Programmable Transcranial Magnetic Stimulation: A Modulation Approach for the Generation of Controllable Magnetic Stimuli

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Introduction

Transcranial magnetic stimulation (TMS) is an important tool used by researchers to study the central and peripheral nervous systems, and by clinicians to diagnose and treat diseases such as depression, stroke and pain. The key advantage of TMS is that it is non-invasive, and carries relatively few risks for test subjects, patients and research animals. Furthermore, the choice of specific TMS stimulation parameters (e.g. timing of pulse sequences) can have either inhibitory or facilitatory effects on brain networks, including induction of long-lasting neuroplasticity [1].

Commercially available TMS technology limits the possibilities for novel stimulation paradigms in neuroscientific experiments. Many of these limitations are inherent in the physical principles by which particular TMS technologies operate. Due to the large instantaneous power demand, conventional TMS devices often use LC oscillator circuits, which generate damped cosine stimuli efficiently and without requiring very large power switches, but they can produce only restricted stimulus shape options.

Design

The rapid advance in power electronics technology has made it possible to more precisely control the peak megawatt electrical power required in TMS devices. Multilevel converters are considered today as a very attractive solution for medium-voltage high-power applications. It is formed by connecting several single-phase H-bridge inverters in series. Each H-bridge has its own isolated DC source.

The proposed TMS architecture uses standard power-electronic modulation techniques with a non-resonant, high-frequency switching architecture to construct arbitrary, high-power waveforms. Specifically, we employ pulse width modulation (PWM) to drive 3-level (pTMS1) and 5-level (pTMS2) cascaded H-bridge circuits in order to create a highly controllable AC output waveform (Fig. 1).

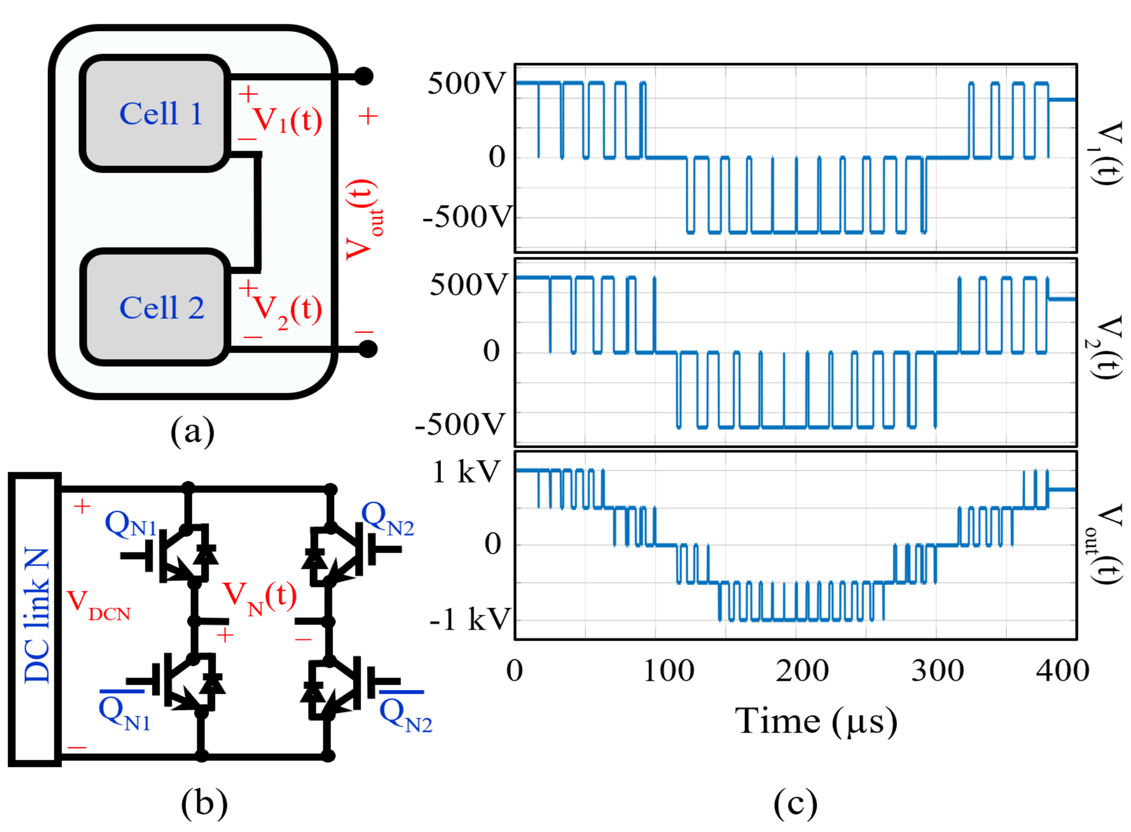

Figure 1. Two-cell cascaded H-bridge power converter (pTMS2). (a): Topology of power cell connection. (b): H-bridge structure, where N represents the cell number. (c): Output voltages of power cells and total output voltage using pulse width modulation. The output pulse is a 5-level 2 kV_{p-p}, 2.5 kHz cosine-shaped equivalent modulated signal.

Experimental results

The proposed single cell architecture (pTMS1) was tested with a cell link voltage of VDC = 1 kV (peak-to-peak voltage 2 kV). For a 2.5 kHz cosine stimulus, the maximum energy delivered to the stimulation coil (D70 Remote coil, Magstim, UK) was measured to be 100.4 joules [2].

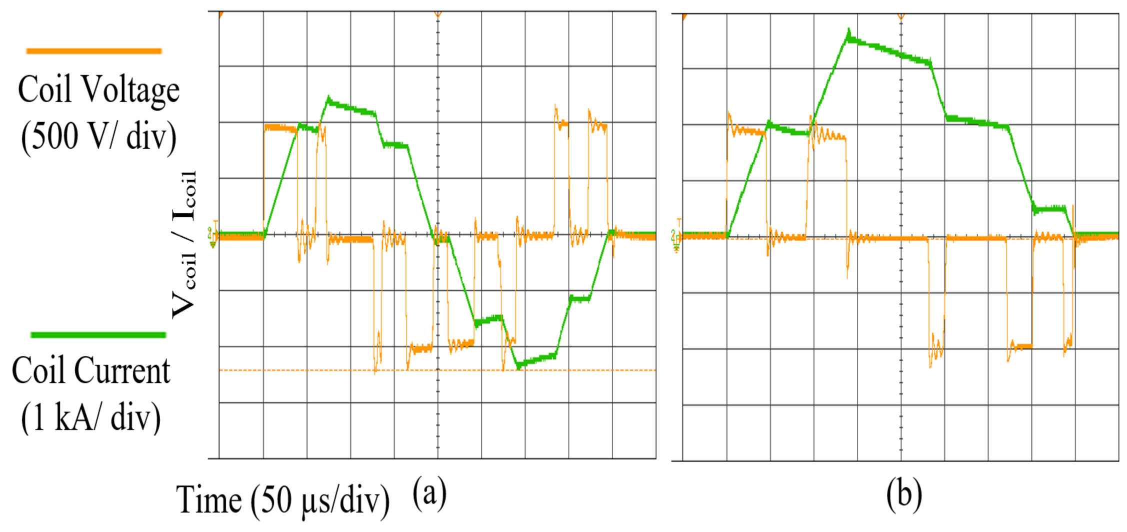

Figure 2. Measured waveforms for 2 different pTMS1 stimuli: Voltage and current for (a) 2.5 kHz Cosine stimulus (biphasic output)- (b) 2.5 kHz Sine stimulus (monophasic output).

The two-cell architecture (pTMS2) was tested with a cell link voltage of VDC = 750 V (peak-to-peak voltage 3 kV). For a 2.5 kHz cosine stimulus, the maximum energy delivered to the stimulation coil was measured to be 195 joules. The achievable frequency starts at 2 kHz and can be increased up to 5 kHz.

According to the measured results, the introduced pTMS technology enables the generation of desired stimulus waveforms in high frequency protocols (up to 1 kHz) at maximum stimulus output (Fig. 3).

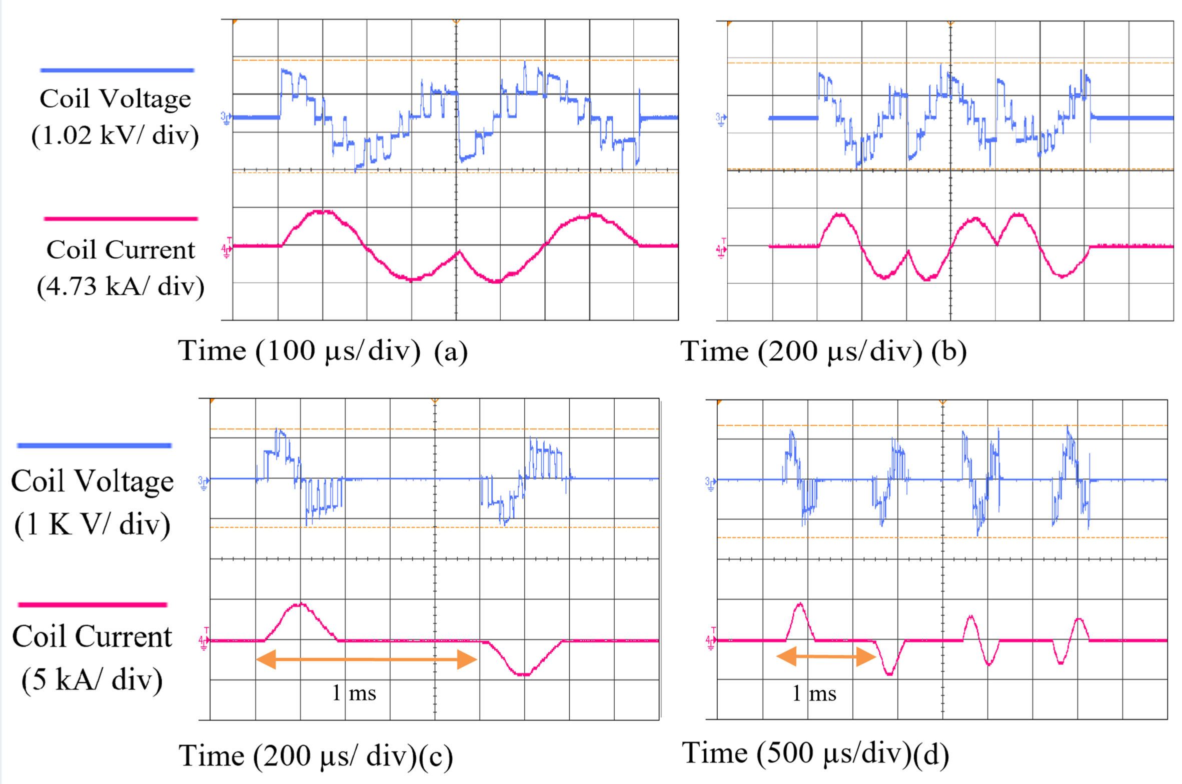

Figure 3. Measured novel waveforms and repetitive protocols: Voltage and current for (a) Double 2.5 kHz cosine stimuli where the two pulses have a phase difference of π radians. (b) Triple 2.5 kHz cosine pulses with different phases. (c) Two 2.5 kHz sine pulses with 1 ms interval, where the two pulses have a phase difference of π radians. (d) Four 2.5 kHz cosine and sine pulses with different phases.

Physiological Response Models

To investigate the effect of a staircase-like stimulus waveform (PWM pulse) on the response and the behavior of a neuron, the leaky integrate-and-fire (RC model) [2][3] and the equations from the single-compartment Hodgkin-Huxley type models [4] were utilized.The modelling of the neural behaviour indicates that the membrane voltage change initiated by the stimuli of the pTMS1 and the pTMS2 devices are close to the reference state, although the neural response to the pTMS2 stimulus is more similar to the defined 2.5 kHz biphasic reference (Fig 4).

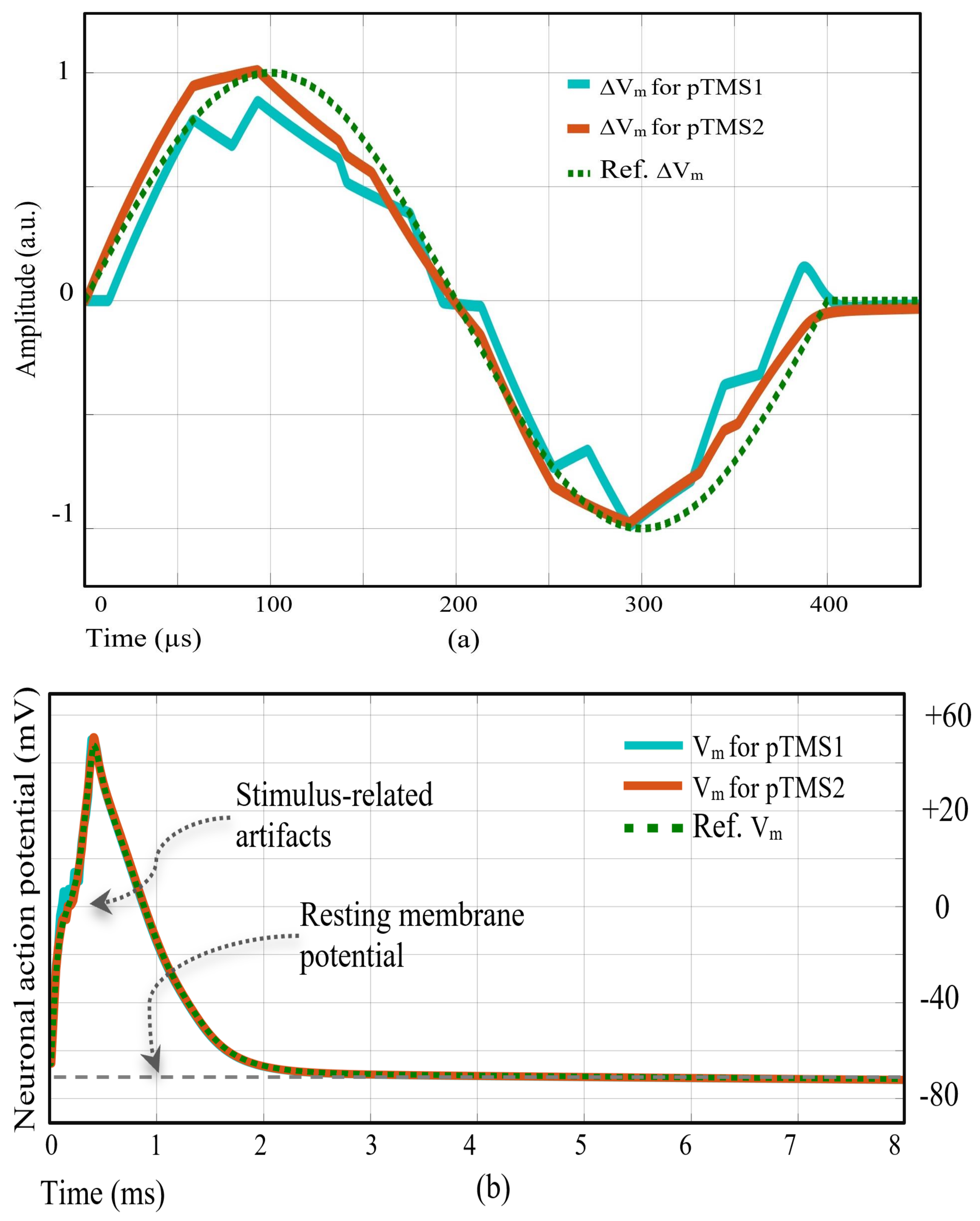

Figure 4. (a) Expected voltage changes in the membrane (ΔV_m) from the RC model, after exposure to the pTMS1 and the pTMS2 magnetic stimuli (time constant of the nerve membrane under electromagnetic stimulation to be in the order of 150 µs). (b) Expected neuronal action potential from the HH model for the biphasic stimuli generated by the pTMS1 and the pTMS2 systems and action potential for the conventional biphasic stimuli, as a reference signal.

Conclusion

The present work illustrates the unique potential of the PWM method and H-bridge inverter topologies to imitate arbitrary magnetic stimuli. More specifically, the implemented pTMS devices are capable of generating more controllable and more flexible pulse shapes and amplitudes. The modular property of this inverter enables the improvement of the neuromodulation waveform by cascading H-bridges. The selected switching patterns allow maximum recovery of the energy delivered to the coil, which enables the generation of rapid repetitive protocols.

Future extensions of this versatile PTMS device to apply new modulation paradigms might aid new treatments of psychiatric and neurological diseases.

References

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