TNI Journal of Engineering and Technology
Vol.2 No.2 July - December 2014

A Single-Battery Switching Boost Converting Pulse Generator for Functional Electrical Stimulation in Rehabilitation Application

Atit Tamtrakarn

Faculty of Electrical Engineering, Thai-Nichi Institute of Technology
1771/1 Pattanakarn Road, Suanluang, Bangkok 10250, Thailand
atit@tni.ac.th

Abstract— **This paper presents an application of using a switching boost converter in combination with two timer ICs for electrical stimulation in rehabilitation. The first timer IC generates a square wave pulse for the switching boost converter, while the second timer IC generates a clocking window for supplying the electrical stimulating signal to the patient in order to evoke a functional movement of the impair muscle of the patient through the specific set of nerves. The circuit implementation in this work can eliminate using of transformers. Thus, the circuit consumes smaller area than the conventional transformer approach and it does not require complicated design methodology. The simulation results show that the output waveform has frequency around 30Hz with pulse width around 220µs and pulse voltage more than 10V which can be used as Functional Electrical Stimulation (FES) device. The circuit can be operated with only a single 3V-battery which is applicable for portable device.**

***Keywords*— Functional Electrical Stimulation, FES, Boost converter, Electrical Stimulation circuit, High-voltage pulse generator**

I. Introduction

Functional Electrical Stimulation is one of an important medical method to help the patients to recover their muscle function. This method is useful for the patient that has good muscle but the brain cannot emit commanding signal to the controlling nerves. Without the commanding signal from the brain, the muscle cannot perform function by itself. This makes the muscle unmovable and leads to atrophy of the muscle due to long-period lack of usage.

Strength muscle can perform functions whenever there is a stimulating signal which is normally generated from human brain. The functional electrical stimulating is a method that supplies a stimulating electrical signal directly into the nerves and the nerves evoke the muscle shrinkage function to make its movement. For example, a paralysed patient cannot move by themselves due to the nerves lose their connection to the brain from whatever reasons, but it does not mean the patient muscle is damaged or unusable in the starting period of paralysis. The stimulating signal from outside directly to the nerves can evoke the muscle to perform its function but the signal must penetrate through the muscle and go deep enough to the nerves. This means the electrical signal must have high enough voltage since it has voltage drop during the penetration until the nerves are stimulated. The key points of this kind of functional electrical stimulation (FES) are the voltage difference of the stimulating signals and the patterns of the stimulating signal in pulse fashion. The stimulating pulse has two parameters which are frequency and duty cycle. According to previous study, we found that the pulse pattern of frequency around 20-100Hz with pulse width of 25-800us is good enough for FES pattern [1]-[2]. It is to say that a simple pulse generator with high enough voltage, less than 80V [2], and surface electrode on human skin can be used as a FES device as well.

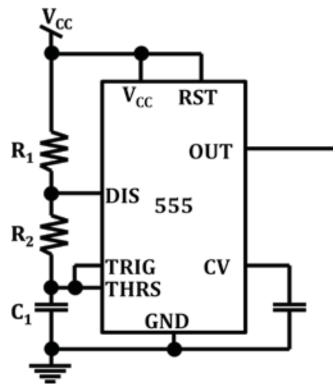


Fig.1 A pulse generator circuit by timer IC555

One circuit approach to make high-voltage pulse generator is using of a transformer as a stun-gun application [3]. However, transformer is huge and heavy equipment that is not suitable for portable device. A boost converter circuit approach is a better way in order to reducing size and weight.

The next section explains a transformer-based circuit approach of a high-voltage pulse generator and section III presents an alternative approach of FES based on switching boost converter in this work. Simulation results and conclusion are summarized in the section IV and section V respectively.

II. Implementation of Electrical Stimulation Device

As described in the previous section, a high-voltage pulse generator with proper frequency and pulse width is applicable for FES.

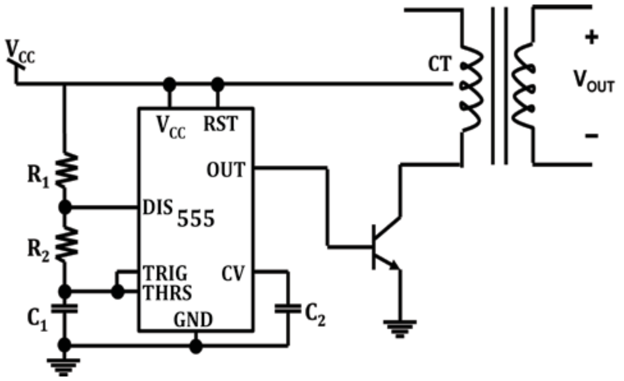


Fig.2 Circuit implementation of transformer-based stun gun

Firstly, a pulse generator with frequency 20-100Hz and pulse width in such sub-millisecond order is simply be accomplished by a timer IC 555. Fig.1 shows a pulse generator circuit by timer IC 555 [4].

Frequency (f) and its high-to-low duty cycle (D) of the circuit are defined by the following equations [4].

$$f = \frac{1.44}{(R_1 + 2R_2)C_1} \quad (1)$$

$$D = \frac{R_1 + R_2}{R_1 + 2R_2} \quad (2)$$

This pulse generator has pulse voltage equals to the supply voltage of the IC which is V_{CC} as shown in the figure. The supply voltage can be as low as 3V [4].

According to the previous section, the functional stimulation by electrical signal can be done by a simple pulse with high-enough voltage. The classic approach of the high-voltage pulse generator is transformer-based stun gun as shown in the Fig.2 [3].

This is a combination of a transformer and a timer IC 555. The timer IC generates pulse signal which is amplified by the transformer to the output probe. The timer IC works out for pulse generation while the transformer does the voltage amplification. Thus, it results in the high-voltage output pulse. The pulse voltage (V_{pulse}) is limited by supply voltage (V_{CC}) of the timer IC and turn ratio (N) of the transformer which can be simply described as follow.

$$V_{pulse} = V_{CC} \times N \quad (3)$$

In the case that a single battery is used as a power supply, the supply voltage is definitely 3V. For a transformer with its turn ratio of 10, the maximum pulse voltage is limited to 30V. This level of voltage is high enough to perform light functional simulation of some muscles like arm and foot.

A transformer is basically large and heavy equipment which is not proper for being used in portable device. Since the patient is basically not preferred heavy device to attach with their body, the lighter and smaller solution becomes necessary for actual usage. This solution is explained in the next section.

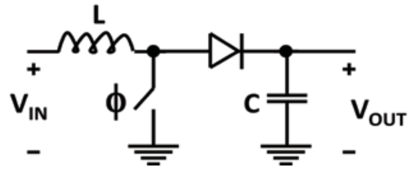


Fig.3 Basic boost converter circuit

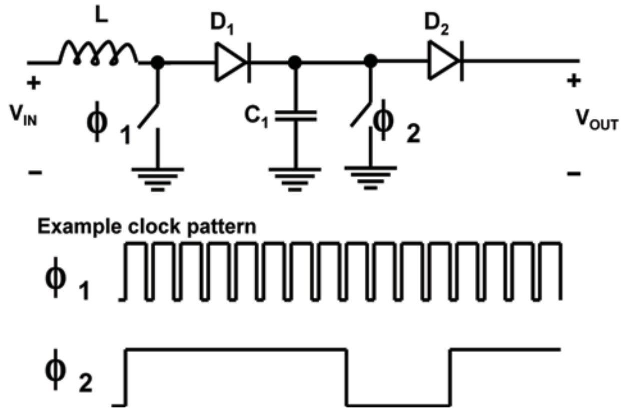


Fig.4 A switching boost-converting pulse generator for FES

III. Switching Boost-Converting Pulse Generator for Functional Electrical Stimulation (FES)

As described in the previous section, the pulse generator with voltage of 10-80V is a key implementation of FES device but the transformer-based circuit consumes too large area and too heavy for portability.

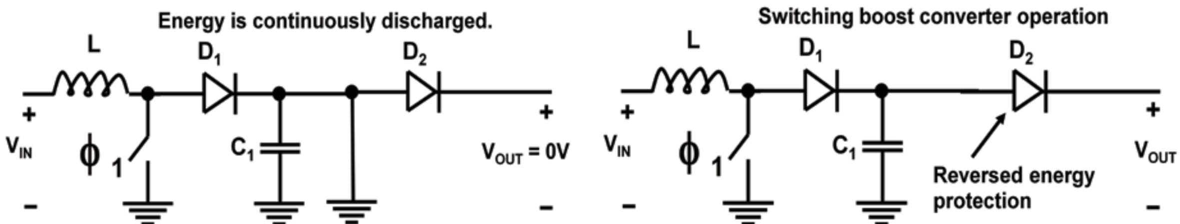
The basic concept is the stimulating voltage must be high enough in order to supply current to the nerves via human skin. Thus, it is necessary to generate this voltage level from the battery supply which has voltage of only 3V. DC-DC boost converter is a good solution for converting DC voltage from 3V to 10V or even higher.

Fig.3 shows basic boost converter circuit. The energy from the battery is stored into the inductor while the clock is turned on. This is called as “Charging phase”. The longer period of this phase, the more energy is stored in the inductor. During this phase, the output is supplied by the stored energy in the capacitor.

When the clock is turned off, the energy is transferred to store in the capacitor and also supply to the output load. Since the energy is summed up with the input voltage, the output voltage level is definitely higher than the input level due to stored energy in the inductor. It is to say that the longer the charging phase, the higher the output voltage.

The clock signal can be generated by a timer IC 555 and the switch can be implemented by only a single NMOS.

The voltage level is boosted up every period of the clock. This means it takes time for the boost converter to ramp up the output voltage. The output voltage must reach the required level within the limited pulse width which is in the range of 25μs to 800μs [1]-[2].



(a) Circuit connection when Φ_2 is on. (b) Circuit connection when Φ_2 is off.

Fig. 5 Switching mechanism of the circuit in Fig.4

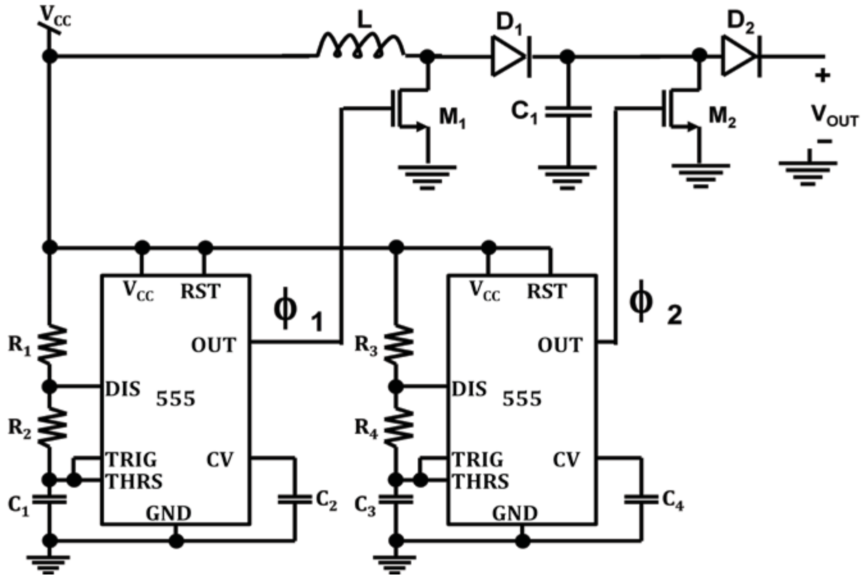


Fig. 6 Complete circuit diagram of the switching boost-converting pulse generator for FES

Hence, it is necessary to have one more set of switch and timer in order to control frequency of the pulse separately from the DC booster clock. The circuit is shown in Fig. 4.

The second switch has 2 duties. The first duty is to control frequency of the output pulse and the second duty is to act as a voltage limiter for the boost circuit. When its clock (Φ_2) is turned on, output of the boost circuit is shorted to ground. The boost circuit output is zero volts regardless of the re-charging frequency of the inductor. During this phase, there is no stimulating voltage at the output.

After the clock Φ_2 is turned off, the output node and the ground node are disconnected and the boosted voltage can be transferred to the patient skin. The mechanism of the clock Φ_2 is shown in Fig. 5(a) and Fig. 5(b) respectively.

During this phase the boost converter generates high output voltage depending on the clock frequency and duty cycle of the first clock Φ_1.

It is obvious that the pulse voltage is created during this phase only. Thus, the pulse voltage is automatically controlled by length of the off-period of the second clock Φ_2. The off-period of this clock is also equal to the pulse width as well.

With this switching scheme, each clock can be implemented by using a single timer IC 555. The complete circuit diagram of the whole system is shown in Fig.6.

As explained, a stimulating signal has three important parameters; pulse voltage (V_p), pulse frequency (F_p), and pulse width (W_p). According to equations (1) and (2), the pulse frequency and the pulse width can be set by the following equations.

$$f = \frac{1.44}{(R_3 + 2R_4)C_3} \tag{4}$$

$$D = \frac{R_4}{R_3 + 2R_4} \tag{5}$$

For the pulse voltage, it is necessary to derive from mechanism of the boost converter which normally generates output voltage as shown in the below equation [5];

$$V_{OUT} = V_{IN}\frac{1}{1 - D_1} \tag{6}$$

where D_1 is duty cycle of the first clock which can be determined from the equation (2).

In most case, it is preferred to note down the equation the term of circuit parameters instead of the system parameter like duty cycle. From the equation (6) and the circuit in the Fig.6, the output pulse voltage can be determined by this equation.

$$V_{OUT} = V_{IN}\frac{R_2}{R_1 + 2R_2} \tag{7}$$

For low clock frequency, the above equation is exactly true and the output voltage level does not deviate much from the calculation. The output voltage, however, can be deviated from the above calculation when the clock frequency is closed

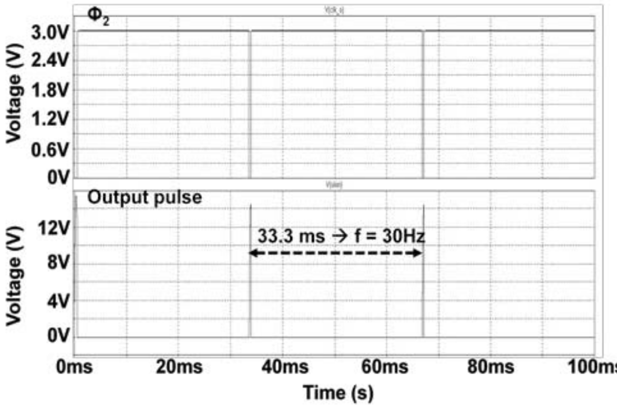


Fig. 7 Simulated output pulse and output clock signal

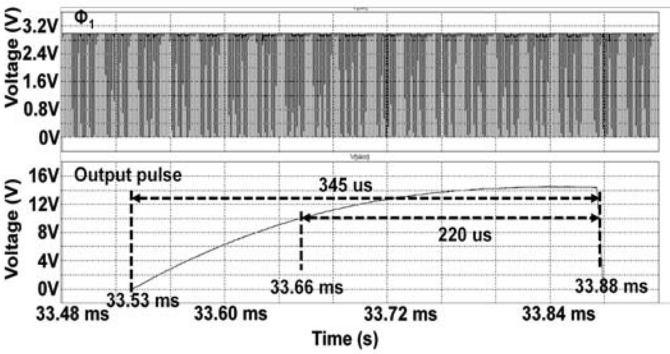


Fig. 8 Pulse width and voltage boosting clock

to the maximum limit of the timer IC 555. The reason behind is rise time and fall time of the clock are not further small compare with the clock period. The effect of rise/fall time causes huge error on the duty cycle of the high-frequency clock.

The limitation of the timer IC 555 determines the accuracy of the equation (7) as well but the equation (6) is still valid if the duty cycle is taken into the calculation instead of the circuit parameters.

This implementation is simple but it is practical for using in portable device in aspect of its size and weight since it is composed of only two timer circuits and a single boost converter with an output switch.

IV. Simulation Results

As a sample case of using the circuit in this work, the system parameters are set as table I.

TABLE I
CIRCUIT PARAMETERS FOR THE SAMPLE CASE

Item	Value
Clock frequency (kHz)	780
Pulse frequency (Hz)	30
Pulse width (micro-second)	220
Pulse voltage (V)	> 10

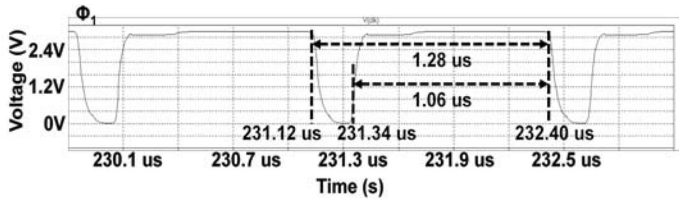


Fig. 9 Boosting clock waveform (Φ_1)

This section shows the simulation results which are based on the above parameters. The circuit simulation is run on LTSpice IV by using timer IC 555 model and power NMOS model inside the LTSpice.

Fig. 7 and Fig. 8 show the simulation result for the output pulse to the human skin which is set at 500 ohms.

Fig. 9 shows the boosting clock Φ_1 waveform. The clock has very large duty cycle (almost 100%) in order to store energy into the inductor as much as possible within the limited time. This enhancement is necessary to increase the pulse voltage to the desired level since the pulse width is very narrow.

The result confirms that the circuit operates to get pulse frequency at 30Hz and the pulse width is approximately 220μs with the pulse voltage in the range of 10V-14V. This result shows that the simulation result matches with the above calculation very well.

The generated pulse is good enough for using as stimulating signal in FES device. Also, the pulse frequency is exactly the same as the second clock Φ_2 as stated in the previous section but the pulse width is a bit different from the second clock since the output pulse requires some time for ramping up and this transient mode consumes time to get the pulse voltage reaches the stimulating voltage level. In this case, the pulse width is 220μs which is 80μs less than the determined parameter. This pulse width, however, is wide enough for nerve stimulation.

V. Conclusions

This work presents an alternative solution for FES device which is simple and applicable to light-weight portable device. The circuit is based on DC-DC boost converter with additional switching scheme. Both switching clocks are simply implemented by two timer ICs 555 and its peripheral devices. The simulation results confirm that the work done in this paper can generate a 10-14V pulse with frequency of 30Hz and pulse width of approximately 220us which is practical for using as functional stimulating signal. Besides, the presented switching boost-converting pulse generator in this work does not require using of any transformer at all.

Acknowledgment

This work is fully funded by Fudo Solutions co., ltd., Thailand under Bio-Medical Electronics Project.

REFERENCES

[1] S. Simcox, G. Davis, A. Barriskill, J. Middleton, I. Bruinsma, M. Duncan, and R. Smith, "A portable, 8-channel transcutaneous stimulator for paraplegic muscle training and mobility-A technical note," *Journal of Rehabilitation Research and Development*, vol. 41 Number 1, pp. 41–52, Jan. 2004.

[2] C. A. Phillips, "Functional Electrical Stimulation and Lower Extremity Bracing for Ambulation Exercise of the Spinal Cord Injured Individual: A Medically Prescribed System," *Physical Therapy*, Volume 69, No.10, pp.56-63, October 1989.

[3] J. Cover, "Weapon for immobilization and capture," U.S. Patent 3803463 A, April 9, 1974.

[4] "TS3V555 data sheet," ST Microelectronics, Geneva, Switzerland.

[5] "Application Report: AN-1994 Modelling and Design of Current Mode Control Boost Converters," Texas Instruments, United State of America, April 2013.