Development of a Circuit for Functional Electrical Stimulation

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***Abstract*—This paper examines the various design of a multiple-purpose portable functional electrical stimulator which is used in surface stimulation of paralyzed muscle of patients with stroke and results in limb activation. The functionality, circuit performance and reliability of the circuits will be examined. Analysis, design, and experimental results are presented.**

***Index Terms*—Functional electrical stimulation (FES), resonant circuit, transformerless.**

I. INTRODUCTION

FUNCTIONAL electrical stimulation (FES) is a form of orthotic/therapeutic treatment that applies transcutaneous electrical current to initiate contractions in muscles, and is commonly used for individuals with spinal-cord injuries (SCIs) or stroke. FES has been used to facilitate upper and lower extremity mobility, improve respiratory function, restore bowel and bladder function, restore male sexual function, and to treat and help prevent secondary complications such as muscle atrophy, spasticity, pressure ulcers, deep venous thrombosis, contractures, and bone demineralization. [1]–[3]

For FES, a controlled electrical stimulus is applied to motor units/nerves to elicit a muscle contraction in an attempt to restore functional movements of a paralyzed musculoskeletal system. Several FES stimulators with microprocessor or microcontroller have been developed to improve lower and upper limb functions in subjects after SCI or stroke [4]. Most of the proposed systems have a more or less fixed design and lack of an open architecture. They generally operate with preprogrammed stimulation patterns that are stored in a lookup table. Often, a single sensor combined with a control algorithm either triggers preprogrammed stimulation sequences or scales and reads the stimulation parameters out of a lookup table [5]. A transformer is also needed to step-up the voltage. The drawback is that this increases the device size and cost, and electromagnetic interference due to the transformer. The design of the transformer is also needed to handle the small mark-space ratio of the pulse. The wide range of amplitude is also restricted because of the fixed transformer turns-ratio.

Various control strategies and circuit design have been developed to provide enhanced functionality, repeatability, and a wide range of stimulation parameters for FES stimulator [3] in order to provide predictability of muscle responses. In general, complicated circuitry and control method are needed for this application which, in turn, imposes designs that are bulky, expensive, and high-power consumption. This paper presents two viable solutions to the problem. The required components are small and the required input voltage is low. The circuits have three degrees of controllability which are amplitude, pulsewidth, and frequency and are ideal candidates for improvement of the FES circuit.

II. FES CIRCUIT USING A STEP-UP TRANSFORMER

Conventionally, FES circuit is designed by using an oscillator which generates necessary pulse by using analogue electronics. The output waveforms including amplitude, frequency, and pulsewidth can be regulated. The output is then stepped up to the required voltage by a step-up transformer.

A. Circuit Description

Fig. 1 shows the schematic diagram of the circuit. It can be divided into two parts. The first part consists of two integrated circuit (IC) timers 555 and some attached components such as resistors, capacitors, and diodes. The first 555 (IC1) is a monostable oscillator and the second 555 (IC2) is an astable multivibrator. The sensor input is reserved for external trigger signal such as a microswitch. The output of the astable multivibrator is a series of pulses. The width duty cycle and the amount of the pulses (pulse frequency) can be controlled by adjusting the value of the resistors (R_1, R_A, R_B) and capacitors (C_1 and C_2). The second part of the circuit consists of four operational amplifiers (OP1–4), a transistor, a transformer, and a set of discrete components. OP1 is used as an error amplifier. OP2 is to amplify the signal to drive the transformer T1. OP3 and OP4 are the current-feedback network. The pulse amplitude can be regulated by R_2. The transformer is used to further step up the output voltage. The function of this part is to transfer the output pulses of the astable multivibrator into a series of current pulses whose amplitude can be up to 100 mA. A current feedback loop is included to ensure the current amplitude.

B. Experimental Waveforms

These waveforms, as shown in Fig. 2 are taking at load $R = 3$ kΩ, switching frequency $fs = 200$ Hz. The inductance of the transformer is 12.2 mH and 4.8 H for the primary side and secondary side. The transformer used is: 50 : 2000

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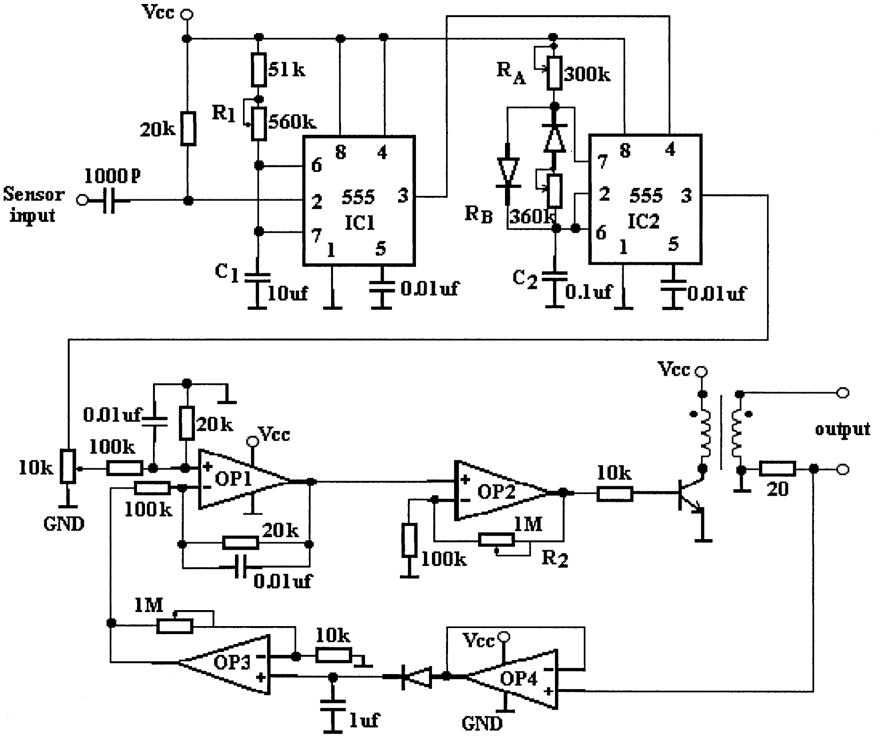

Fig. 1. Typical circuit of a transformer-based FES.

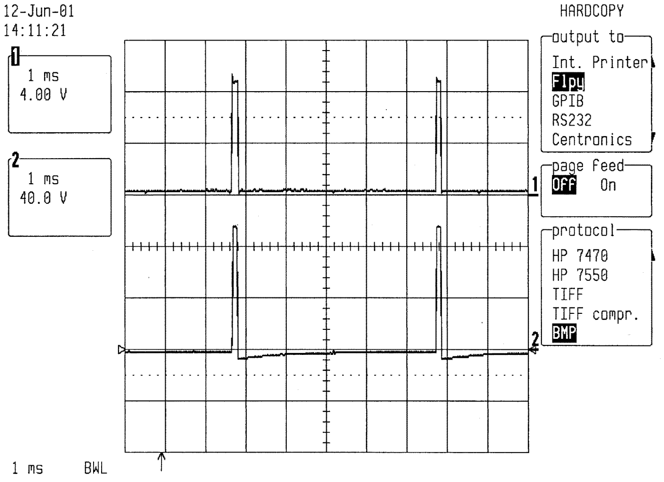

Fig. 2. Typical waveforms of a transformer-based FES. (Channel 1: output of OP2; Channel 2: output of the transformer.)

using an Rm8 core. It can be seen that the output waveforms has a negative voltage for the recovery of the transformer's magnetizing current.

III. FES Circuit Using Zero-Voltage Switching Resonant Technique

A. *Circuit Description*

Fig. 3 shows the schematic diagram of the circuit. The circuit is based on resonant converter [6] which has been used in power conversion but rarely used in medical electronics. Fig. 4 shows the idealized waveforms of the circuit. It consists of two transistors and a set of resonant components C_1 and L_1. C_2, L_2, and R are amplitude regulating components. The operation of the circuit can be derived in the following stages of operation:

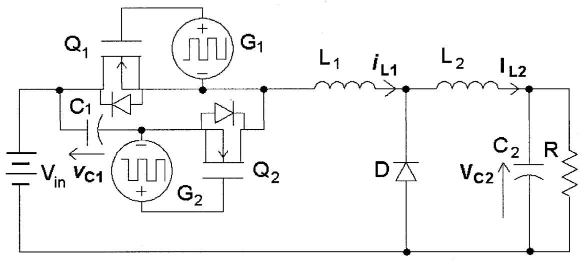

Fig. 3. Proposed resonant circuit for FES.

State 1 $[\mathbf{t}_0 - \mathbf{t}_1]$: Both transistors are turned off. C_1 is charged with current in L_2. The equation is, therefore

$$\nu_{c1} = \frac{I_{L2}}{C_1}t. \tag{1}$$

State 2 $[\mathbf{t}_1 - \mathbf{t}_2]$: When C_2 rises to V_{in}, C_1 and L_1 start to resonate. The circuit equations can be described as

$$i_{L1} = I_{L2} \cos \omega_o t \tag{2}$$

$$\nu_{C1} = V_{\text{in}} + Z I_{L2} \sin \omega_o t \tag{3}$$

where $\omega_o = 1/\sqrt{L_1 C_1}$ and $Z = \sqrt{L_1/C_1}$. This state terminates after a quarter of resonant period.

State 3 $[\mathbf{t2} - \mathbf{t3}]$: Since Q_2 is already being off, the current i_{L1} cannot pass through Q_2 to C_1 because the body-diode of Q_2 will no longer conduct. C_1 is, therefore, electrically disconnected from the circuit. The voltage of C_2 is, therefore, maintained at

$$V_{C1} = V_{\text{in}} + Z I_{L2} \tag{4}$$

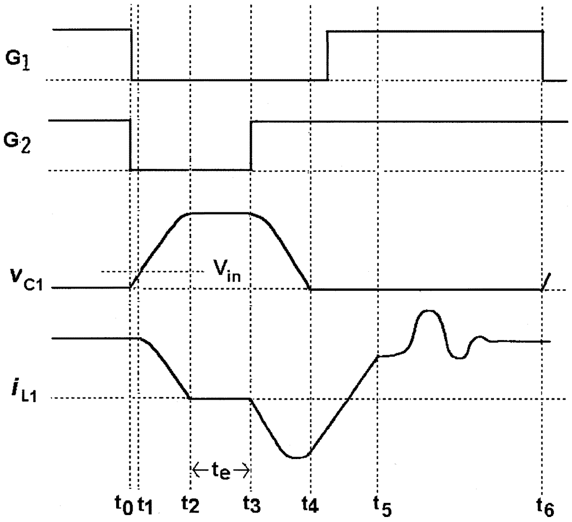

Fig. 4. Idealized waveforms of the double-mode circuit.

Therefore, the amplitude of V_{C1} is controlled by V_{in} and I_{L2}.

State 4 $[\mathbf{t}_3 - \mathbf{t}_4]$: This state can be terminated by turning on Q_2. The resonance of C_1 and L_1 as described in State 2 then resumes. The state equations can be written as

$$i_{L1} = -I_{L2}\sin\omega_o t \tag{5}$$

$$V_{C1} = V_{\text{in}} + ZI_{L2}\cos\omega_o t \tag{6}$$

when V_{C1} reaches zero and cannot resonate to negative because the body-diode of Q_1 conducts.

State 5 $[\mathbf{t}_4 - \mathbf{t}_5]$: The magnetic energy stored in L_1 is needed to be reset to zero before the whole operation cycle finishes. i_{L1} is now discharged linearly by V_{in}. The equation is shown to be

$$i_{L1} = I_{L2}\cos\left(\pi + \sin^{-1}\frac{V_{\text{in}}}{ZI_{L2}}\right) + \frac{V_{\text{in}}t}{L_1} \tag{7}$$

State 6 $[\mathbf{t}_5 - \mathbf{t}_6]$: No operation occurs for L_1 and C_1. L_2 and C_2 is then energized by V_{in} as a low-frequency resonance which is not the concern of this paper because they do not contribute the necessary output for the FES.

B. Description of the Application

Surface electrodes will be affixed to different muscle groups of the upper extremity for stimulation and monitoring the muscle activities an electromyographic (EMG) system. The muscle activities through the control system is used to trigger/control proposed device and generating the muscle contractions through electrical stimulation by deriving the voltage across C_1. The accuracy and the reproducibility of the stimulator will also be evaluated. It can be seen from Fig. 3, that the width of the waveform mainly depends on the duration of State 3. The durations of the States 1, 2, and 4 are usually designed to be much smaller compared to the duration of State 3. The amplitude of the signal depends on I_{L2} which is controlled by R through the following:

$$\nu_{C1} = V_{\text{in}} + Z\frac{V_{C2}}{R} \tag{8}$$

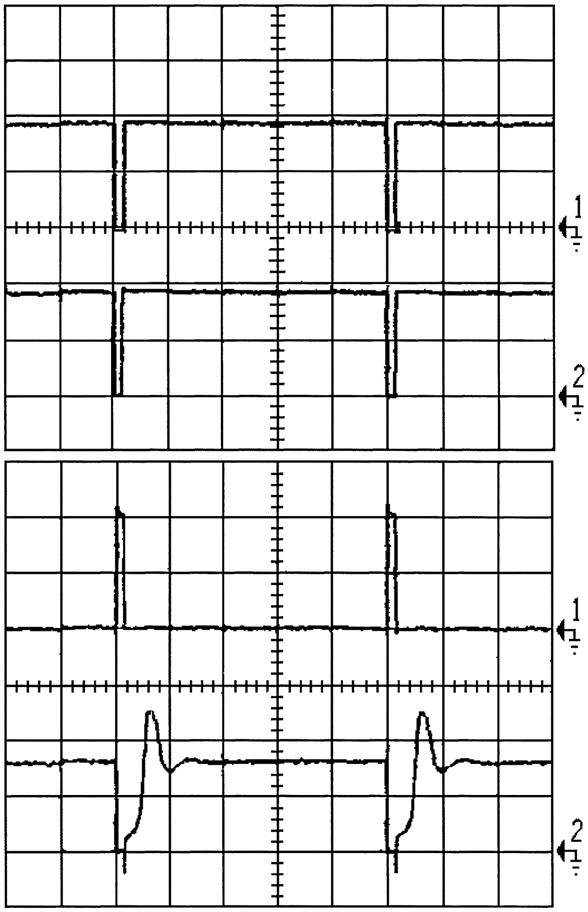

Fig. 5. Experimental waveforms of the proposed circuit.

where V_{C2} is derived by equating the input and output energies of the system, which as

$$V_{C2} = 1 - \frac{f_p}{2\pi f_o\left(\frac{\phi}{2} + \alpha + (/ - \cos\alpha)\phi\right)} - t_e f_p \tag{9}$$

where $\phi = (R/Z)/(V_{C2}/V_{\text{in}})$, $\alpha = 2\pi - \sin^{-1}\phi$, $f_o = \omega_o/(2\pi)$, and $f_p = (1/t_6 - t_0)$.

The three degrees of freedom of control of the stimulation signals are summarized as follows:

1) pulse amplitude (A_P) is adjusted by R;
2) pulsewidth (W_P) is controlled by the off-state of Q_2 or approximately equal to t_e;
3) pulse frequency (f_P) is varied by controlling the frequency of the cycle—the frequency of gate signals of Q_1 and Q_2.

C. Experimental Verification

The stimulator is designed according to the following specifications: input voltage $V_{\text{in}} = 9$ V, minimum value of pulsewidth $W_P = 20$ μs, amplitude $A_P = 20$ V $-$ 200 V, and frequency $f_P = 1$ Hz $-$ 1 kHz. The parameters used are: $L_1 = 0.6$ mH, $C_1 = 68$ nF, $L_2 = 10$ mH, and $C_2 = 10$ μF. The circuit has been tested for these specifications. Fig. 5 shows the experimental waveforms. The generated signal can give up to 100-mA pulse current for stimulation. The three control stimulation parameters are working well.

IV. DISCUSSION

The two proposed circuits have been analyzed, built and tested. The performance of two circuits is very similar and both can provide the required pulse pattern for use as an FES. The first circuit is an analogue electronic circuit, which requires a transformer to step up the voltage. The transformer is required to step up the voltage from 9 to 200 V. The design is critical because it needs to handle a pulse current of at least 100 mA. The transformer is also the most bulky and expensive component in the circuit. The component count is also high, therefore, in practice, surface-mount devices are needed.

The second circuit is based on a zero-voltage switching resonant techniques. The main feature of the circuit is that no transformer is needed. Therefore, it obviously has the advantage of no large magnetic components. The resonant component L_1 and C_1 and the dc choke L_2 are very small as it can be seen in Section III-C. The component count is also very small. The pulse currents are mainly derived from C_1 and, therefore, the selection of C_1 is very critical. C_1 must be large enough to support the energy required to the load (patient). The present selection of 68 nF is sufficient for the operation as an FES.

V. CONCLUSION

Two flexible electronic circuits have been developed for FES. The generated signal has a wide variation of the pulsewidth, controllable amplitude, and frequency. Both of the advantage and disadvantage have been discussed. The resonant circuit proposed has a preferred feature and require less component and no need to install a transformer. It also has a low component count. The circuit is simple and is operated from a 9-V voltage supply or battery.

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