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Four-channel current switching device to enable multi-electrode magnetic resonance current density imaging

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***Abstract*— Neurostimulation with multiple scalp electrodes has shown enhanced effects in recent studies. However, visualizations of stimulation-induced internal current distributions in brain is only possible through simulated current distributions obtained from computer model of human head. While magnetic resonance current density imaging (MRCDI) has a potential for direct in-vivo measurement of currents induced in brain with multi-electrode stimulation, existing MRCDI methods are only developed for two-electrode neurostimulation. A major bottleneck is the lack of a current switching device which is typically used to convert the DC current of neurostimulation devices into user-defined waveforms of positive and negative polarity with delays between them. In this work, we present a design of a four-electrode current switching device to enable simultaneous switching of current flowing through multiple scalp electrodes.**

I. INTRODUCTION

Magnetic resonance electrical impedance tomography (MREIT) and magnetic resonance current density imaging (MRCDI) are two applications of magnetic resonance imaging (MRI) where external electric currents are delivered to an imaging object while simultaneously acquiring MR images. The external current produces extra phase in MR images which is measured in both MREIT and MRCDI. MREIT and MRCDI uses this phase to measure the underlying low-frequency electrical conductivity and the induced in-vivo current distributions, respectively, in the imaging object.

MREIT and MRCDI have come a long way starting from the feasibility studies in phantoms and animals to the pre-clinical trials in humans [1]. For human studies, MREIT has administered a maximum of 3 mA current to human knee [2] whereas MRCDI has administered a maximum of 1.5 mA to human brain [3]. Notably, higher current amplitude and duration increases the signal-to-noise (SNR) in both MREIT [4] and MRCDI [3], [5]. However, sensation of humans to current delivery also increases with higher amplitude. Therefore, large sized electrodes are traditionally used in both these techniques to minimize the current density and sensation.

In MREIT, four electrodes are attached to the imaging object in two orthogonal directions to the main magnetic field of the MRI scanner [1]. However, current is only delivered through a pair of electrodes at a time. The current delivery in MRCDI is same as MREIT, but the requirement of two orthogonal directions for current delivery is not necessary [3], [5]. There is growing interest in applying MRCDI to image the neurostimulation-induced internal current distributions in the brain in-vivo [3], [5]. However, existing studies have only demonstrated MRCDI with conventional two-electrode neurostimulation such as two-electrode transcranial direct/alternating current stimulation (tDCS/tACS) [3], [5]. Notably, neurostimulation has evolved from traditional two-electrode current delivery with large sized scalp electrodes to recently introduced systems allowing current delivery through multiple small-sized scalp electrodes [6]. Therefore, improvement is necessary in MRCDI to image current density distributions from multi-electrode neurostimulation systems.

In MREIT and MRCDI, the current delivery is synchronized within each repetition time (TR) of the MRI pulse sequences using TTL trigger signal from MRI scanner. Current delivery occurs only after the TTL trigger signal appears. However, depending on the multi gradient echo (MGRE) or multi echo spin echo (MESE) pulse sequence, the polarity of current switching may vary with a TR. There should also be "zero-current" time spans to avoid current flow during the radio-frequency (RF) pulses in MRI. All these requirements demand fast switching of current from one polarity to other polarity or to "zero-current" mode. Traditionally, all these features were implemented using a custom-designed current source suitable for use in both MREIT and MRCDI [7], [8], [9]. However, a switch box was recently used to implement this function which enabled performing MRCDI with a commercially available two-electrode tACS system [3].

In this work, we present the design of a current switching device for a four-electrode neurostimulation system. The device was designed using EAGLE, an electronic design automation (EDA) software, and tested in a laboratory setup using a 25 m long coaxial cable required to capture the TTL trigger signal from our MRI scanner's equipment room.

II. CURRENT SWITCHING DEVICE

The concept design, logic for current switching in four-electrode neurostimulation system, and the algorithm of microcontroller program are described in detail in Fig 1 (a)-(e) and in sections II-A and II-B for gradient echo pulse sequence with interleaved current delivery (alternate current polarity in subsequent TRs).

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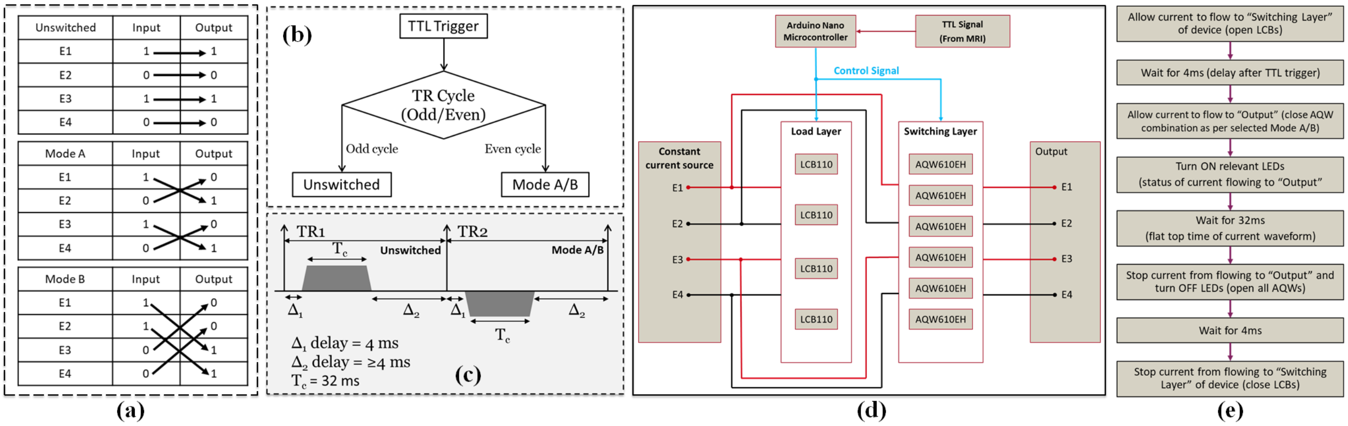

Fig. 1. (a) Current switching logic for three modes: "Unswitched", "Mode A", "Mode B" (b) Flow chart for logic of Arduino program for an interleaved current delivery (alternate current polarity in subsequent TRs) (c) Implementation of Arduino code for gradient echo pulse sequence (d) Block diagram of concept of switching device design (e) Flow chart for Arduino code to implement current delivery in gradient echo pulse sequence.

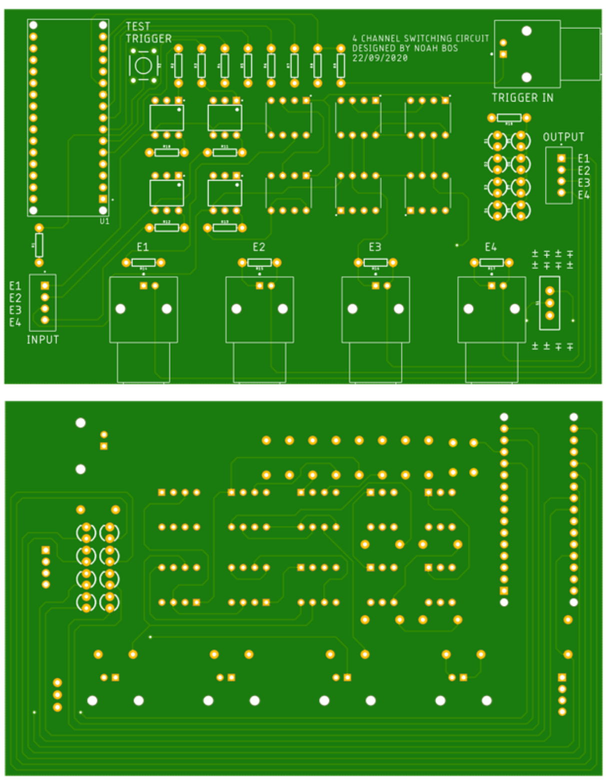

Fig. 2. Top and bottom views of PCB for our current switching device

A. *Current switching device design*

Arduino Nano board was used to control pins of solid-state relays and implement the shape of current waveform. The concept design of switching device consisted of two functional layers. The purpose of the first layer (labeled as "Load Layer" in Fig 1 (b)) was to provide a load (or return path) for each channel of the current source when "zero-current" needs to be implemented in the current waveform, thereby preventing current flowing to the output (the imaging object in MRCDI or MREIT). Four single-pole, normally closed LCB110 relays were used to develop this layer, each paired with a 100 Ω series resistor.

The second layer (labeled as "Switching Layer" in Fig 1 (b)) was used to control current flow to the output (the imaging object in MRCDI or MREIT) and is responsible for current switching. The switching layer used six AQW610EH NO/NC relays, effectively providing twelve single-pole single-throw (SPST) switches in parallel. Each input channel was connected via three separate SPST switches to three different output electrodes, as each output electrode must be able to accept an input for the three modes of current delivery: (a) Unswitched mode, (b) Mode A, and (c) Mode B. This means that output channel E1 could pass current from input channels E1, E2, or E3. This logic is further demonstrated in Fig 1 (a) through the arrows indicating the interconnections between input and output channels. Care was taken to ensure that the active connections for both the Arduino control signal and the electrode signal for each of the three cases (1 (a)) was connected to the same type of pole due to variations in the switching times of the AQW (NC_{off} = 1 ms, NO_{off} = 0.08 ms, NC_{on} = 0.3 ms, NO_{on} = 0.5 ms).

Laboratory testing of current switching of all four electrode channels was enabled through inclusion of four 1 $k\Omega$ resistors and 50 Ω BNC connectors for monitoring of current waveforms in oscilloscope. An additional 50 Ω BNC connector was included to accept the 5V TTL trigger from MRI. A test trigger button was added to the circuit to allow the board to be tested without a TTL trigger and an SPDT slide switch was added to toggle the device between Mode A and Mode B (1 (a)). The device used 4-pin vertical JST connectors for connection of current source cables at the input and the cables carrying the switched current to the output. The device also used four red LEDs to represent anodal current and four blue LEDs for cathodal current which act as indicators to denote the mode in use and whether the present cycle is an odd or even cycle of that mode.

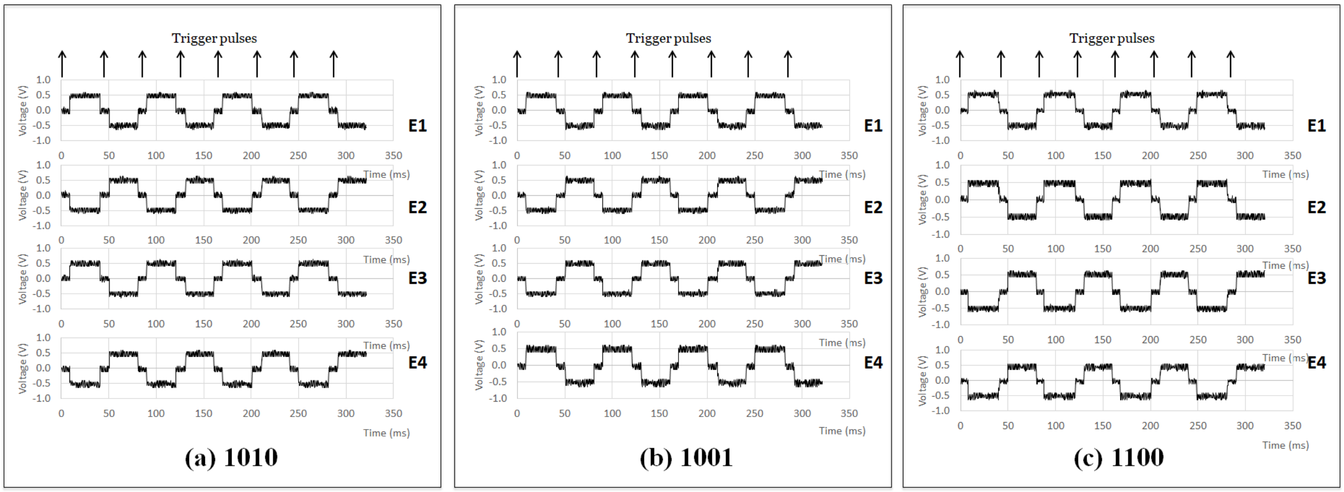

Fig. 3. Current switching waveforms for three electrode configurations measured with oscilloscope

B. Current waveform generation

The switching device was designed to work with a four-electrode neurostimulation system. Considering two anode and two cathode electrodes being used at a time for neurostimulation, there are six possible ways of delivering current: 1010, 0101, 1001, 0110, 1100, 0011. Here, 1 indicates anode electrode at input (or positive polarity of current flow at output) and 0 indicates cathode electrode at input (or negative polarity of current flow at output). It was assumed in the device design that the current source programs one of these six electrode configurations at the input side of the device after which they are not changed during one MRI session of data collection.

As mentioned earlier, there were only three modes of operation. Each of them required a different relay combination. Fig 1 (b), (c), and (e) demonstrate the logic used to implement the Arduino code for gradient echo pulse sequence. The section of code responsible for controlling the relays and producing the current waveform was put into two separate functions: Mode A and Mode B. The mode is manually selected by the user at the beginning of the experiment (before current delivery) with the SPDT slide switch mounted on the PCB. The Unswitched mode which passed the input current to the corresponding output electrode was used for the odd cycle of TR loop and the Mode A or B were used for the even cycle of the TR loop. These three modes are called only when a trigger signal is received, either from the test trigger button or a TTL signal from the MRI. Four functions were added for the LED lighting schemes to indicate whether the current switching has occurred. An OFF STATE function was also included which opens all switches, preventing current flowing to the output, as well as turning off all LEDs.

III. LABORATORY TESTING EXPERIMENTS

A. Setup for testing of current switching device

The current switching device was tested in laboratory using the following equipment:

- Rigol DS1054Z Digital Oscilloscope
- Tortech ISO-300ES Isolation Transformer
- Keithley Model 2461 SourceMeter SMU Instrument
- Aim-tti Instruments TG5012A Function Generator
- 3×75 Ω BNC Coaxial Cables
- 2×50 Ω BNC Coaxial Cable
- Custom 25m CLF195 LMR195 equiv Coaxial Cable

The Keithley SourceMeter was used in place of a commercial neurostimulation system to deliver the current to the switching device. Current amplitude was set to 1 mA and connected to the input of the device with the power rail on a breadboard. The device was tested using the four channel Rigol oscilloscope which was powered through the Tortech isolation transformer. A custom testing board was connected to the output of the device to act as a load. The four BNC connectors on the PCB were connected directly to the Rigol oscilloscope allowing all four channels to be analysed simultaneously. The connections were made using three 75 Ω coaxial cables and one 50 Ω cable. Ideally, the impedance would be the same for all channels however a fourth 75 Ω cable was unavailable at the time of testing.

B. Testing experiments

Two experiments were required to verify the operation of the switching device. The first was concerned with the switching waveform and the second was used to verify that the circuit could be used with an MRI trigger coming through the 25 m custom coaxial cable (the distance from the RF-shield panel in our MRI equipment room to the trigger port).

The first experiment was performed using the test trigger on the device. Holding the trigger down, the output waveform was captured for the four channels simultaneously for the six different electrode configurations: 1010, 0101, 1001, 0110, 1100, and 0011 (1 - anode, 0 - cathode). The output was also tested when there was no trigger to ensure that there was no leakage current, as this could be a safety issue.

The second experiment required the Aim-tti function generator to simulate the TTL trigger signal that would come from the MRI scanner. The function generator was set to a 5 V pulse function with a period of 40 ms and pulse duration of 3 ms. The pulse function was first verified on the oscilloscope and then connected to the BNC trigger input on the device with the 25 m long 50 Ω coaxial cable. The output waveform was again captured for all four channels simultaneously for the same six electrode configurations: 1010, 0101, 1001, 0110, 1100, 0011. The output was again tested for leakage current to ensure safety.

C. Data processing

The output waveforms were exported from the oscilloscope as *.csv files. The current waveform data was processed in MS Excel. A truncated version of this data is shown in Fig 3 for four wavelengths and approximately 320 ms.

IV. DISCUSSION

We presented a current switching device design to be integrated with a four-electrode neurostimulation system for current delivery to four electrode MREIT and MRCDI experiments. While we only showed test results for gradient echo pulse sequence, the device is capable of implementing current delivery for any kind of pulse sequence such as multi echo spin echo (MESE) or multi gradient echo (MGRE). This should be done by choosing a proper combination of "Unswitched" and "Mode A/B" functions in the Arduino code.

The noise present in Fig 3 results is not indicative of device performance. The current source in experiments was not ideal however was sufficient for testing the correct operation of the device, with more testing required in future with the Neuroelectrics constant current source. The current source was set to output 1 mA however each electrode only received 0.5 mA as the electrode pairs were supplied in parallel through the breadboard power supply rail. There is no significance to the value chosen for the 1 $k\Omega$ resistor across the BNC connectors other than ease of voltage calculation in later testing. For these reasons the voltage measurements in these results are ignored, with the results serving to demonstrate the capability of the device switching all six electrode configurations. However, only the results for 1010, 1001, and 1100 were included in Fig 3 as the waveforms for the inverse electrode configurations are phase shifted versions of these waveforms.

A 25 m long coaxial cable was necessary for our MRI site, where the switching device need to be placed closer to the RF-shield panel in the MRI equipment room, but the TTL trigger box is placed at the MRI console room (the operator bench). Since the distance between these two locations was 25 m, we tested our device with a 25 m long BNC cable carrying TTL trigger signal. There were concerns of signal loss, transmission delays, and impedance mismatching which could have led to reflections, ringing, and overshoot in the top of the leading edge and bottom of the trailing edge. However, the second experiment was successfully performed using the custom coaxial cable, indicating that the Arduino Nano should be able to receive the TTL trigger signal from MRI scanner and differentiate between high/low control signals.

V. CONCLUSION AND FUTURE WORK

We presented a current switching device design and successfully tested it in laboratory with a 25 m long BNC cable for TTL trigger signal. Future work should include testing this switching device with our Neuroelectrics [10] system which is a multi-electrode MRI-compatible neurostimulation system. Two tests should be performed before the device should be used with human subjects: tests within laboratory and then tests inside an MRI scanner.

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