High-Power Current Source with Real-Time Arbitrary Waveforms for *In Vivo* and *In Vitro* Studies of Defibrillation

Ilija Uzelac[1], Mark Holcomb[2], Ronald S Reiserer[3], Flavio H Fenton[1], John P Wikswo[3]

[1]Georgia Institute of Technology, Atlanta, GA, USA
[2]Susquehanna University, Selinsgrove, PA, USA
[3]Vanderbilt University, Nashville, TN, USA

Abstract

Defibrillators are standard tools for treating cardiac fibrillation; however, the mechanisms by which they terminate deadly cardiac arrhythmias are still not fully understood, and optimizations to lower energies are very desirable. Clinical defibrillators do not provide a precise control of shock timing, duration, and voltage (current), and operate with fixed waveforms. Therefore, they are not suitable for research, particularly when studying low-energy defibrillation methods that require an examination of arbitrary and strictly timed waveform shocks of varying strength and duration. We present a custom-made microcontroller voltage–to-current converter (V2CC) with an output isolated from the Earth ground, capable of delivering up to 1 A continuously and up to 5 A into a 40 Ω load for >500 ms in a pulsed regime. For currents lower than 5 A, the load resistance can be higher, so that the product current times resistance is guaranteed to be up to 200 V. Bandwidth is in excess of 1 kHz, timing accuracy, response time, and rise and fall times are better than 10 µs. In addition, multiple safety mechanisms are implemented to protect the device and the operator. In our feedback control experiments the device has been tested successfully on isolated rabbit hearts. The V2CC is primarily designed to be used in ex vivo cardiac experiments, but is suitable for a wide variety of settings that require a high-current source of arbitrary waveforms.

1. Introduction

Commercial defibrillators use mostly biphasic truncated exponential (BTE) and rectilinear biphasic (RBW) waveforms. A BTE defibrillator delivers initially a peak current followed by an exponential decrease of current strength due to the capacitor bank discharge. It is important to highlight that a successful defibrillation actually depends on the delivery of adequate average current[1,2] more than the high peak currents, which are associated with decreased ejection fraction and other myocardial dysfunctions[3,4]. Several studies have shown that average current is responsible for defibrillation[5,6] and is a better descriptor than total energy and voltage, generally used in the selection of appropriate therapeutic doses, regardless of biphasic waveform and energy strength[7]. If patient outcomes were all about energy, increasing the duration of a shock would improve defibrillation success, because it would increase the energy of a shock, but a higher energy setting does not necessarily mean an increase in current. The longer the shock continues, there is more decay in the delivered current, resulting in a lower average current. Therefore, defibrillators that vary duration of a shock to compensate for variations in transthoracic impedance to generate a given energy may be short on adequate current. Studies have shown that biphasic shocks longer than 10 ms actually increase the defibrillation threshold[8]. Increasing the voltage as impedance compensation also doesn't mean higher current, even though it does deliver the desired or higher energy. RBW defibrillators, on the other hand, keep the current and duration of the waveform constant as impedance varies. Commercial biphasic defibrillators are still based on energy as descriptor for a therapeutic dose. Manufacturers should be encouraged to design current-based biphasic defibrillators as an alternative to the energy–based devices to avoid inappropriate defibrillation doses when transthoracic impedance varies.

1.1. Voltage–to-Current Converter

Our V2CC device is primarily designed for *ex vivo* studies that range from small rabbit hearts to swine hearts, and it resembles both implantable and external defibrillators. Because of its fast response times and precise timing accuracy (both at around 10 µs), the V2CC is suitable for experiments involving a variety of feedback control techniques, including the use of signals obtained from complex cardiograms. Furthermore, precise timing allows monitoring defibrillation shocks with other instruments, such as cameras, optical sources, and any other electrical stimuli that need to be synchronized with the device.

2. Design

Figure 1 shows a block schematic of the V2CC. The operational core is designed around the transimpedance amplifier The logic core is designed around a microcontroller that provides proper operational mode.

The power supply unit consists of a 120/240 V 250VA isolation transformer that provides a rectified DC voltage of 240 V_{rms}, and is switched on/off with the DPST solid-

isolated 16-bit A/D converter that digitizes external arbitrary waveform in the range of ±5 V, where 1 V on the input corresponds to 1 A on the V2CC output. The digitized signal is subsequently transferred over digital isolators to a 16-bit D/A converter, which drives the transconductance amplifier. Additionally, the digital output *Sign* signal from the ABS module serves as an external interrupt for the microcontroller to set the same polarity on the V2CC as the sign of the input waveform.

Current and voltage sense bipolar isolation amplifiers are designed in the same way as the ABS isolation amplifier. The output voltage from the voltage sense

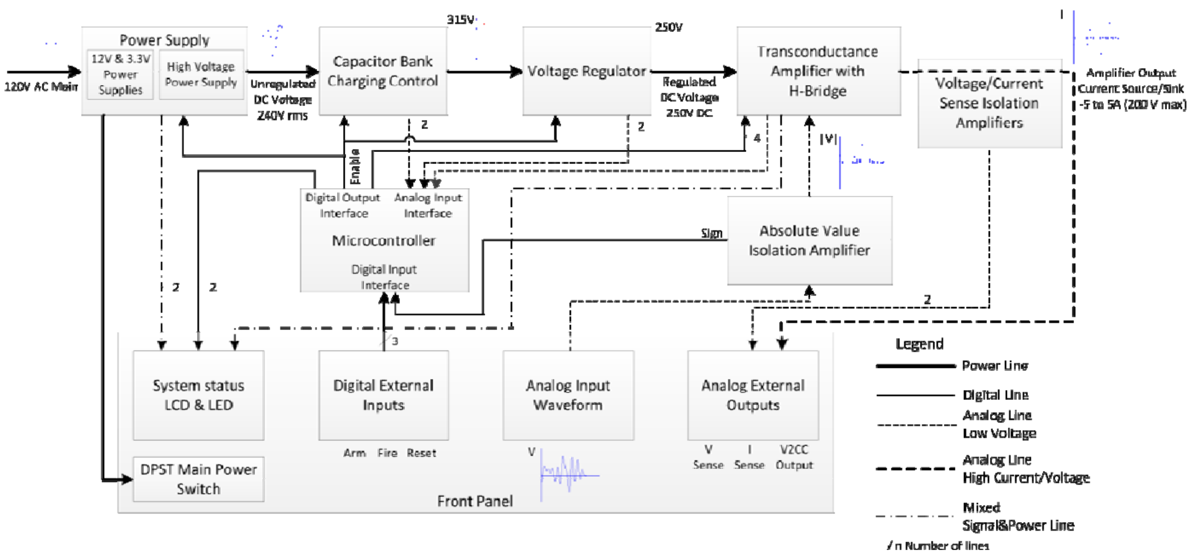

Figure 1. Schematic block of the V2CC.

state relay by way of the digital *Enable* signal from the microcontroller. Initially at power-on, as a security mode, only two low-voltages are available (3.3V and 12V)

The Capacitor Bank Charging Unit (CBU) consists of four 10,000 µF capacitors with an inrush, current-limiting circuitry of 1A and a voltage of up to 315 V. As a safety measure, a pair of normally closed solid-state relays, controlled by software with the *Enable* signal, is implemented to discharge the capacitor bank when powered-off.

The voltage regulator provides regulated 250 V DC, and its operation is controlled by software with the *Enable* signal. To protect the V2CC output from short circuits and overcurrent, the voltage regulator limits the output current to 5 A and has a short circuit protection activating within nanoseconds when the output of the voltage regulator drops below 200 V. The voltage on the output is held constant when the capacitor bank is rapidly discharged. As it takes at least 500 ms for the capacitor bank to discharge from 315 V to 250 V and maximally 4.5 s to charge up again, the duty cycle is 10%. With lower currents the duty cycle increases to 100% (≤1 A).

The absolute value isolation amplifier (ABS), has an

isolation amplifier is scaled so that 1 V represents 40 V on the V2CC output, while 1 V from the current sense isolation amplifier output represents 1 A on the V2CC output.

The transconductance amplifier is designed as a classic unipolar voltage-controlled current source where current is proportional to the output voltage from the ABS module with a gain of 1 S, meaning that the full output of 5 A is for an input of 5 V (Figure 2). Compliance voltage is minimally 200 V. Bipolar operation is provided with the H-Bridge placed in series. Polarity across the H-Bridge is controlled with the *H-Bridge* +/- digital lines set by the microcontroller. It takes about 1 µs to switch the polarity, and during this time interval the transconductance amplifier is disenabled with the *T-Amp Block* digital signal line to prevent possible current spikes at zero-crossing. As a safety mechanism, the mechanical reed relays are placed on the output from the H-Bridge, keeping the V2CC output disconnected. Relays are controlled with the *RR-Enable* digital signal from the microcontroller. Keeping the output disconnected when the device is not stimulating prevents any zero leaking current to avoid half-cell effects at the electrode-tissue interface[9]. *RR-Status* is an output digital line from the amplifier module to the microcontroller. It indicates the status of the reed relays, as an additional safety measure. Due to the slow response of mechanical relays (~30 ms), the output also can be kept disconnected by disenabling the H-Bridge with the user-controlled digital input signal, termed "*Fire,*" enabling the H-Bridge within 10 µs.

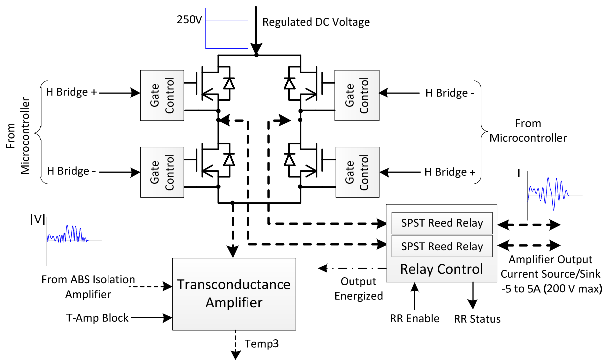

Figure 2. Transconductance amplifier.

2.1. Microcontroller

The microcontroller module uses an 8 MHz MSP430F169 Texas Instruments microcontroller. It assures proper working of the V2CC modules and provides the operator with status messages. Its inputs and outputs are divided into four sections: analog inputs, digital inputs, digital outputs, and a serial port communication. Five analog inputs sampled at 1 ksps are: *Temp1*, *Temp2*, *Temp3*, *V Cap*, and *V Reg*. They respectively correspond to the heat-sink temperature of the capacitor charging module, voltage regulator, transconductance amplifier, voltage across the capacitor bank and voltage at the output of the voltage regulator. If during normal operation temperature exceeds 50 ºC, the voltage across the capacitor bank falls lower than 250 V, or the voltage reading from the voltage regulator is outside of the range 240-260 V, the device will shut down and disconnect the V2CC output. Digital output signals are: *Enable, H-Bridge+*, *H-Bridge–*, *RR-Enable*, *T-Amp Block,* and front panel control lines that control the LCD on the front panel and drive the "System Running/Charging LED". Digital input signals from the front panel are *Arm, Fire*, and *Reset* and internal signals *Sign* and *RR-Status*. When *Arm* is activated, the microcontroller will enable the output reed relays by activating *RR-Enable*, but only if all other relevant parameters are within their specified range. In the same way only when *Fire* signal is active the microcontroller will activate *H-Bridge–* or *H-Bridge+*. If *Arm* is inactive, the active *Fire* will be ignored. Through the serial port the microcontroller port communicates wirelessly with the PC over the pair of XBee modules for debugging purposes to read the values of all the microcontroller digital and analog lines.

On the front panel are located the digital inputs *Arm* and *Fire,* analog waveform input, analog voltages representing the current and voltage on the V2CC output, the main switch, the LCD panel (shows the values of the five analog input signals to the microcontroller and a current operational mode), and the LEDs. LEDs indicate the main power, the energizing of the high voltage power supply, the proper running/charging conditions, and energizing of the V2CC output. Figure 3 shows the inner assembly of the V2CC without the front panel.

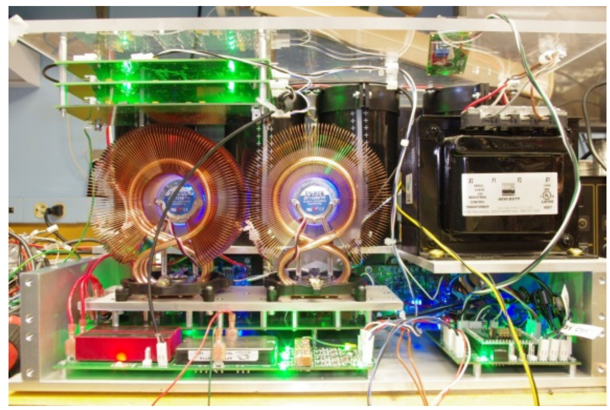

Figure 3. Assembled device without the front panel.

2.2. Theory of operation

In the startup mode, during the power-on cycle, the microcontroller ignores any digital/analog input from the front panel and monitors all digital/analog signals to ensure that they are in their predefined range. Subsequently, the microcontroller activates the *Enable* signal and enters into the Charging mode. When voltage across the capacitor bank reaches at least 305 V, the V2CC enters into the running mode and all analog/digital signals from the front become relevant. In order to deliver the specific waveform shock, the operator needs to activate both *Arm* and *Fire* signals. For fast responses of 10 us, *Arm* can be activated continuously, and *Fire* will activate the H-Bridge that keeps the V2CC output in high impedance. In the event of an error, the device will shut down and normal operation can be restored by using the *Reset* button.

3. Results

To illustrate the versatility of the device, Figure 4 shows examples of squared and sinusoidal bipolar output waveforms of 5 A for two different frequencies (10 Hz and 1 kHz) delivered into a 40 Ω load and measured from the current sense output. At 1 kHz the influence of the low-pass filter in the transconductance amplifier is visible. The device has been used successfully in defibrillation experiments on isolated whole rabbit hearts, with the optical mapping experimental procedure described elsewhere[10,11,12]. Figure 5 shows examples of successful defibrillation using extreme regimes of high and low energies. The upper traces show the fluorescence transmembrane potential signal of cardiac cells integrated over a portion of the right ventricle; the lower traces are from the defibrillation shocks designed to replicate a BTE defibrillator and multiple low-current feedback shocks.

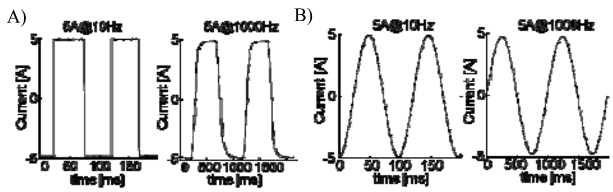

Figure 4. Examples of the waveforms produced with the V2CC into 40Ω load. A) Square waveform. B) Sinusoidal waveform.

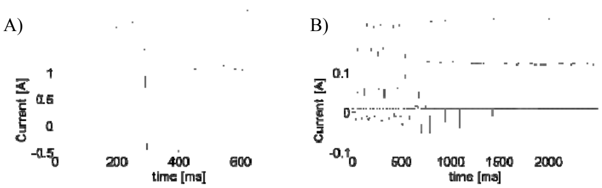

Figure 5. Examples of defibrillation. A) Single high-energy shock. B) Multiple low-energy shocks.

4. Conclusions

We have demonstrated a versatile, microcontroller arbitrary-waveform current-source device suitable for scientific experiment of defibrillation that is capable of delivery high energies as well as multiple pulses of arbitrary wave forms. The device has proven to be effective for testing single defibrillation shocks as well as for multiple shocks using feedback control. In a case that higher currents are needed the V2CC can be easily modified thanks to its modular design.

5. Disclaimer

The design of this device is not certified by any individual or organization, nor is intended for use on human subjects. The authors do not accept any responsibility for injury or death that might occur as a result of proper or improper use of this device. Given these caveats, the system we have developed is robust and well suited for a wide variety of experiments, including, but not limited to, cardiac defibrillation.

Acknowledgements

This work is supported in part by an FDA contract, NIH Grant R01 HL58241-11 through the American Recovery and Reinvestment Act of 2009, and the Vanderbilt Institute for Integrative Biosystems Research and Education (VIIBRE).

References

[1] Weilun Q, Chen B, Li Y, Freeman G. Average current is better than peak current for the prediction of defibrillation success in a porcine model of cardiac arrest. In: Heart Rhythm 2013: Annual Scientific Sessions. Denver 2013.

[2] Malkin RA, Guan D, Wikswo JP. Experimental evidence of improved transthoracic defibrillation with electroporation-enhancing pulses. IEEE transactions on bio-medical engineering 2006;53(10):1901–10.

[3] Mittal S, Ayati S, Stein KM, et al. Transthoracic cardioversion of atrial fibrillation : comparison of rectilinear biphasic versus damped sine wave monophasic shocks. Circulation 2000;101:1282–7.

[4] Tang W, Weil MH, Sun S, et al. The effects of biphasic and conventional monophasic defibrillation on postresuscitation myocardial function. Journal of the American College of Cardiology 1999;34(3):815–22.

[5] Dorian P, Wang MJ. Defibrillation current and impedance are determinants of defibrillation energy requirements. Pacing and clinical electrophysiology : PACE 1988;11(11 Pt 2):1996–2001.

[6] Kerber RE, Kieso RA, Kienzle MG, et al. Current-based transthoracic defibrillation. Am J Cardiology 1996;78(10):1113–8.

[7] Ristagno G, Yu T, Quan W, Freeman G, Li Y. Current is better than energy as predictor of success for biphasic defibrillatory shocks in a porcine model of ventricular fibrillation. Resuscitation 2013;84(5):678–83.

[8] Dixon EG, Tang AS, Wolf PD, et al. Improved defibrillation thresholds with large contoured epicardial electrodes and biphasic waveforms. Circulation 1987;76(5):1176–84.

[9] Nikolski V, Sambelashvili A, Efimov IR. Anode-break excitation during end-diastolic stimulation is explained by half-cell double layer discharge. IEEE transactions on bio-medical engineering 2002;49(10):1217–20.

[10] Sidorov VY, Uzelac I, Wikswo JP. Regional increase of extracellular potassium leads to electrical instability and reentry occurrence through the spatial heterogeneity of APD restitution. Am J Physiol Heart Circ Physiol 2011;301(1):H209–20.

[11] Cherry EM, Fenton FH. Visualization of spiral and scroll waves in simulated and experimental cardiac tissue. New Journal of Physics 2008;10(12):125016.

[12] Fenton FH, Luther S, Cherry EM, et al. Termination of atrial fibrillation using pulsed low-energy far-field stimulation. Circulation 2009;120(6):467–76.

Address for correspondence.

Ilija Uzelac
Georgia Institute of Technology-School of Physics, 837 State Street, Atlanta, Georgia, 30332-0430
ilija.uzelac@physics.gatech.edu