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A Compact 1200 V, 700 A, IGBT-Based Pulse Generator for Repetitive Transcranial Magnetic Stimulation in Vivo Laboratory Experiments on Small Animals

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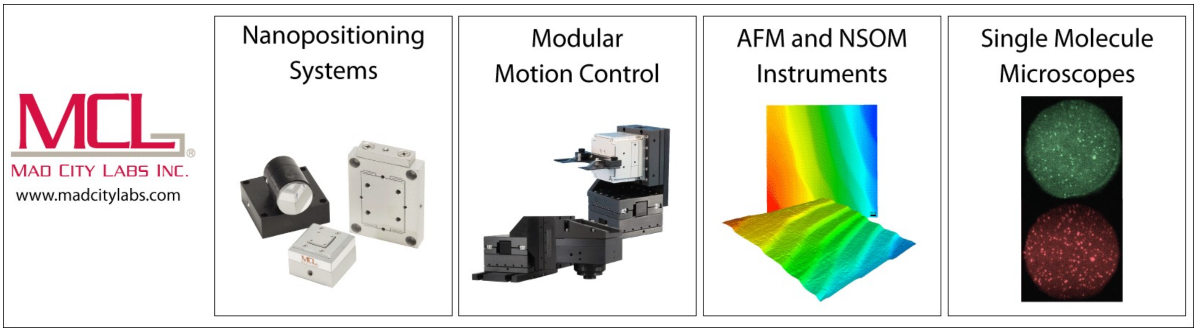

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ABSTRACT

An insulated-gate bipolar transistor (IGBT) pulse generator for repetitive transcranial magnetic stimulation used for *in vivo* laboratory experiments on small animals, such as mice, is reported. The pulse generator is based upon an IGBT that can switch 700 A of current for 1 ms and that has a DC breakdown voltage of 1200 V. The duration of the design's output pulse is controlled by, and follows, an input trigger pulse. The voltage amplitude of the output pulses is determined by an external high-voltage power supply and the energy stored in a 330 μF capacitor bank. The approach enables the amplitude of the voltage applied across the coil, the length of time the voltage is applied, and the number of times the voltage pulses are applied all to be controlled and adjusted to facilitate a wide range of experimental options. This paper provides a detailed schematic of the design, design discussions, and some representative experimental results. Additionally, the reported design can be scaled to higher currents by using an IGBT with a higher current rating.

I. INTRODUCTION

Transcranial magnetic stimulation (TMS) is a noninvasive form of brain stimulation in which a changing magnetic field is used to cause electric potential differences in neurons that lead to action potentials. These stimulations can be both singular (TMS) and repeated (rTMS). An electric pulse generator, or stimulator, is connected to a magnetic coil, which, in turn, is placed passively on the scalp of the test animal. The stimulator generates a changing electric current within the coil, which induces a magnetic field; this field then causes a negative resting potential of neurons to become more depolarized, reaching the "threshold" and firing an action potential.[1,8] TMS has shown diagnostic and therapeutic potential in the central nervous system with a wide variety of disease states in neurology and mental health, with research still evolving. The work reported here investigates the effects of TMS using *in vivo* laboratory experiments involving mice. Adverse effects of TMS are rare and include fainting and seizure. Other potential issues include discomfort, pain, hypomania, cognitive change, hearing loss, and inadvertent current induction in implanted devices, such as pacemakers or defibrillators.[2]

A commercial TMS system is shown in Fig. 1. Note that the system is not compact and is impractical to use in *in vivo* laboratory experiments involving mice where the corresponding size of the coil must be greatly reduced and comparable to the size of the mouse's head. Furthermore, the commercial system has a lack of focality and the magnetic field created by the coil excites too large of an area.

The two key components of a TMS test system are the coil and the pulse generator that provides a pulse of current to the coil to generate the magnetic field.[3] These two components can be altered to create broad or focal stimulation, which are two key variables of effective neurostimulation. To drive a TMS coil, a high voltage, V_L,

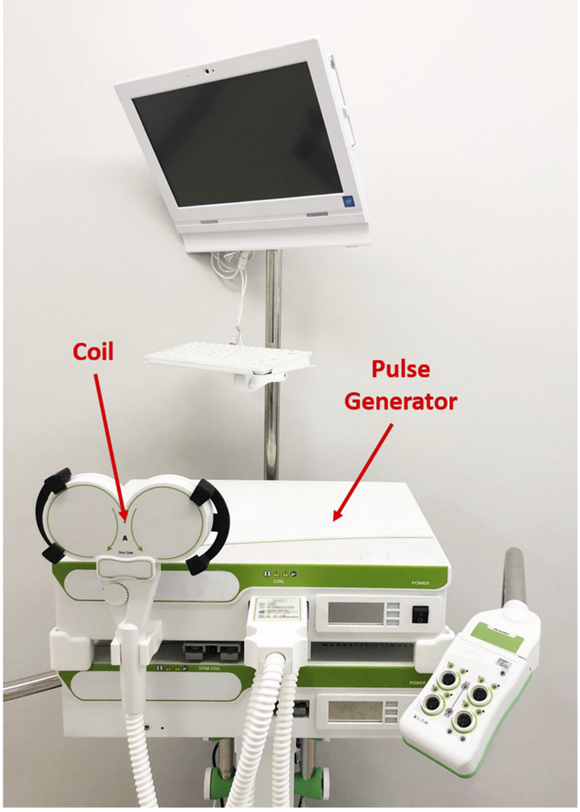


FIG. 1. Commercial TMS system.

is applied across the coil, which causes, neglecting the coil's series resistance, the coil's current, I_L, to linearly increase. Therefore, for example, if 1000 V is applied across a 2 mH coil, the current will rise because $\frac{dI_L}{dt} = \frac{V_L}{L}$ at a rate of 500 A/ms. This simple calculation illustrates why most commercially available pulse generators cannot be used to drive TMS coils. Most commercially available units are designed to drive a 50-Ω load or, in some cases, a purely capacitive load, such as a Pockels cell or deflection plates in a vacuum tube, for example. Relatively speaking, the currents in these applications are much lower than what is needed for a TMS coil. For example, there is a pulse generator that supplies 1000 V to a 50-Ω load and only supplies 20 A of current, which is not enough for this application.

This paper reports the design of a pulse generator that can supply upward of 700 A of current while having a switching voltage of 1200 V. The duration of the output pulse is controlled by an input trigger pulse. If the input trigger pulse is a series of ten pulses, each having a width of 500 μs and being spaced apart by 1 ms, then the output pulses will also have widths of 500 μs and be spaced apart by 1 ms. The voltage amplitude of the output pulses is determined by an external high-voltage power supply and the energy storage in the pulse generator, which is a capacitor bank having an equivalent capacitance of 330 μF. The limitations of the energy storage capacitors can be significant and are discussed in more detail later in this paper.

II. DESIGN CONSIDERATIONS FOR DRIVING TMS COILS

The coils used for the TMS experiments on mice *in vivo* in this work are formed by wrapping, or spooling, magnet wire around a plastic bobbin, as shown in Fig. 2. Also shown in this figure is the measurement of an important parameter of the coil, namely, its series resistance (the coil in Fig. 2 has 23.3 Ω of series resistance). The details of the construction of coils can be found in Ref. 4, and are not discussed further here. Rather, here, the focus will be on two particular aspects of the coil design, namely, the maximum voltage one can use and how series resistance is ultimately responsible for limiting the current flowing in the coil and thus the generated magnetic field. Before discussing these issues further, it is important to note the considerable size difference between the coils used for humans shown in Fig. 1 and a coil used for small animals shown in Fig. 2. In a coil used for human rTMS, the wire diameter can be considerably larger and the insulation around the wire can be considerably thicker. This leads to much smaller resistance and higher breakdown voltages than those in the coils used for small animals, such as mice.

One of the issues encountered in the development of the pulse generator, discussed in this paper, is related to the maximum voltage that could be applied to the coil. In one experiment, the coil was designed to be small, with fewer turns and thinner magnet wire with a correspondingly thin insulating coating. The result was that as the voltage of the pulses was increased, arcing between adjacent wires in the coil was both observed and heard. While the pulse generator discussed in Sec. III could switch 1200 V across a coil, it failed to be usable with coils that did not have a thick enough insulation on the wires to avoid arcing.

The series resistance of the wire used in the coil can have a significant and limiting impact on the performance of the TMS system. For example, if an ideal 2 mH coil (no series resistance) has 1200 V applied across it, then the current would rise at a rate of 1200 V/2 mH or 600 A/ms. However, if the 2 mH coil had a 5-Ω series resistance, the current will not linearly rise and is also being limited to 1200 V/5-Ω or 240 A. The effects of series resistance in this situation are shown in Fig. 3.

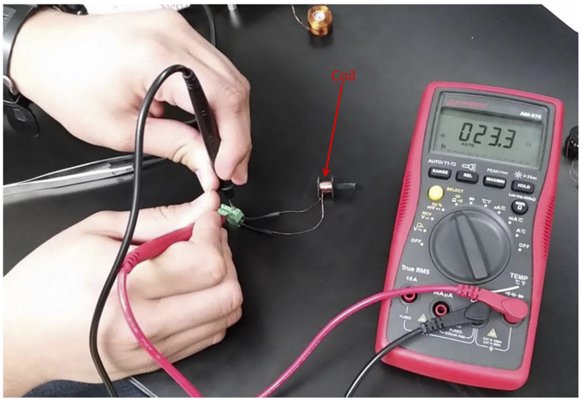


FIG. 2. Resistance of a plastic bobbin TMS coil used for initial board tests.

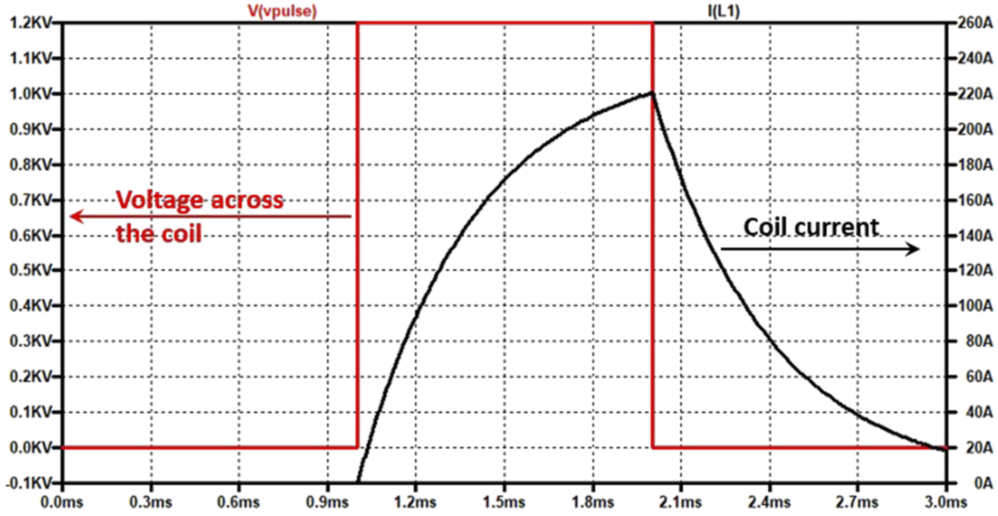


FIG. 3. The effects of a 5-Ω series resistance when 1200 V is applied across a 2 mH coil.

III. PULSE GENERATOR USING AN IGBT SWITCH

The schematic of the pulse generator design is shown in Fig. 4. The first design consideration was the type of switch that should be used for both high voltage and high current. Ultimately, an insulated-gate bipolar transistor (IGBT) was selected as the switch. There were several reasons for this, including ease to drive (turn the switch on and off), high speed, and high-voltage and high-current switching capabilities. To provide some background before discussing the design in Fig. 4, a few comments on the other switches considered are appropriate.

The first switch considered was the avalanche transistor.[5] While avalanche transistors can be stacked to achieve higher voltages and they are simple to use, they are generally limited to currents less than 100 A. In addition, there is no easy way to control either the amplitude of the output pulse via a power supply or the output pulse width.

The next switch considered, and experimentally tested in this development, was a thyristor, a silicon-controlled rectifier (SCR). While the output amplitude of a pulse generated using an SCR can be controlled, adjusting the output pulse width is difficult for

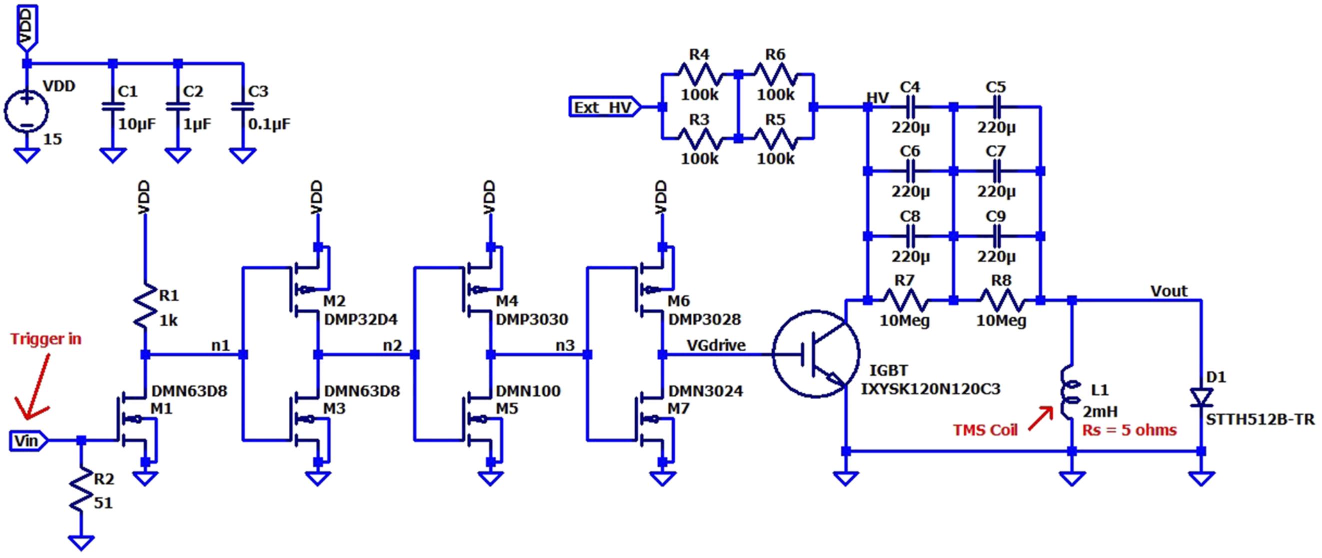


FIG. 4. Complete schematic of the IGBT-based pulse generator.

laboratory experiments where the pulse width must be easily varied, that is, not varied by changing the value of a circuit component, such as a capacitor. The SCR can only shut-off when the current through it goes to zero or the control gate goes more negative than the cathode of the SCR. However, SCR designs can switch significant current, and they are easy to drive, which is likely why they are used in commercial TMS systems.[6] Our experimental results comparing SCRs to IGBTs, having comparable current capabilities as indicated on their corresponding data sheets noting IGBT data sheets focused on operating with pulses and SCR data sheets focused on operating at 60 Hz AC, indicated that the tested IGBTs had much lower switching resistance than the tested SCRs. Reference 6 also presents an IGBT design that can supply 7000 A of current with a controllable pulse width. In the design, the inductor is connected to the emitter terminal of the IGBT instead of the collector as in most pulse generators. This requires an isolated gate driver to ensure that the gate potential of the IGBT rises with the IGBT's emitter potential. Both the IGBT and gate drive components of the pulser are large, resulting in a relatively spread-out instrument that is expensive.

The last switch we considered was the power MOSFET.[7] While power MOSFETs are relatively easy to drive and fast and the output pulse width can be relatively easily controlled, they have limited current switching capabilities, generally, less than 100 A, especially at higher voltages. Power MOSFETs are used, however, in the design presented in this section to drive the IGBT.

The part numbers of the important components of the pulse generator in Fig. 4 are listed in Table I. The pulse generator is connected to the TMS coil through a capacitor bank having an effective capacitance of 330 μF. The 10 MΩ ballast resistors are used to ensure an equal voltage drop across each capacitor, which are rated as having a maximum voltage of 600 V. This approach ensures that the capacitive bank can hold off 1200 V under DC conditions.

Prior to switching (the trigger input going high and the IGBT turning on), the collector of the IGBT [labeled high voltage (HV) near the top left capacitor labeled C_4] in Fig. 4 is charged to the external high-voltage supply labeled Ext HV in the schematic. The resistors (R_3–R_6) connected between Ext HV and HV are arranged to provide a 100 kΩ resistance, which limits the current pulled from the external high-voltage supply to keep from tripping and shutting off this supply (the resistor value should be set depending on the limitations of the HV power that is used). Considering that there is a maximum voltage that can be applied across a resistor to avoid damaging it, the voltage applied here was halved by using series resistances to minimize the voltage drop across each resistor.

If 1200 V is supplied to the pulse generator, the collector of the IGBT charges up to 1200 V. The output voltage, Vout, which is the top of the TMS coil, is at ground prior to triggering the pulse generator. When the IGBT turns on, its collector goes to ground. Considering the voltage across the capacitor bank cannot change instantaneously, the output of the pulse generator, the top of the TMS coil, goes to −1200 V (see Fig. 5 at 1 ms). Also shown in Fig. 5 is how the output voltage and current change with repetitive pulses when the pulse generator is driving a 2 mH coil with 5 Ω series resistance. The output voltage droops because of the finite energy stored in the capacitive bank. Adding more capacitance reduces this droop, but for the present application, the droop was not a factor. Responses evoked from the motor cortex in mice were measured by electromyograph (EMG) and electroencephalograph (EEG). The measurements were recorded and observed ($n = 21$) using only 500 V, so the full potential of the pulse generator was not utilized.

When the IGBT shuts off, at 2 ms in Fig. 5, for example, the energy stored in the TMS coil must be removed. For this purpose, a freewheeling diode, D_1, was added. Without this diode, the current in the TMS coil would not have a path to flow, so Vout would rise unchecked until breakdown occurred in the circuit. This would quickly lead to circuit failure, so D_1 is an important component of the pulse generator. The diode selected, STTH512B-TR, is a relatively fast switching device having low capacitance. Its specified pulsed current rating, from its datasheet, is very low for some potential output currents. However, since no failures were observed with this diode, even at currents beyond values specified in its datasheet, it was decided to continue using this device instead of a slower and higher capacitance diode.

The driver circuit in Fig. 4 consists of M_1–M_7 and R_1. When the trigger input is at ground, M_1 is off and its drain, labeled n1, is at VDD (15 V here). This turns M_3 on and shuts M_2 off; thus, node n2 gets pulled to ground. This turns M_4 on and shuts M_5 off pulling n3 to VDD. This then turns M_7 on and M_4 off, ensuring the

TABLE I. Component values for the pulse generator in Fig. 4.

Schematic	Description	Digi-key part number	Manufacturer part number
M1, M3	MOSFET N-CH 30V 380MA SOT323	DMN63D8LW-13DICT-ND	DMN63D8LW-13
M2	MOSFET P-CH 30V 250MA SOT323	DMP32D4SW-7DICT-ND	DMP32D4SW-7
M5	MOSFET N-CH 30V 1.1A SC59-3	DMN100-FDICT-ND	DMN100-7-F
M4	MOSFET P-CH 30V 700MA SC59-3	DMP3030SNDICT-ND	DMP3030SN-7
M7	MOSFET N-CH 30V 9.78A TO252-3	DMN3024LK3-13DICT-ND	DMN3024LK3-13
M6	MOSFET P-CH 30V 27A TO252	DMP3028LK3-13DICT-ND	DMP3028LK3-13
IGBT	IGBT 1200V 240A 1500W TO264	IXYK120N120C3-ND	IXYK120N120C3
D1	DIODE GEN PURP 1.2KV 5A DPAK	497-5767-1-ND	STTH512B-TR
C4–C9	CAP ALUM 220UF 20% 600V SNAP	493-14693-ND	LGN2X221MELC50
	TERM BLOCK PLUG 2POS STR 7.62MM	277-2434-ND	1 777 723
	TERM BLOCK HDR 2POS 90DEG 7.62MM	277-6070-ND	1 720 466

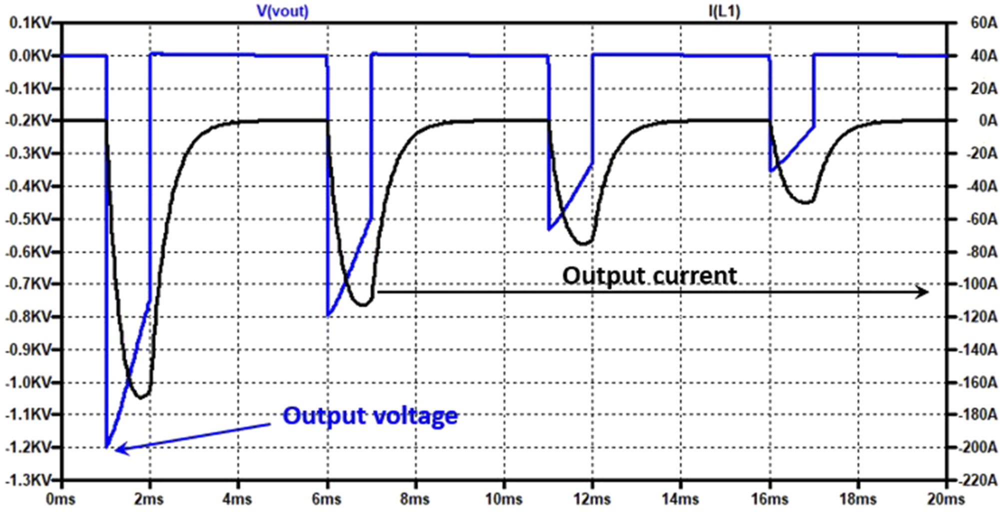


FIG. 5. Simulating the operation of the pulse generator in Fig. 4.

gate of the IGBT, that is, VGdrive, is at ground. The drive capability of the MOSFETs is increased as the signal moves from the trigger input to the gate of the IGBT. For example, the DMN63D8LW has a maximum pulsed drain current of 1.1 A, while the DMN100 has a maximum pulsed drain current of 4 A. This increase in drive strength as the signal moves through the driver toward the IGBT gate results in significant, high-speed drive capability with limited driver switching current pulled from VDD.

When the trigger input signal goes high, M_1 turns on and n1 is pulled to ground. This results in n2 going to VDD, n3 going low, and finally VGdrive going high, turning on the IGBT. The effective capacitive load of the IGBT driver (R_1–R_2 and M_1–M_7) is well above 0.01 μF. This is the capacitance that M_7 and M_6 must charge and discharge quickly for good IGBT switching action. For this to occur, there needs to be a good source of charge locally stored on the printed circuit board. C_1–C_3 are used for this purpose. Three different sizes and types of capacitors are used to minimize the effects of their effective series resistance, which changes with frequency. This keeps VDD at a steady level for proper driver operation.

IV. EXPERIMENTAL RESULTS

The fully assembled TMS pulse generator printed circuit board can be seen in Fig. 6. One of the goals of the printed circuit board (PCB) design was to create a compact footprint to make it easier to use for *in vivo* testing (the commercial TMS system shown in Fig. 1 is bulky and impractical for the purposes of *in vivo* tests of small animals). For convenience, a high-voltage euro-style connector was used to allow for easy interchangeability between different coils. In addition, a custom plastic bottom cover was designed and 3D printed to add a layer of safety when handling the board for testing. The TMS board went through a few initial experiments to test the high-voltage limits of the circuit.

The experiments were conducted in the following manner. The TMS board was connected to two power supplies, one at a constant 15 V for the on-board driver circuit and one for the varying high-voltage used to charge the on-board capacitor bank. In addition, a function generator was connected to the signal input that controls the driver, which, in return, controls the switching of the IGBT.

The coil used in the following experiments was made from a lower gauge magnet wire (as shown in Fig. 6). The coil had an inductance of 145 μH and a resistance of 2.33 Ω (1.33 Ω series resistance of the coil and an additional resistance of 1 Ω to ground, which was added to measure the current through the inductor).

For the first two experiments, a 600 V high-voltage supply was used. The input trigger pulse was set to have a width of 1 ms. The output of the pulse generator is shown in Fig. 7 where the current through the inductor (the oscilloscope set to 50 A/div and 200 μs/div with an input pulse width of 1 ms) goes to ~225 A.

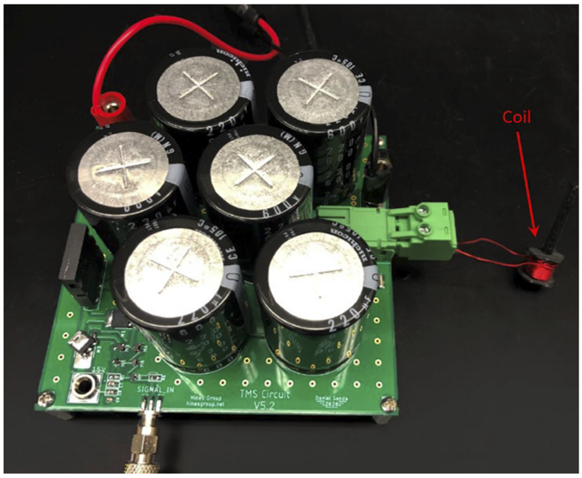
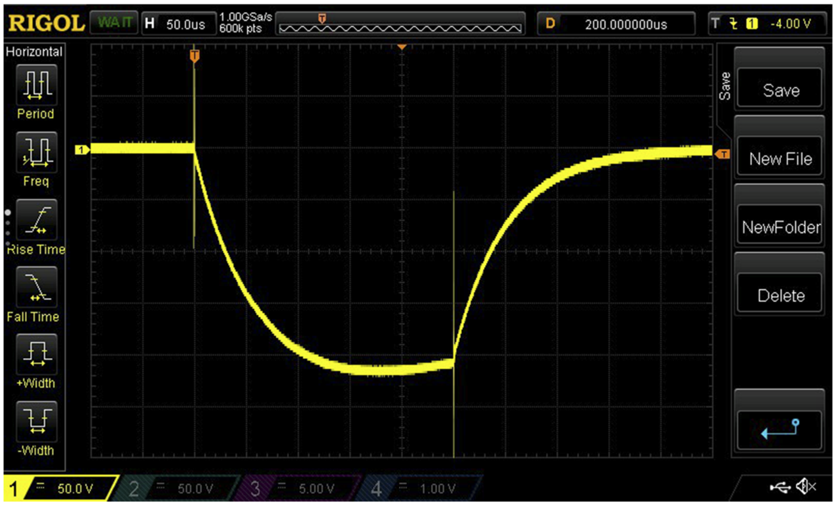


FIG. 6. IGBT-based pulse generator PCB (114.2 × 120.6 mm^2).



RIGOL WAIT H 50.0us 1.00GSa/s 600k pts

D 200.000000us

T 1 -4.00 V

1 50.0 V 2 50.0 V 3 5.00 V 4 1.00 V

FIG. 7. Current through the 145 μH coil using 600 V showing 50 A/div and 200 μs/div.

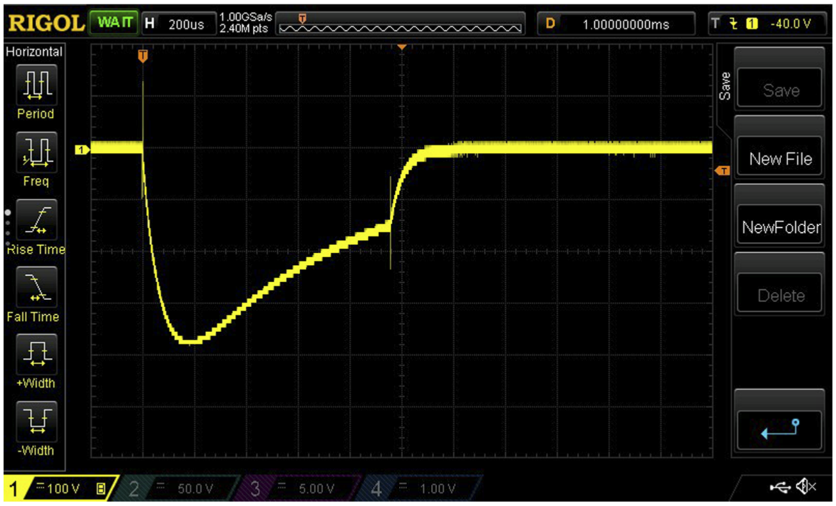
RIGOL WAIT H 200us 1.00GSa/s 2.40M pts

D 1.00000000ms

T 1 -42.0 V

1 50.0 V 2 50.0 V 3 5.00 V 4 1.00 V

FIG. 8. Current through the coil showing 50 A/div and 200 μs/div.



RIGOL WAIT H 200us 1.00GSa/s 2.40M pts

D 1.00000000ms

T 1 -40.0 V

1 100 V 2 50.0 V 3 5.00 V 4 1.00 V

FIG. 9. Current through the coil when the power supply is increased to 1200 V. Scale is 100 A/div and 200 μs/div.

For the next experiment, four input trigger pulses were used, each staying high (to trigger the pulse generator) for 250 μs and then low for 250 μs. The output of the pulse generator is shown in Fig. 8. The decrease in the energy stored in the capacitors over time is evident by the change in the amplitude of the current output pulses.

The last experimental results are shown in Fig. 9. In this experiment, the power supply was increased to 1.2 kV. Again, a 1 ms input trigger pulse was used. The output pulse amplitude goes to roughly 380 A of current.

V. DISCUSSION

A limitation of the current design, which is how quickly it can be triggered (used) again after the energy stored in the capacitors is depleted, is the high-voltage charging circuit. In the current design, the effective 100 K resistor charging the effective 330 μF capacitance results in a 33 s time constant. To fully charge the capacitor bank then requires about 3 min (more than five time constants). This was a design choice due to limitations of the high-voltage power supply used to charge the pulse generator in the laboratory experiments. The high-voltage supply used in these results was limited to supplying 5 mA of current, and if a circuit tried to pull more than this, it would shut off and need to be reset. Simply by lowering the value of the 100 K resistor, the charge time can be reduced. However, the issue is designing, or finding, a high-voltage power supply that can supply large currents and large voltages (which, generally speaking, is a dangerous combination). For example, if the charging resistor is reduced from 100 to 1 K, the time before the pulse generator can be used again drops to a few seconds. However, supplying 1200 V to the capacitor bank through a 1 K resistor would then require 1.2 A peak current. Again, most high-voltage supplies (but not all) cannot supply this high of a current while supplying a thousand volts.

Finally, the IGBT selected in the design presented in this paper can be replaced with an IGBT that can switch considerably more current. The driver portion of the pulse generator reported here was designed to be robust and capable of driving a considerably larger IGBT input capacitance. This allows for the use of an IGBT that can switch, for example, greater than 2000 A of current, which may be useful if longer output pulses or when smaller coil inductance and resistance are desirable. TMS is becoming a frontline therapeutic for the treatment of many psychiatric disorders. The creation of small cost-effective units will have an immediate impact by advancing our understanding of the basic science of how TMS affects the brain. Ultimately, these impacts could lead to new therapies and treatment paradigms in humans.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

REFERENCES

[1] H. R. Siebner, G. Hartwigsen, T. Kassuba, and J. C. Rothwell, "How does transcranial magnetic stimulation modify neuronal activity in the brain? Implications for studies of cognition," Cortex **45**(9), 1035–1042 (2009).

[2] S. Rossi, M. Hallett, P. M. Rossini, and A. Pascual-Leone, and Safety of TMS Consensus Group, "Safety, ethical considerations, and application guidelines for the use of transcranial magnetic stimulation in clinical practice and research," Clin. Neurophysiol. **120**(12), 2008–2039 (2009).

[3] J. Selvaraj, P. Rastogi, P. Gaunkar, R. L. Hadimani, and M. Mina, "Transcranial magnetic stimulation: Design of a high current magnetic pulse generator with custom coil for the application on small animals," in *2018 IEEE International Magnetics Conference (INTERMAG)* (IEEE, 2018).

[4] M. T. Wilson, A. D. Tang, K. Iyer, H. McKee, and J. Rodger, "The challenges of producing small coils for transcranial magnetic stimulation of mice," Biomed. Phys. Eng. Express **4**, 037002 (2018).

[5] R. J. Baker, "High voltage pulse generation using current mode second breakdown in a bipolar junction transistor," Rev. Sci. Instrum. **62**(4), 1031–1036 (1991).

[6] A. V. Peterchev, R. Jalinous, and S. H. Lisanby, "A novel transcranial magnetic stimulator inducing near rectangular pulses with controllable pulse widths (cTMS)," IEEE Trans. Biomed. Eng. **55**(1), 257 (2008).

[7] R. J. Baker and B. P. Johnson, "Stacking power MOSFETs for use in high speed instrumentation," Rev. Sci. Instrum. **63**(12), 5799–5801 (1992).

[8] It is important to note that TMS elicits a response not by causing action potentials but instead by making the probability more likely for them to happen. TMS works by a field property not by a single action potential by changing the threshold for many groups of neurons (Ref. 1, Sec. III, paragraphs 2 and 3, "populations of axons").