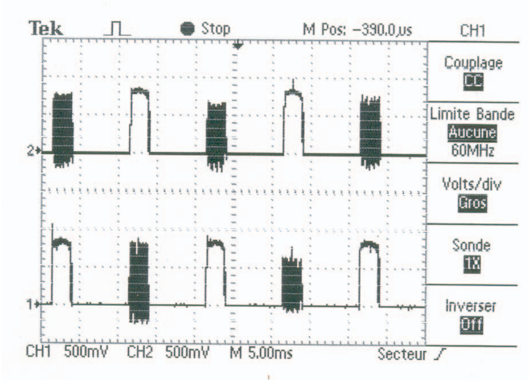

Fig. 11. State of thyristors conduction

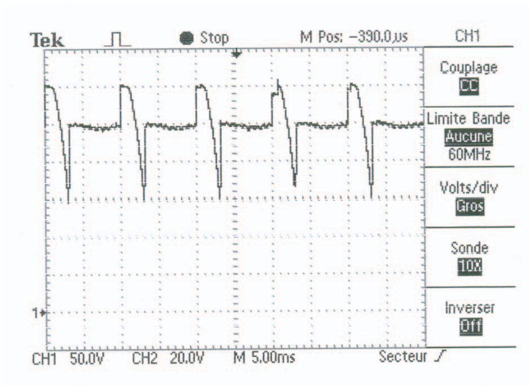

Fig. 12. Control voltage of DC motor

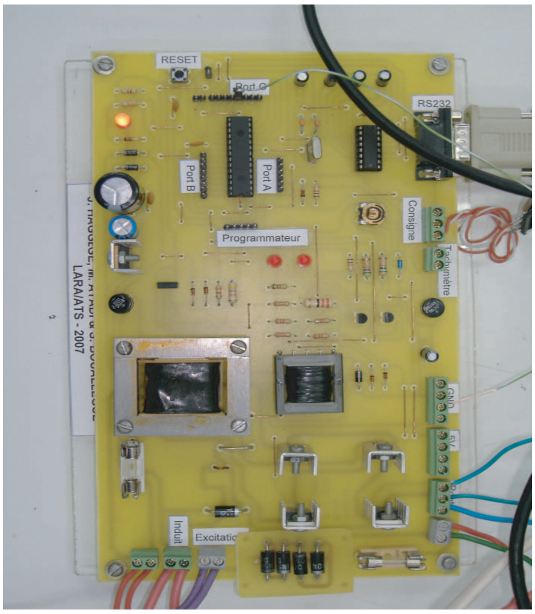

Fig. 13. Developed electronic circuit

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