

Design and Implementation of a High Voltage Source for Biphasic Electrical Stimulators

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Abstract – Biphasic constant current (CC) stimulators are used in functional electrical stimulation applications. These stimulators require positive and negative high voltage (HV) sources in order to deliver the programmed CC pulses to load. For example, applying symmetrical biphasic CC pulses with 50 mA amplitude to a 1 kΩ load requires positive and negative supply rails of 50V and -50V, respectively. In this study, a HV source based on a switched inductance boost DC/DC converter and a switched capacitor voltage inverter is designed and implemented in order to satisfy the HV requirements of biphasic stimulators. Performance of the proposed HV topology is satisfactory for CC pulses of 35 mA applied to a 1 kΩ load.

Keywords–biphasic current source; high voltage; switched inductor; switched capacitor; DC/DC converter

I. INTRODUCTION

Functional electrical stimulation (FES) is a technique based on injecting electrical current pulses to excitable biological tissue. A bodily function is restored in patients with neurological disorders. Foot drop correction, hand grasping and releasing control, bladder and bowel control, standing assistance, cough and breathing assistance are some of the FES applications [1]. In FES applications, electrical stimulators are used for delivering constant voltage (CV) or constant current (CC) pulses to body. CC stimulators are used in many applications, where stable physiological response is required since CC stimulators result more stable response in terms of muscle contraction consistency and repeatability compared to CV stimulators. Biphasic current is preferred in many CC stimulation applications since it reduces charge accumulation risk by providing bidirectional ion flow [2].

Biphasic CC stimulators should satisfy output voltage requirements of the load. For example, applying a symmetrical biphasic current waveform with 50 mA amplitude to a 1 kΩ load requires positive (V_{HV}^+) and negative (V_{HV}^-) high voltage (HV) levels of 50V and -50V, respectively. Ilic et al. used a multi-output flyback DC/DC converter to provide V_{HV}^+ and V_{HV}^- [3]. The flyback converter isolates the output stage with low voltage electronics. However, utilization of the flyback transformer increases device size and may cause electromagnetic interference. Non-isolated switched inductance (SI) boost and buck-boost DC/DC converters can be utilized for generating V_{HV}^+ and V_{HV}^- , respectively [4], [5]. Recently, Karpul et al. expressed that boost converters are noisy and difficult to implement. They proposed utilization of cascade-

connected commercially available switched capacitor (SC) converters to supply V_{HV}^+ and V_{HV}^- [6].

In this study, it is aimed to design and implement a HV source for biphasic CC stimulators. The proposed HV source is a hybrid topology based on conventional boost DC/DC converter and SC voltage inverter. Physical realization of the proposed HV source is documented and performance of the proposed topology is evaluated by using physical experiments.

II. A BIPHASIC CC SOURCE

A biphasic CC source is considered as shown in Fig. 1 [2], [5]. Output current (i_{out}) is adjusted by using set voltage (v_{set}) and resistors (R_{set1} , R_{set2}). Operational amplifier 1 (OP1), bipolar junction transistor (BJT) 1 (Q1), R_{set1} and OP2, Q5, R_{set2} adjust positive (i_p) and negative output current (i_n), which are applied to load resistance (R_{load}) through sourcing and sinking current mirrors composed of Q2, Q3, Q4 and Q6, Q7, Q8, respectively. Stabilizing resistors (R_{stb}) are used to provide i_{out} insensitive to base emitter voltages of the BJTs [2]. i_p and i_n can be expressed as

$$i_p = \frac{v_{set}}{R_{set1}} \leq \frac{V_{HV}^+ - 2V_{CE-sat}}{R_{load} + R_{stb}} \quad (1.1)$$

and

$$i_n = \frac{v_{set}}{R_{set2}} \leq \frac{V_{HV}^- - 2V_{CE-sat}}{R_{load} + R_{stb}}, \quad (1.2)$$

where V_{CE-sat} is collector emitter saturation voltage of the BJTs.

III. PROPOSED HV SOURCE AND ITS CONTROL

Proposed HV source for satisfying V_{HV}^+ and V_{HV}^- requirements of biphasic CC stimulators is composed of an SI boost DC/DC converter and an SC voltage inverter as shown in Fig.2. The boost converter is an SI converter used for stepping-up input voltage (V_{in}) [7]. As shown in Fig. 2 (a), the boost converter is composed of an inductor (L), a controllable switch (S), a diode ($D1$) and an output capacitor (C_{out1}). Output voltage (V_{out}) of the boost converter (V_{HV}^+) can be controlled through pulse width modulation (PWM). When the PWM signal is high, energy is stored in L through V_{in} and S . The energy stored in L is transferred to C_{out1} through D_1 as the PWM signal is low. In electrical stimulation applications, boost converters operate in discontinuous conduction mode (DCM) since ripple component of inductor current (Δi_L) is generally greater

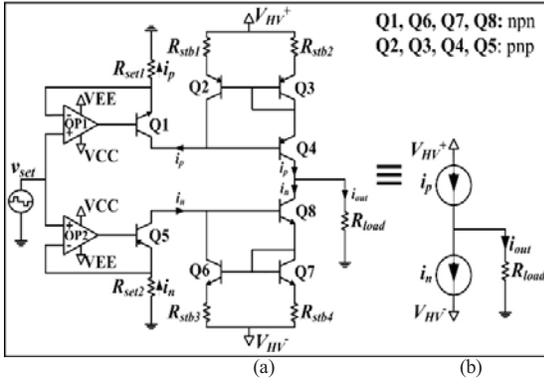


Figure 1. A biphasic CC source (a) and its equivalent circuit (b).

than its DC component (I_L) due to low i_{out} (~ 1 -100 mA) and high V_{out} (~ 100 V) requirements. Voltage conversion ratio of the boost converter (A_V) in DCM can be expressed as

$$A_V = \frac{V_{out}}{V_{in}} = \frac{1 + \sqrt{1 + 2D^2 R_{load} T_s / L}}{2}, \quad (2)$$

where D and T_s are duty cycle and period of the PWM signal, respectively [7].

Hybrid converters composed of SI and SC converters are used in industrial applications, such as power sources of liquid crystal displays (LCD) [8]. By utilizing a similar perspective, V_{HV} requirement of the biphasic stimulator can also be satisfied with an SC inverter connected to the switching node (A) of the boost converter. By using this topology, V_{HV}^+ and V_{HV}^- requirements of the biphasic stimulator can be satisfied with a single controllable switch (S) and an inductor (L). As shown in Fig. 2 (a), the SC inverter is composed of diodes $D2$, $D3$, pump (C_p) and output (C_{out2}) capacitors. Switching signal required at input of the SC inverter is supplied by voltage on A (V_A). When V_A is high ($V_A = V_{HV}^+$), $D2$ and $D3$ are forward and reverse biased, respectively. C_p is charged through $D2$ to $V_{HV}^+ - V_{fw}$, where V_{fw} is the forward voltage drop of the diodes. When V_A is low ($V_A = 0$), the voltage on B is equal to $-(V_{in} - V_{fw})$ due to the voltage on C_p . As a result, $D3$ is forward biased and C_{out2} is charged through $D3$ to $-(V_{in} - 2V_{fw})$. For continuous operation of S , V_{HV}^- can be expressed as

$$V_{HV}^- = -[V_{HV}^+ - 2V_{fw} - i_n / (fC_p)], \quad (3)$$

where f is switching frequency and $1/(fC_p)$ is output impedance of the SC inverter.

Output voltages of the proposed HV topology are controlled using the process shown in Fig. 2 (b). V_{HV}^+ and V_{HV}^- are measured as V_{m1} and V_{m2} by using resistor dividers composed of R_{m1} and R_{m2} . V_{m2} is inverted by an inverting amplifier ($V'_{m2} = -V_{m2}$). V_{m1} and V'_{m2} are compared with a voltage reference (V_{ref}) obtained from a resistor-capacitor (R_{st}, C_{st}) soft start circuit. Comparator outputs are buffered and fed into a NOR gate in order to generate a reset signal (R), which is active when both V_{m1} and V'_{m2} are above V_{ref} . In the next step, R and a PWM signal are fed to a set-reset (SR) latch which is used to control the gate driver.

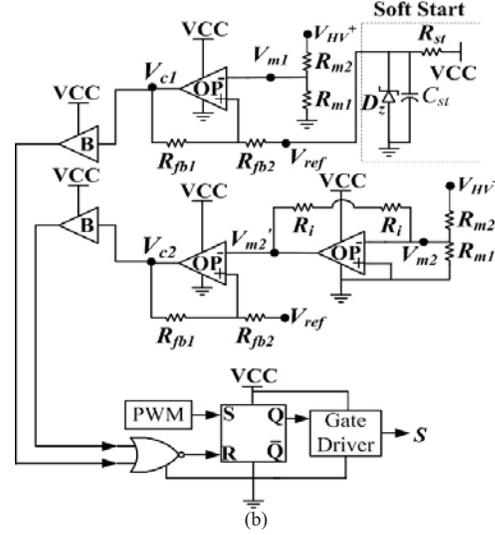
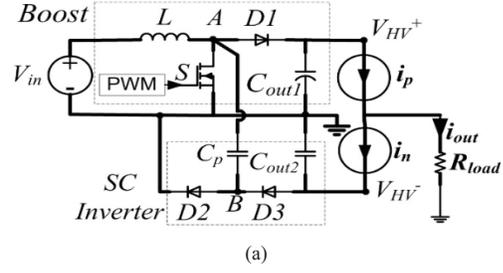


Figure 2. Proposed HV source for biphasic CC stimulators (a) and its output voltage control process (b)

Start-up procedure of the proposed topology can be explained as follows. No-load condition is considered. Initially, V_{ref} is zero due to the soft start circuit. V_{in} charges C_{out1} to $V_{in} - V_{fw}$ immediately. C_{out2} is also charged to a very low level. Therefore, initially, both V_{m1} and V_{m2}' are above V_{ref} and the switching signal (S) of the gate driver is zero. As V_{ref} reaches V_{m2}' , S becomes active, both V_{m1} and V_{m2}' (equivalently V_{HV}^+ and V_{HV}^-) increases. During the start-up, V_{m2}' tracks V_{ref} . On the other hand, V_{m1} overshoots V_{ref} since V_{ref} reaches V_{m2}' at first. However, both V_{m1} and V_{m2}' increase in similar rates if C_{out1} and C_{out2} are chosen equally. In biphasic stimulation applications, i_p and i_n are supplied by V_{HV}^+ and V_{HV}^- , respectively. During the application of i_n to R_{load} , S regulates V_{m2}' (equivalently V_{HV}^-) to V_{ref} . During this period, V_{m1} (equivalently V_{HV}^+) also increases and overshoots V_{ref} . When i_p is applied to R_{load} , V_{m1} decreases through V_{ref} and S regulates V_{m1} as soon as V_{m1} reaches V_{ref} .

IV. PHYSICAL REALIZATION

The proposed HV source is implemented as a printed circuit board. Properties of the HV source are summarized in Table I. A biphasic CC source based on the circuit in Fig. 1 is used as the load of the HV source. The biphasic CC source is controlled by a signal generator composed of a microcontroller and a digital to analog converter as explained in [5]. A resistive load of 1 k Ω is used at the output of the biphasic CC source. Experimental set-up is shown in Fig. 3. The HV source

TABLE I. Properties of the Implemented HV Source

Component	Part Name and/or Properties
VCC (V_{in})	12V
S	IRF530, n-channel MOSFET
$D1, D2, D3$	SB560, Schottky Diode
L	ABCO, 10 μ H, 1A
C_{out1}, C_{out2}	Secon, 63V, 47 μ F electrolytic
C_p	Weidy, 63V, 680 nF polyester
NOR gate	RTL logic, 10 k Ω , BC237
Gate Driver	IR2153 Self Oscillating Gate Driver, $f = 180$ kHz
OP	LM324, quadruple operational amplifier
R_{m1}, R_{m2}, R_i	1 M Ω , 10M Ω , 1 M Ω
Soft Start (D_z)	Zener Diode, $V_{break} = 3.2$ V
Soft Start (R, C)	10 k Ω , 47 μ F

is supplied by a 12V DC power source. Quiescent current of the HV source is 40 mA. Transient and steady-state characteristics of the HV source are measured by using a 2-channel oscilloscope with 100 MHz bandwidth (AA Tech ADS3202B).

V. EXPERIMENTAL RESULTS

The implemented HV source is turned on for no load condition. Oscillograms for transient response of $V_{m1}, V'_{m2}, V_{HV}^+$ and V_{HV}^- are shown in Fig. 4. As shown in Fig. 4, V_{m1} and V'_{m2} increase suddenly as V_{in} is applied. V'_{m2} tracks V_{ref} as soon as V_{ref} reaches V'_{m2} . V_{m1} (equivalently V_{HV}^+) is relatively constant when V'_{m2} is smaller than the initial level of V_{m1} during start-up. During this stage, the stored energy in L is transferred to the SC inverter since $D1$ is reverse biased. As V'_{m2} reaches V_{m1} , both V_{m1} and V'_{m2} (equivalently V_{HV}^+ and V_{HV}^-) reach steady-state. It is observed that both V_{HV}^+ and V_{HV}^- reach the steady-state values of 38.4V and 39.2V in a 500 ms time period.

Amplitude and frequency of the biphasic CC source are adjusted as 35 mA and 50 Hz. In order to observe the steady-state characteristics of the proposed HV source for different CC load conditions, the pulse widths of i_p and i_n are adjusted as 1 ms, 3 ms, and 10 ms. Oscillograms for the steady-state response of the HV source for different CC loads are shown in Fig. 5. As shown in Fig. 5, ± 35 V is observed on the 1 k Ω load due to the i_p and i_n pulses with 35 mA amplitude. As shown Fig. 5 (b, d, f), i_n pulses discharge C_{out2} which decreases V_{HV}^- . The controller drives S in order to regulate V_{HV}^- . During the period in which S regulates V_{HV}^- , V_{HV}^+ also increases and overshoots the reference level, as shown Fig. 5 (a, c, e). The additional energy stored in C_{out1} during the overshoot periods are dissipated by the i_p pulses. The average V_{HV}^+ values are measured as 38.8 V, 38 V, and 38 V for the i_p and i_n pulse widths of 1 ms, 3 ms, and 10 ms, respectively. The corresponding average V_{HV}^- values are 39.2 V, 39.6 V, and 37 V, respectively. It is seen that the proposed HV source can supply i_p and i_n pulses with 35 mA amplitude and different pulse widths.

VI. DISCUSSION AND CONCLUSIONS

A HV source satisfying the requirements of a biphasic CC stimulator is designed and implemented. V_{HV}^+ is supplied by the SI boost converter with 4 basic components ($L, S, D1, C_{out1}$). The boost converter with

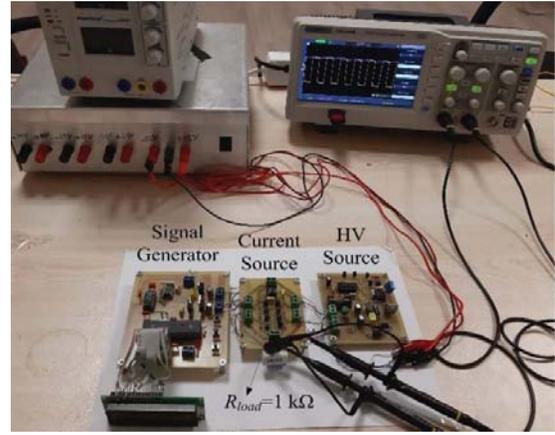


Figure 3. The experimental set-up.

minimum number of components is very easy to implement. V_{HV}^- is easily obtained by adding two diodes and two capacitors ($D2, D3, C_p, C_{out2}$) to the switching node of the boost converter. By using a relatively high switching frequency of 180 kHz, the boost converter is realized with a small inductance of 10 μ H. Size of the proposed HV source is kept small (i.e. 75 \times 88 mm²) although through-hole discrete components are used as shown in Table I.

In desktop and portable applications, the HV source can be supplied by a medical grade power source and a battery, respectively. Excluding the inductor and capacitors, the HV source can be implemented as an integrated circuit. Steady-state V_{HV}^+ and V_{HV}^- measurements are between 37 V and 39 V for different conditions. Using the HV source, shaped bipolar current pulses between 37 mA and -39 mA can be supplied to a 1 k Ω load. i_{out} rating can be improved by adjusting V_{HV}^+ and V_{HV}^- through $V_{ref}, R_{m1},$ and R_{m2} . As expressed in [4] and [5], 12V to 100V conversion can be obtained with the proposed single stage SI boost converter. Larger voltage swing in the order of 300V can be achieved with two-stage SI boost converters [4]. The proposed HV topology provides regulated v_{out} for different i_{out} conditions, whereas v_{out} of the cascaded SC inverter solution in [6] will decrease as amplitude and duty cycle of i_{out} increases due to the output impedance of the inverters. The HV solution in [6] is evaluated for a low i_{out} level of 1 mA which is much smaller than the i_{out} level of 35 mA used in this study. The proposed HV topology is a design competitive low-cost solution for commercial stimulators with large currents.

As shown in Fig.5, V'_{m2} tracks V_{ref} and V_{m1} overshoots V_{ref} during the operation of the HV source. The overshoot in V_{m1} can be eliminated by using a chopper composed of a resistor and a ground referenced switch in parallel with C_{out1} . In this configuration, the chopper will remove the additional energy stored in C_{out1} , when V_{m1} overshoots v_{ref} . Designers can also add a logic to the system to block S if V_{m1} reaches a certain threshold, as a potential safety measure. Output voltage tracking characteristics of the

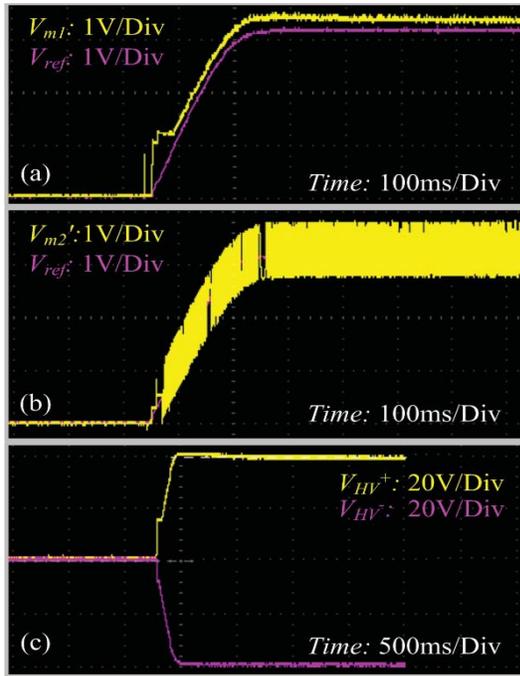


Figure 4. Oscilloscopes obtained for the transient response of V_{m1} (a), V_{m2} (b), V_{HV}^+ and V_{HV}^- (c).

proposed HV source can be changed by applying a different logic design in the control block shown in Fig 2 (b). For example, if a NAND gate is used instead of the NOR gate, V_{m1} will track v_{ref} . For the control block with a NAND gate, the turn-on process of the HV source can be explained as follows. At first, V_{m1} and V'_{m2} increase suddenly as V_{in} is applied. S is zero since V_{ref} is below V_{m1} and V'_{m2} . As V_{ref} reaches V'_{m2} , S remains zero since V_{ref} is still below V_{m1} . As V_{ref} reaches V_{m1} , S becomes active and regulates V_{m1} to track V_{ref} . V'_{m2} also increases during the period in which S is active. In the steady-state, V_{m1} tracks V_{ref} , whereas V'_{m2} is below V_{ref} . During the i_p pulses, S becomes active and regulates V_{m1} , which also increases V'_{m2} . However, S is not active during the i_n pulses which decreases V'_{m2} . It is observed that the control block regulates the measured voltage which V_{ref} reaches first. As shown in Fig. 5, C_{out1} and C_{out2} filter out the high frequency switching noise in the steady-state V_{HV}^+ and V_{HV}^- waveforms. Therefore, the noise is not observed as a problem for the SI boost converter and SC inverter which is mentioned in [6].

V_{HV}^- can be obtained by using an SI buck-boost converter with inverted output [5]. However, utilizing a buck-boost converter has several disadvantages. The first one is to use an additional inductor which will increase the size of the HV source. The second disadvantage is the need for a high side controllable switch. Since there is a single input voltage source, an isolated gate driver for the high side switch is not an option. Standard half bridge MOSFET gate drivers with bootstrap function are not suitable for the high side switches of the buck boost converters. Using a p-channel MOSFET seems to be the only solution. As the third disadvantage, the buck-boost topology also requires a separate output voltage control block, an oscillator and a gate driver.



Figure 5. Oscilloscopes obtained for the steady-state response of V_{HV}^+ (a, c, e) and V_{HV}^- (b, d, f) for i_p and i_n pulses with 35 mA amplitude and 1 ms (a, b), 3 ms (c, d), and 10 ms (e, f) pulse-widths. Yellow waveforms represent i_{out} . Purple waveforms represent V_{HV}^+ (a, c, e) and V_{HV}^- (b, d, f). Voltage and time divisions are 20V/div and 10 ms for both channels.

Finally it can be concluded that the implemented HV source topology can be used in any application requiring bipolar voltages in addition to biphasic electrical stimulators.

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