Optimization Control of an Electrical Stimulation System

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Abstract— *In order to improve the strength of training and muscular rehabilitation, we propose an embedded system of programmable control for an external functional electrical stimulation (FES). The system is designed to generate a signal of programmable waveform to control the intensity of stimulation. This command sets the electrical stimulation of the patient, in term of muscular contraction according to the training needed. In this article, we propose an embedded system electrical stimulation based in two original methods of the optimization control, either by programming a binary counter memory or via a microcontroller with external memory.*

The final circuit is based on a microcontroller, a memory and a digital-analogue converter. This system allows efficient training for athletes and a good practice of electrotherapy.

Keywords— Muscular rehabilitation; Embedded system; Electrical stimulation; Programmable waveform; Optimization control; Electrotherapy.

I. INTRODUCTION

All actions of the body's muscles are caused by commands from the central nervous system (CNS). To contract a muscle, this system sends a signal that can be simulated electrically and which is called stimulus. The operation that simulates the stimulus to attack the muscles is called muscular electro-stimulation and we succeeded in a previous work in conceiving a system which makes electrotherapy [1].

The present work completes what has been done before in order to improve the system, which was based on a manual control, by adding a programmable command which will automate the muscular stimulation. We propose two novel methods to achieve this objective, and we have made proof of the advantages and disadvantages of each method.

The purpose of the programmable control is to generate an automatic command of the stimuli amplitude. This is in order to permit effective and efficient development of customized applications in electrotherapy.

II. PRINCIPE OF ELECTRO-STIMULATION

Electro-stimulation or electrotherapy was once a training technique for the athletes, it means the use of electricity as a method of therapy [1, 2, 3, 4]. Today, it is notably widely spread in the world of amateur and professional sports. Its field of application is very large. It covers among others the improvement of sports performance, physical recovery, muscle building, physical rehabilitation, pain management, improvement of body aesthetics. It has already shown great success as with pacemakers to regulate the rhythm of the heartbeat, cochlear hearing implants restaurant, or even more recently deep brain implants aiming at deleting shakings in the illness of Parkinson [1, 2, 4]. Recently, some researchers have shown the effectiveness of this technique to control the movement of muscular body by deep brain stimulation and interacting with the nervous system [5, 6].

To understand how the different types of current used by clinicians and physiotherapists is important to describe their characteristics [3, 7]. There are two type of current; alternating current (AC), bi-phasic, and direct current (DC), monophasic. It may be continuous or pulsatile. Monophasic current are polarized (they circulate only between the positive and negative electrodes); the bi-phasic currents have a polarity which is permanently reversed. Thus, the polarity effects are minimized or eliminated with the biphasic current to reduce the risk of cutaneous burns [1, 3, 7, 8].

Electro-stimulation is to contract and relax muscles by electrical impulses often rectangular shape, while playing on several parameters such as pulse duration, current intensity, pulse frequency and also the shape of the train pulses [2, 3]. For the intensity, it must be adjusted by the subject according to her level of tolerance and the objective fixed by the physiotherapist.

An electrical stimulation system comprises a source of energy, an electronic circuit for generating electrical stimuli, and electrodes. The two electrodes are placed on the path of the nerve or target engine closer to the drive plate or motor point, where the nerve fibers connect to the muscle fibers. Generally, two techniques of FES were developed, namely external stimulation with electrodes placed on the patient's skin and an internal stimulation with surgically implanted electrodes [9, 10].

The system of electrical stimulation that we conceived in a work before (Fig. 1) [1], serves for generating a signal, of external electrical stimulation for functional re-education, which is of low frequency (50 Hz) and of well determined impulse width (625 us), but of modifiable amplitude via a floor of manual command. The medium value of the signal is always null, what avoids a muscle familiarization, an undesirable cutaneous ionization or a polarization of the metallic prosthesis.

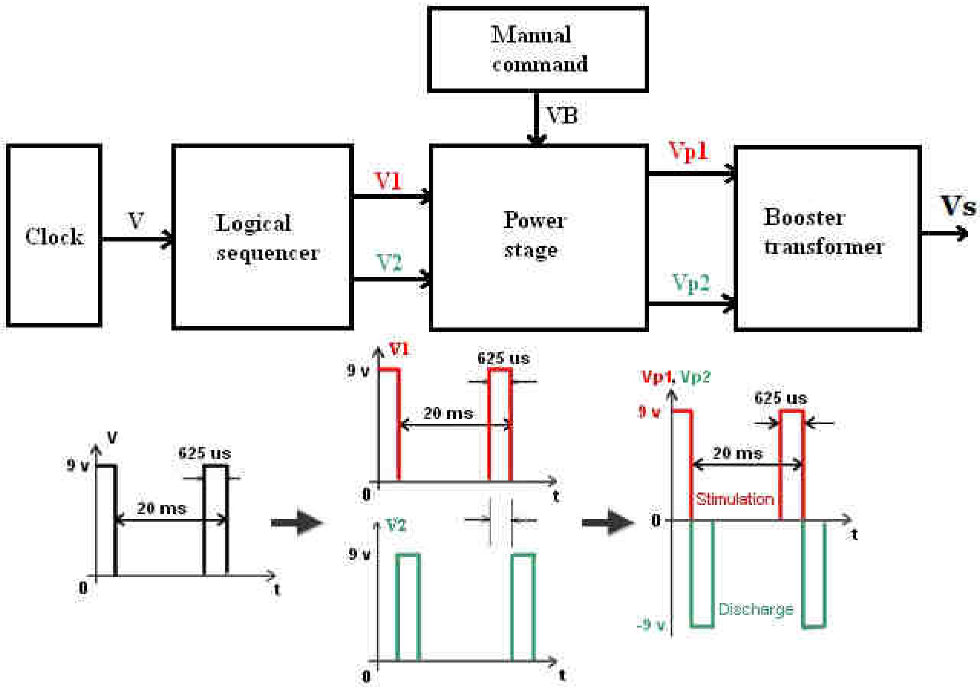

Fig.1: Block diagram of the electrical stimulation system

This stimulator triggers the action potential by a stimulus applied to the motor nerve of a muscle. The muscle contracts during application of the stimuli and the force increases to a level reflecting the applied current intensity. Then it relaxes in the rest phase and strength drops at the end of the last stimulus [1, 2].

At the level of the entire muscle, the integration of responses of each motor unit (MU) gives an overall muscular response, whose the intensity modulation is mainly done by the number of MUs recruited. In the FES technique, the recruitment of motor units is related to the activation of motor axons that are excited. This recruitment is defined firstly by the excitability threshold of each axon, secondly by their relative distance with electrode, and finally by the intensity of stimulus [11].

There are two types of impulse responses: Response to the intensity and response to the stimulus frequency [12]. Since we set the frequency and duration of the pulse stimuli, only the first answer will be treated in this work.

Fig. 2 shows the muscular response by increasing intensity of the pulse train. For all intensities less than $I_{threshold}$ there is no response from the muscle, they are sub-threshold intensity stimulation. From $I_{threshold}$ to I_{sat}, the pulses generate muscular responses that increase in force as the intensity increases. This is because the number of recruited axons increases with the intensity of the pulses, therefore, the number of activated MU increases causing a larger force. Muscle responses keep the same maximum amplitude (F_{max}) from an intensity called saturation intensity (I_{sat}), this is due to the fact that all muscular fibers were recruited [3, 12].

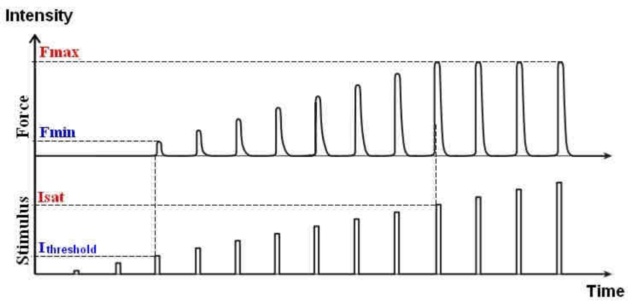

Fig.2: Muscular responses of different intensities stimuli

Therefore, the muscular contraction strength can be modulated in amplitude of stimuli. Thereby, we can make a progressive stimulation that permit efficient control of muscular strength.

The stimulation intensity in this electric stimulator is directly modified with the command signal V_B, thus we propose here to give a waveform to the signal V_B. The waveform is inspired from the natural movement of the muscle which is based on four phases of time: contraction, maintenance, relaxation and rest. These phases can be modified and depend on the aim of rehabilitation, as well as the patient's condition. In the next section we will describe the system of the programmable command which will serve for well controlling the shape of the stimulation signal.

III. METHODS

In this section, we present two original solutions of embedded system to generate the waveform of the signal VB; which represents the programmable amplitude control of the stimulator. First, we designed a memory system with a binary counter and secondly we replaced the binary counter with a microcontroller.

3.1 Memory and binary counter

In the first solution, we proposed to program a memory by a number of bytes that constitute the digital control signal with which we want to regulate the stimulation amplitude. We needed a memory and a binary counter for addressing. For this, we chose the memory EPROM 27C64, with advantage to read it only with a binary counter 12 bits. Then, the output of this memory is directly connected to an analogue digital converter as shown in Fig. 3.

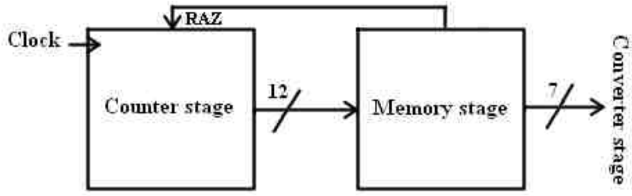

Fig.3: Block diagram of the memory with binary counter

At the output of the memory stage we have 7 bits to transmit digital data to the converter and a bit number 0 to reset the counter.

The V_B signal of manual command previously mentioned is analogue of a period T and depending on the durations T_C, T_M, T_D and T_R. We have created a digital image of that form, which will be stored in a memory and read by a binary counter. Fig. 4 shows the evolution of the simulated digital signal V_B and its presentation in memory.

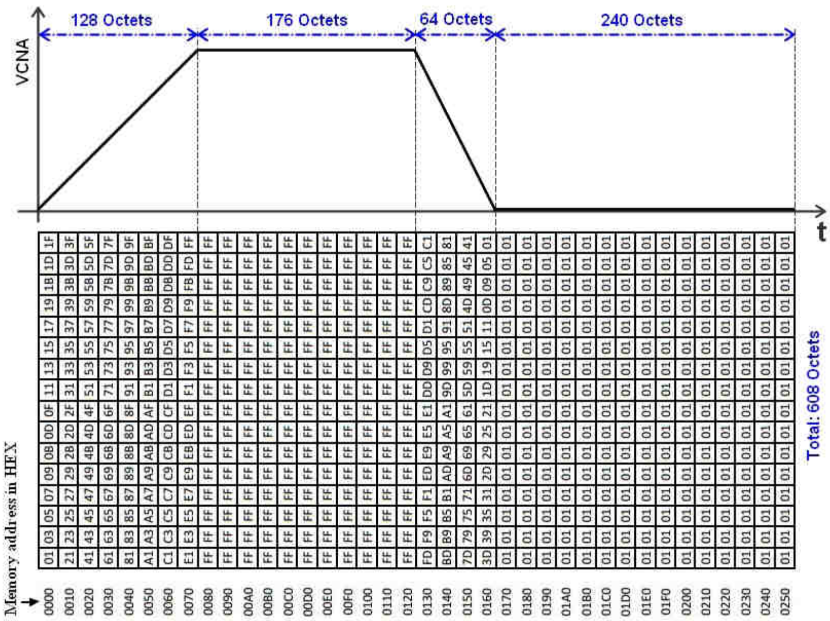

Fig.4: Evolution of the VB signal and its presentation in the memory

This approach allows us to carefully control the amplitude of the stimulation signal by manipulating the evolution of the amplitude V_B. Thus, we can program a stimulation that respects a waveform as in the exemplary program shown in the figure above.

We estimated the maximum number of necessary bytes is 4096 bytes, and that is large enough to set the shape of the signal V_B. The transmission time of a byte is $T_O = 30$ ms, therefore, the maximum total time for the stimulation process is $T_P = 122.88$ s, that is nearly two minutes.

We also thought to provide a broad choice of program for the VB shape signal that goes up to eight different programs in their temporal parameter: T_C, T_M, T_D and T_R. This requires us to use a storage space of 32 kilo bytes. The memory we have chosen and which its capacity is 64 kilo bytes organized on eight pages of eight kilo bytes is sufficient to that case.

To extend or reduce the period of stimulation process (T_P), it requires expanding or decreasing the period of the master clock that determines the reading time of the memory, which limits the dynamic setting of the control signal. To remedy this problem, we proposed a second option based on a microcontroller which permits efficient and dynamic control of memory and transfer time.

3.2 Microcontroller with memory

3.2.1 The used memory

In the second solution we mentioned it is better to use a type of memory which can be managed easily by the programming (read / write), then we chose an I2C serial communication memory and can be managed by any microcontroller. Fig. 5 present the block diagram of the proposed solution.

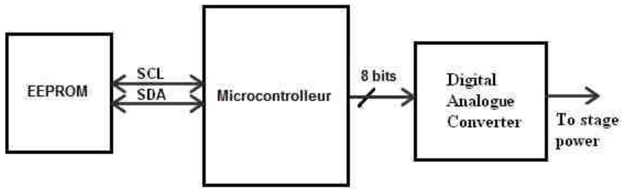

Fig.5: Block diagram of the memory with microcontroller

We chose the external EEPROM that is a storage component, accessible in writing as in reading by a microcontroller via a serial link based on the I2C protocol. And, with some specific orders we can read and write to the EEPROM while respecting the internal structure and addressing associated with the component.

The organization of bytes that forms the stimulus program is not different with what we saw in the first solution. What are changing here are just the type of memory used and the use of a microcontroller instead of binary counter.

3.2.2 Data transfer protocol

First, we have the I2C protocol or IIC for Inter-Integrated Circuit, as its name indicates is the most adaptable for communications between integrated circuits and only to communicate with a memory type 24CXX EEPROM. It requires two lines for serial communication (Fig. 5), one for clock synchronization connected on the serial clock line pin (SCL) and another for the transfer of data connected on the serial data line pin (SDA).

Then, there are two ways to transfer the bytes to the converter via a port of 8 bits, either treating data by byte or by group of bytes. The first is simple: we get a byte from EEPROM and sends it directly to the output port. The second is to receive all the bytes or group of bytes, and then treat them one by one in the microprocessor and then send them to the converter.

The last is faster than the first because the read byte by byte takes longer than the sequential reading of a set of data. However, it requires more random access memory (RAM) on the processor, at least 4096 bytes, which is not available in the family of low cost 16F8XX processors we use and that have a maximum of 512 bytes. For that reason we chose the first method. In addition, in order to consume less time in this process, we chose to use a full port is the port B to send samples of the signal.

The microcontroller can manipulate the playing time between each byte of memory and reset the program automatically or manually. Furthermore, the use of a microcontroller allows us to consider a different approach; it is generating the wave directly by the microcontroller using only a few parameters.

3.2.3 Generation of the wave V_B by microcontroller

To generate the wave V_B seen in Fig. 4, we created and embedded a program called auto-stimulation in the PIC microcontroller. The main program consists of four sub-functions: Contraction, Maintenance, Relaxation and Rest. The program asks to enter parameters, particularly periods characterizing the wave and then it starts to execute the four sub-programs according to the logic diagram in Fig. 6:

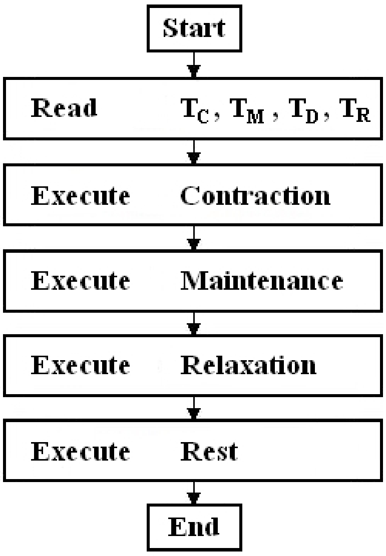

Fig.6: Logic diagram of digital waveform generation

After reading and validating data T_C, T_M, T_D and T_R, the program sequentially executes the functions contraction, maintenance, relaxation and rest in order.

3.3 Digital to Analogue converter

For digital-to-analogue conversion we need a converter that has a resolution of 8 bit input, a stabilization of speed and a voltage margin exceeds 9 volts. For this we chose the DAC0808 which is further characterized by:

- Input 8 bits to be that gently with a full port of the microcontroller 16F877A;
- Fast stabilization typically 150 ns;
- A power margin from ± 4.5V to ± 18V;
- Low power consumption: 33mW at ± 5V;
- Compatible with TTL and CMOS technologies.

The main diagram of this component is shown in Fig. 7. This converter behaves as a negative current generator, thus we have added in its output an operational amplifier (U741) as an inverter to convert the negative current in a positive voltage.

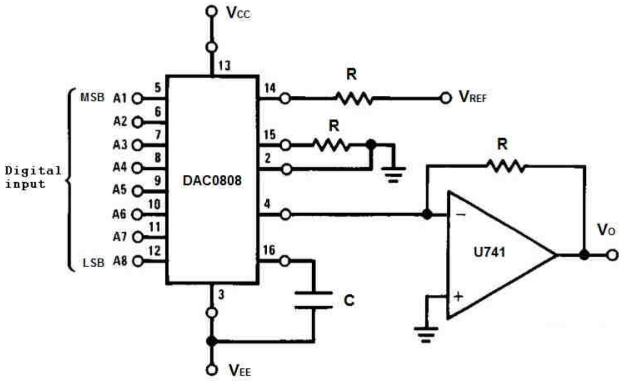

Fig.7: Digital analogue converter for an output VREF

The DAC0808 receives an octal data value between 0x00 and 0xFF on the inputs A_1 to A_8 and converted it into an electric current Io through the output pin number 4, according to the following equation:

$$I_O = -\frac{V_{REF}}{R}\left(\frac{A_1}{2^1} + \frac{A_2}{2^2} + \cdots + \frac{A_8}{2^8}\right)$$

We have the output voltage of the U741 device is given by $V_O = -\frac{I_O}{R}$ and the resistance between the output of the U741 and its negative input is chosen equal to the resistance of reference (pin 14 in DAC0808), therefore the voltage V_O becomes:

$$V_O = V_{REF}\left(\frac{A_1}{2} + \frac{A_2}{4} + \cdots + \frac{A_8}{256}\right)$$

Knowing that A_1 represents the most significant bit (MSB) of the data byte and A_8 is the least significant bit (LSB). The maximum voltage of the signal of automatic control can be adjusted by the reference voltage of the converter V_{REF}.

IV. RESULTS AND DISCUSSIONS

All system of command has been tested with software of simulation. The following Fig. 8 shows the assembly of the programmable control system comprising the EEPROM, the microcontroller 16F877A and the digital analogue converter DAC0808, with the power stage of the electro-stimulator.

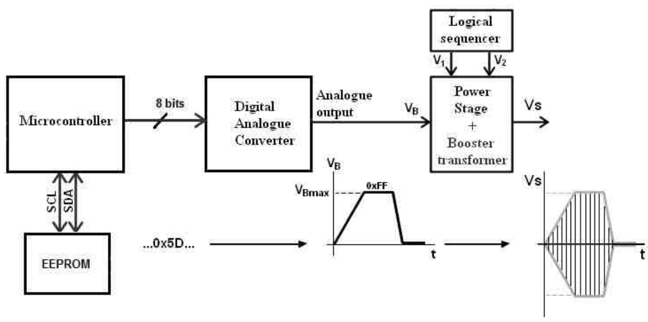

Fig.8: Assembly of the programmable control system

The signals V_1 and V_2 are respectively the stimulation signal and the discharge signal, from the logical sequencer stage, and V_S is the output signal of the power floor after being amplified by a booster transformer.

The Fig. 9 shows the signal V_B obtained in simulation by the programmable control system. The maximum value V_{Bmax} of the signal is approximately the same as the reference voltage of the converter which is 9 V.

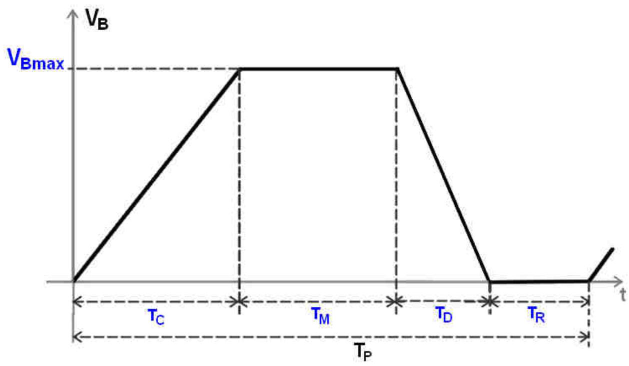

Fig.9: Measured simulation of the programmable control signal V_B

The durations T_C, T_M, T_D and T_R are respectively equal to 50 s, 50 s, 25 s, and 25 s. These values are the parameters of an example program, that we gave to the microcontroller to generate the digital waveform VB. In this case we have the period of programmable command is:

$$T_P = T_C + T_M + T_D + T_R = 150\ s$$

On the power stage, the introduction of automatic control showed the modulation effect follows the waveform of the control signal. The simulation result of the output system is shown in Fig. 10.

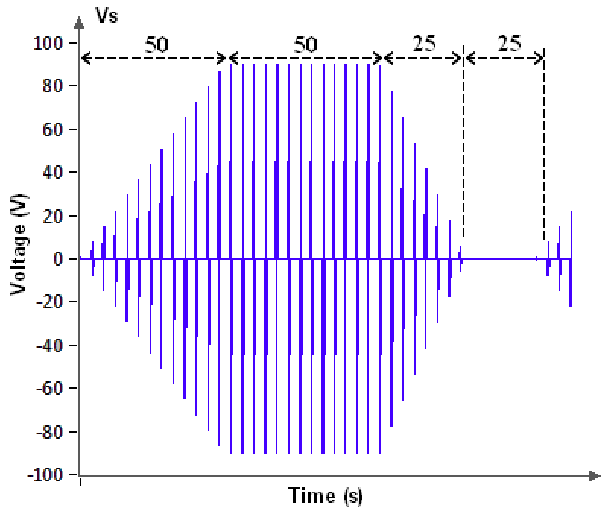

Fig.10: Waveform stimulator output signal

The final developed system is presented in Fig. 11. It consists of the electrical stimulator, a computer to program the command signal and of an acquisition card to acquire stimulation signal with LabVIEW.

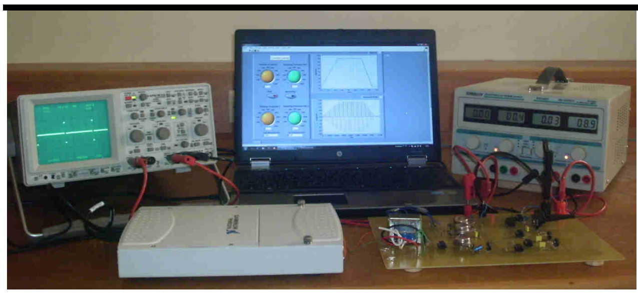

Fig.11: Realization of the electro-stimulator with programmable command

Fig. 12 represent the stimulation signal V_S measured at the power stage output. The current pulse is generated with equal amplitude and duration for both positive and negative pulse. Since the positive pulse equals the negative pulse, ideally, the net charge transfer is zero. This configuration ensures that there is zero net charge transfer at the end of each stimulation cycle and that avoid charge accumulation by the electro-stimulator.

The pulses amplitude follows the command signal waveform V_B. The stimulation part of V_S (positive pulses) increases during T_C causing a contraction of the stimulated muscle which is maintaining during T_M when V_S keeps a constant value (V_{max}), and then, when V_S begins to decrease, the muscle is relaxing at T_D phase and takes a rest time of T_R, until a new contraction pulse and so on. The time between two stimuli is 20 ms and its impulsion width is 625 µs, these values are exactly the same as what is fixed by the clock signal.

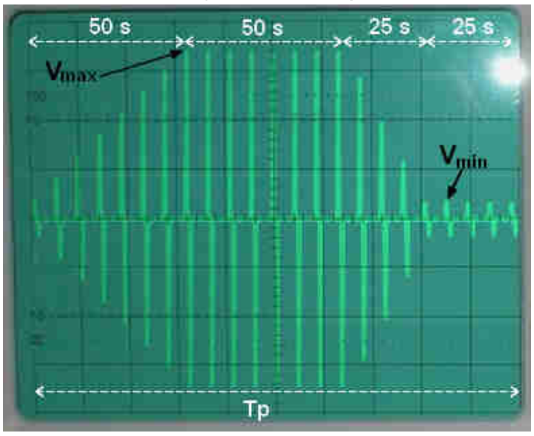

Fig.12: Measured voltage of the stimulation signal shape obtained at the power stage

Known that $V_S = \eta * V_B$, the output of the booster transformer may up to V_{max} = 90 V. The minimal value V_{min}, also adjusted by the command signal V_B, is the electric muscular threshold from which a muscle can be excited, in that case V_{min} = 5 V.

In addition, the dynamic evolution of the stimulus amplitude permits to provoke all levels and types of muscular fibers in the same time. Consequently, the muscle practices a progressive exercise. Therefore that makes the functional rehabilitation or the training of strength more efficient and very compatible with daily athletics activities. This dynamic training can be programmed by user via a simple user interface of LCD and key board. He can also regulate the pulse width and frequency of stimulation signal to practice other therapeutic applications as needed.

V. CONCLUSION

Our electrical stimulation system is to provoke the body muscles by a well-defined electrical pulse train. We have previously realized this system with a manual control of the stimulus amplitude. In this work, we have improved our system with a programmable control to make it easily adaptable and efficient during treatment muscular rehabilitation. To do this, we have proposed two solutions; the first is based on the 27C64 memory and the 4040 binary counter in order to read this memory. The second solution consists of the 16F877 microcontroller that can be used either to choose a program stored in the external memory 24C128, or execute the algorithm that automatically generates a digital waveform from the temporal parameters. Then, the DAC0808 converter is used to convert the digital signal into analogue signal. This system allows us good control of muscle response during the time of treatment characterized by the sequence: contraction, maintenance relaxation and rest. This novel method make the rehabilitation session more efficient and flexible for more electrotherapy applications. Finally, a graphical user interface (GUI) is envisaged to enhance the efficiency of stimulator use and to make easy the supervision of functional rehabilitation exercises.

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