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Development of Computer Controlled FES System with Improved Circuit Design

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Abstract: An advanced computer controlled system for FES is developed that is aimed to give successful control to the electrical stimulation of muscle which is the time-varying nonlinear system. The performance of control systems is designed to be robust and can adapt to change in system gains. A DSP is programmed with Simulink for the study. In the circuit side, the new design of FES circuit is proposed that is connected together with the computer system. The circuit can give sufficient voltage without magnetic transformer that can also reduce significantly the circuit size and weight.

Key words: Functional electrical stimulation (FES), DSP, transformerless

INTRODUCTION

The loss of ability of the upper arm is resulted after the cervical spinal cord injury. The functional electrical stimulator is now used for restoring the motor function of the upper extremity for the daily living activities. However, FES systems based on open-loop control are associated with problems related to lack of sensitivity to either external disturbance or changes in the internal parameters of the system being stimulated (e.g., fatigue phenomena, muscle habituation, muscle spasticity). For an optimized definition of the controller, a mathematical model of the stimulated system has been developed (Tang *et al*., 2005; Tsui *et al*., 2004). Although some muscle models for FES applications have been studied in recent years (Dariush *et al*., 1998), most muscle models for FES have been controlled by stimulus intensity determined by pulse amplitude or width. Stimulus frequency control of FES is necessary for restoring motor function. Watanabe and Futami (Watanabe *et al*., 1999) studied stimulus frequency and force relationship for FES application and got some important findings. One of these is that the stimulus frequency control has ability to make more precise control and smoother motion.

For all these reasons, considerable effort has been directed toward developing FES systems based on closed-loop, which means that the movement produced is measured in real time with sensors and the stimulation pattern is modulated accordingly. This is especially for the proposed application. Since musculoskeletal behaviour varies greatly among different patients, therefore an improved computer control system is needed. So far there are many advanced control strategies are reported (Qi *et al*., 1999).

In order to have successful control, the FES should provide variable frequency, amplitude and pulse width. This is so called 3 degrees of freedom of circuit. On the other hand, the FES generally requires a high voltage up to 200 V pulse voltage in order to generate the sufficient current for muscle stimulation. For low battery operation, it is very difficult to give high voltage requirement. In most case, a step-up transformer is needed. However, the transformer is usually the bulky components in the circuit and its cost and design also imply certain complication in the development. A novel circuit design is proposed that can give required high voltage without the need of a transformer. Therefore the bulky component is eliminated and therefore the power density, cost and reliability are increased.

This study is to describe an integrated system that is using the above two techniques which is a computerized system with improved transformerless FES circuit. Experimental results of the new FES circuit with the computer control is presented with the design and analysis results of the circuit proposed.

CIRCUIT INTERFACING

Three degree of freedom of circuit: The three degrees of freedom is to provide adjustment to the following three parameters of the output waveform: Pulse amplitude A, frequency and mark-space ratio M_1. Figure 1 shows the

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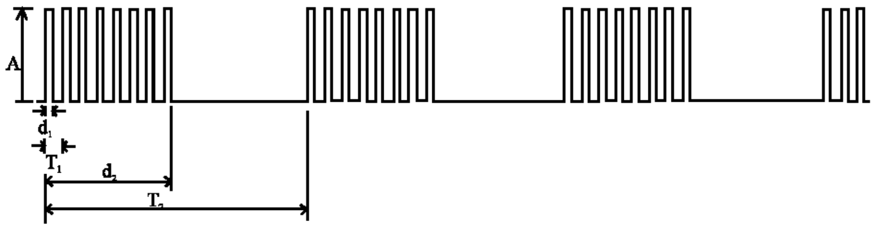

Fig. 1: Pattern of the FES signal

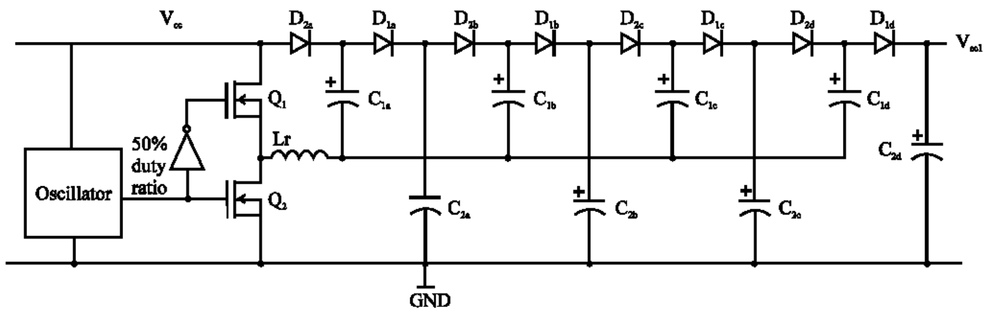

Fig. 2: The setup converter to give high voltage of V_{cc}

pattern of the waveform generated. The pattern consists of cluster which is having the mark-space ration of M_2 and frequency f_2. In side the cluster, there are secondary pulse which has mar-space ratio of M_1 and frequency f_1. Their equations can be given by:

$$M_1 = \frac{d_1}{T_1} \tag{1}$$

$$f_1 = \frac{1}{T_1} \tag{2}$$

$$M_2 = \frac{d_2}{T_2} \tag{3}$$

$$f_2 = \frac{1}{T_2} \tag{4}$$

Frequency is varied from sub-audio to kHz and the amplitude of the output voltage is needed to increase to more than 200 V in order to provide suitable current for the excitation. Therefore the circuit must be designed with capability. The above parameters are adjusted in order to provide different treatment need. Each cluster of pulses are repeated with a fixed frequency f_2. In fact overall control parameter is increased from 3 degrees of freedom to 5 control parameters, A, M_1, M_2, f_1 and f_2.

The pulse generated is designed by electronic circuit such a monostable oscillator or generated by digital signal processor. The control parameter can be achieved by some resistor and capacitor. Using DSP, all the above parameters can be easily adjusted by software.

In order to increase the current amplitude of the FES, the output stage of the FES is driven by a pull up transistor with a high driving voltage $V_{cc}1$ whose voltage is several times higher than the source voltage V_{cc}. The high voltage $V_{cc}1$ is supplied by a special circuit which is namely resonant switched capacitor circuit. The main feature of this circuit is to give sufficient voltage for the FES without using transformer for voltage stepping. The circuit can therefore ensure the output pulses of the astable multi-vibrator to produce a series of current pulses whose amplitude can be up to 100 mA. A current feedback loop is included to ensure the current amplitude.

High voltage step-up power converter: The main element of the system is a resonant switched capacitor circuit which is a step-up converter as shown in Fig. 2. The circuit can provide higher voltage but without transformer or inductor. In convenient circuit (Dariush *et al*., 1998), a pulse transformer is usually needed for the stepping-up the voltage. The present circuit does not require any magnetic devices. The principle of operation of the circuit is discussed as:

The transistors Q_1 and Q_2 are the main switching components of the power converter. When Q_1 is switched on, C_{1a} is charged by V_{cc}. Its voltage then reaches V_{cc} with some ripple. Because there is an inductor in series with C_{1a}, the current of Q_2 rises from zero in a gradual manner, therefore its switching loss is small.

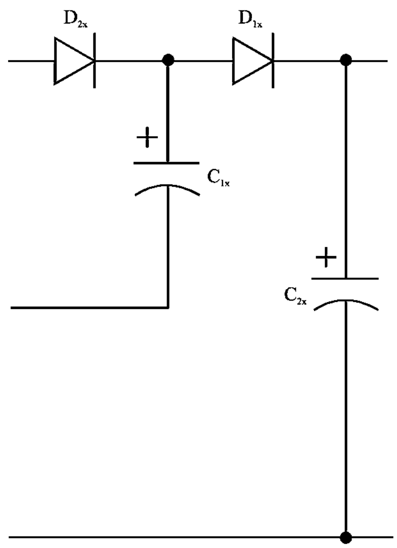

Fig. 3: Step-up cell for the switched capacitor converter (The subscript x represent a, b, c,. .)

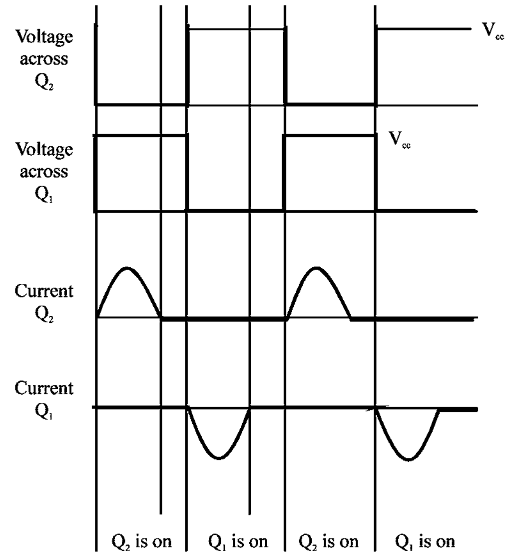

Fig. 4: The switching waveforms of the resonant switched-capacitor converter

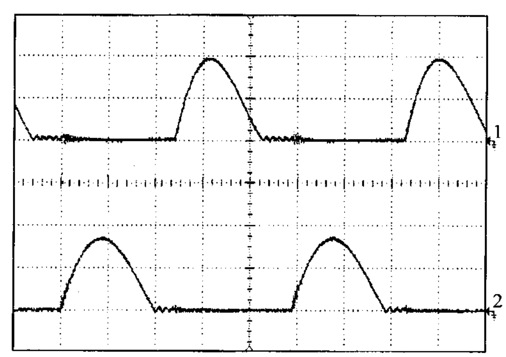

Fig. 5: Experimental results of the switching devices (top: Q_2 current 1A/div; bottom: Q_1: 1A/div; 2 μs/div)

Due to the resonance feature of C_{1a} and L_r, the current through Q_2 or L_r then resonates back to zero and the antiparallel diode D_{2a} stops its current from reversing. The resonant current stops. Q_2 can then be turned off under zero-current switching.

In the next half cycle, Q_2 has been turned off and Q_1 is turned on, C_{1a} is connected by Q_1 in series with V_{cc}. Its total voltage is 2 V_{cc} and to charge C_{2a}. Therefore the voltage on C_{2a} is equal to 2 V_{cc}. Again, because of the presence of L_r, the current through Q_2 or L_r also increases gradually from zero and therefore its switching loss is low. The resonant current resonates down to zero and cannot reverse because of D_{2a}. Therefore Its current stops and Q_1 can then be turned off.

In fact when Q_2 is turned on, C_{1b} is connected in parallel with C_{2a} through L_r. Therefore the voltage on C_{1b} is equal to 2 V_{cc}. Therefore when Q_1 is next turned on, C_{1b} is connected in series with V_{cc} through Q_1 to charge C_{2b}. The voltage on C_{2b} is 3 V_{cc}.

Similar C_{1c} is charged to be 3 V_{cc} and C_{1d} is charged to 4 V_{cc}. The voltage on C_{2c} is 4 V_{cc} and on C_{2d} is therefore 5 V_{cc}. It can also be seen that the circuit is formed by four step-up cells. Each step-up cell is formed by 2 diodes and 2 capacitors as shown in Fig. 3 in cascade in order to increase the output voltage. If high pulse voltage is needed, the step-up cell can be added accordingly. Each cell can produce an additional voltage of V_{cc}.

Resonant switching: The two transistors Q_1 and Q_2 are under zero-current switching. Figure 4 shows the current waveforms of the Q_1 and Q_2 Each transistor's current is sinusoidal current waveforms. It implies that the switching devices are switched under zero-current switching condition. The transistor's current finishes conduction before the adjacent the transistor is turned off. This also implies that it is under zero-current switching off. The product of the transistor's voltage and current is the loss of the transistor. During the transistor turning on and turning off, because the transistor's current is zero at the instant of switching, therefore the switching loss is very small. Therefore the switching loss and the emitted electromagnetic interference are low. For information, both transistors are switched into the saturation region of the transistor, i.e. during its turning on, the voltage across the transistor is zero, therefore the conduction loss is also very small. It implies that the proposed step-up circuit has good switching and conduction capability.

The experimental waveforms of the resonant switched capacitor are shown in Fig. 5. The operational parameters are:

Q_1 and Q_2 = IRF520, Lr = 0.2 μH, C_{1a}-C_{1d} and C_{2a}-C_{2c} = 20 μF. It can be seen that the current of Q_1 and Q_2 are the same as the theory. Experimental results also find that the output voltage is 62.1 V with an input voltage of 12.5 V. This thus confirms that the voltage V_{cc} applied to the three-degrees of freedom circuit can give suitable output simulation voltage as needed.

COMPUTER INTERFACING

Control: Control methods of stimulation have been studied by some authors. For example, digital fixed parameter PI and PID controllers have been used to obtain robust control of isometric muscle force in animal models (Chizeck *et al.*, 1998) and in the human upper (Crago *et al.*, 1991) and lower (Abbas and Chiseck, 1991) extremities.

In this study, a simple method is presented that uses a good arm to train the malfunctioned arm to improve the activity. The implementation of the computer system is simple. Therefore it reduces the training cost, material cost and can be portable. The most important thing is that the performance is satisfactory and has been confirmed by experimental verification.

Experimental implementation: The system is implemented in a computer controlled FES. The above control scheme is installed in Matlab with Simulink that is through a DSpace DSP1103 DSP system. It is a real time direct drive system. The software generated waveform can be connected directly to drive the patient. The experimental control diagram is shown in Fig. 6. The muscle model is now replaced by the patient's wrist muscle. The PID controller's output is connected to a Pulse Width Modulation (PWM) circuit which generates the electrical signal for the surface electrodes. The average voltage of the PWM pulse is controlled by the output of the PID controller. It is then passed through a selector switch to a DAC which is then connected to the FES. There are two inputs for each phase of the FES. The Desire angle input1 is the angle of the good arm where the MUX ADC is the measured angle from the malfunctioned arm. The controller system is to generate PWM signal to train the malfunctioned arm to follow the good arm.

Experimental results: Figure 7 shows the cockpit of the DSP1103 system. Two graphs can be seen in the Data Acquisition windows which shows the angle of the wrist and the PWM pulse of the FES. The left graph shows the desired angle in red whereas the measured angle of the wrist is shown in green. The voltage of the signals, frequency, desired output angle are shown in the digital display. The control parameters including the proportional constant, integral constant (P2) are also shown.

Figure 8 shows another experimental results with the desired signal varies in a trapezoidal manner. Whenever there are disagreements between of the angles derived from two wrists, a PWM signal is generated to stimulate the bad wrist to move until the two angles are the same.

The system has been tested with more than 10 personnel and satisfactory has been found. The movement of one wrist can induce the movement of the other arm until both wrists are synchronous. In fact, the above setup can also be extended to perform training of other complicated movement such as right-handed person becoming both-handed person.

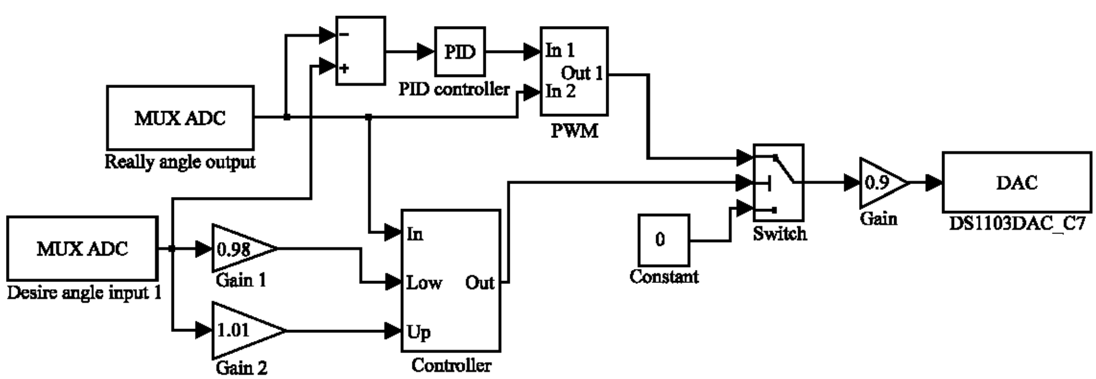

Fig. 6: Experimental setup of the FES system using DSP

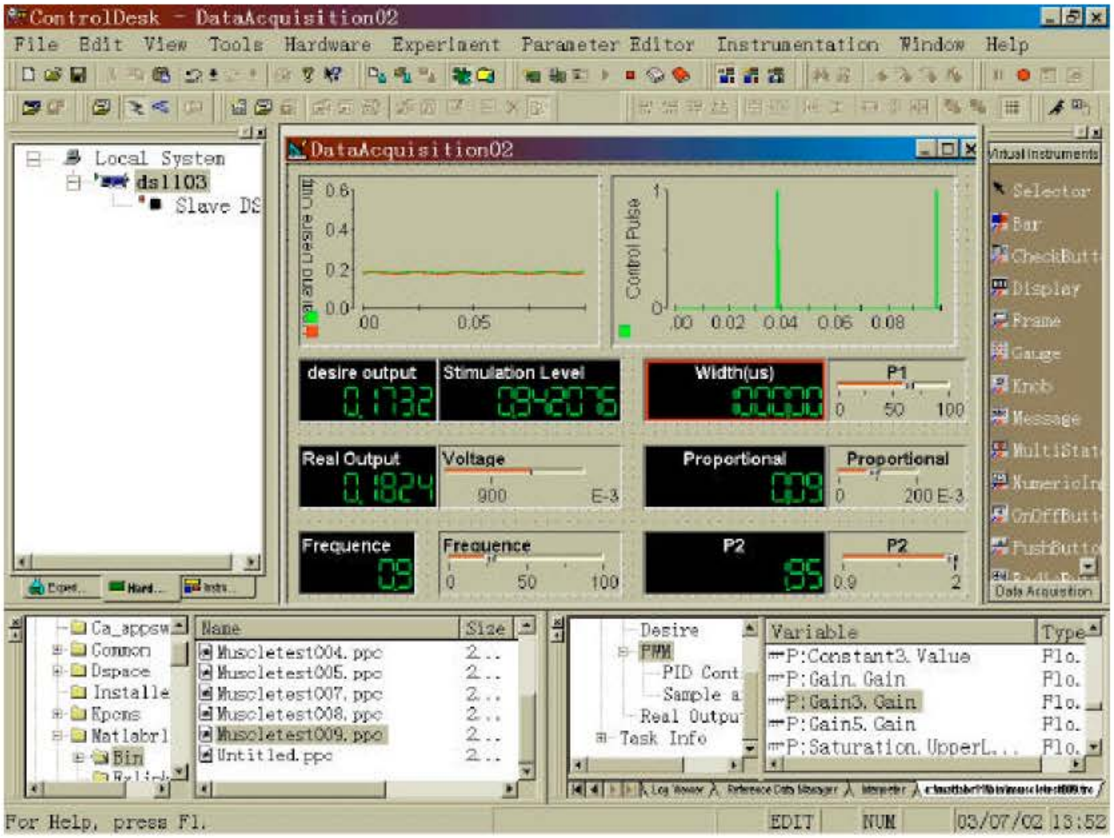

Fig. 7: Cockpit of the FES system

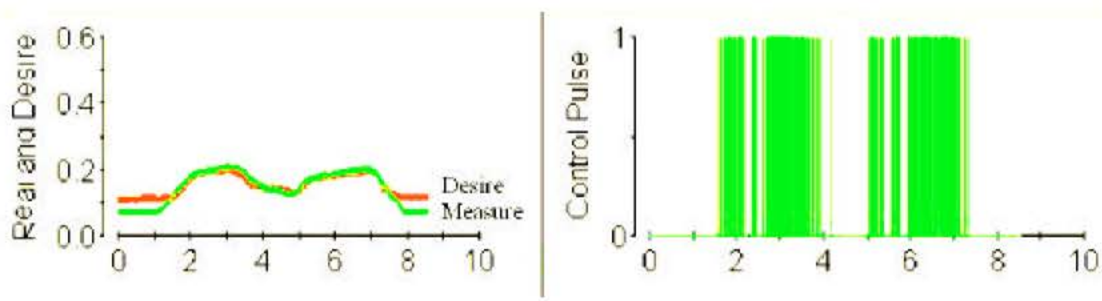

Fig. 8: Experimental results of the FES system (Control output pulse to the electrode: Measure, the reference signal: Desire)

CONCLUSIONS

A review on the current muscle model and control method for FES has been presented. The oscillator is based on 5 control parameters and can be generated by electronic circuit or DSP. The high current need is realized by a step-up power converter, namely switched-capacitor resonant converter which increases the voltage to 5 times of the source voltage. A PID controlled FES has also been described. The system is based on a closed loop configuration to train a bad arm with a good arm. The advantage is that a patient can use the proposed setup to do the rehabilitation in his/her own convenience. The system has been tested in a simulation environment using three different muscle models and has proven to give satisfactory response. The system is then implemented in a real FES with DSP controlled. Good agreement between the desired movement and the output movement can be obtained. The system has been tested for over 10 persons and they are found the system useful and user friendly.

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