34th Annual International Conference of the IEEE EMBS
San Diego, California USA, 28 August - 1 September, 2012

Circuit Topology and Control Principle for a First Magnetic Stimulator with Fully Controllable Waveform

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Abstract— **Magnetic stimulation pulse sources are very inflexible high-power devices. The incorporated circuit topology is usually limited to a single pulse type. However, experimental and theoretical work shows that more freedom in choosing or even designing waveforms could notably enhance existing methods. Beyond that, it even allows entering new fields of application.**

We propose a technology that can solve the problem. Even in very high frequency ranges, the circuitry is very flexible and is able generate almost every waveform with unrivaled accuracy. This technology can dynamically change between different pulse shapes without any reconfiguration, recharging or other changes; thus the waveform can be modified also during a high-frequency repetitive pulse train. In addition to the option of online design and generation of still unknown waveforms, it amalgamates all existing device types with their specific pulse shapes, which have been leading an independent existence in the past years. These advantages were achieved by giving up the common basis of all magnetic stimulation devices so far, i.e., the high-voltage oscillator. Distributed electronics handle the high power dividing the high voltage and the required switching rate into small portions.

I. Introduction

The principle of electrical stimulation of neurons with skin electrodes or invasive methods has been known for several centuries and is nowadays a standard tool in medicine. The required device technology for electrical stimulation is very simple. Furthermore, the relatively low currents are compatible with mass-produced semiconductors and allow very flexible control of the current dynamics, i.e., the waveform.

Electrical stimulation, however, is not appropriate for many applications where pain due to the high current densities at the electrode-skin contact becomes intolerable or where the target area is shielded by a poor conductor, such as bone. Magnetic stimulation is an alternative which induces the stimulating fields and currents directly into the tissue and circumvents the surface contact. It allows relatively focal activation of neuron populations in the brain [1]–[5] and was reported to outperform even neuromuscular electrical stimulation due to a presumably better penetration [6], [7]. In contrast to electrical stimulation, the required power for magnetic stimulation is several orders of magnitude higher. Coil currents of several thousand ampères have to be controlled during a pulse. The high-voltage circuit technology for magnetic stimulation is relatively expensive and inflexible due to the costly electronic components.

All commercially available stimulation devices are based on harmonic oscillators. A capacitor is charged to a certain high-voltage level; for triggering the pulse, a switch, usually a thyristor, connects the stimulation coil to the capacitor. The approximately sinusoidal current flow is interrupted after a few cycles (biphasic and polyphasic devices) or damped by a resistor (monophasic devices). The waveform is accordingly characteristic for a certain device and can hardly be changed. In currently available commercial devices, the pulse source determines the waveform. Changes are only possible with circuit modifications and only within a very small range.

However, several studies show that the efficacy of neuromodulation induced by repetitive magnetic stimulation can be notably increased by the use of appropriate waveforms [8]–[13]. The limited technology counteracts that and illustrates the needs for improved devices.

First steps towards more flexibility have been proposed [14], [15]. Such devices use semiconductor switches which can be turned off for providing control over the pulse width for the first time, but the available waveform space is still relatively limited and far from that in electrical stimulation.

The key challenge is the high power in combination with the high dynamics of stimulation pulses. High-voltage semiconductor components, such as insulated gate bipolar transistors (IGBT), thyristors, and gate turn-off thyristors (GTO) are rather slow devices; switching modulation, as common in power electronics, is not an option for these components in the case of magnetic stimulation. Maximum switching rates of high-voltage semiconductors in the low Kilohertz range are inappropriate for switching modulation during pulses which have themselves already a basic frequency of $(5-10)\,\mathrm{kHz}$. Experiments with compact high-voltage IGBT inverters for controlling the stimulation waveform have usually failed so far [16]. To the knowledge of the authors, there is no successful approach of academic or commercial designers that has been able to solve the problem since the first magnetic stimulation devices [17].

We discuss a pulse-source technology which allows almost absolutely arbitrary waveforms. This technology gains its flexibility from the fact that it gives up the classical high-voltage oscillator. Both the high power and the high frequency are divided into small controllable portions such that the output is composed of small independent components which can be controlled separately [18].

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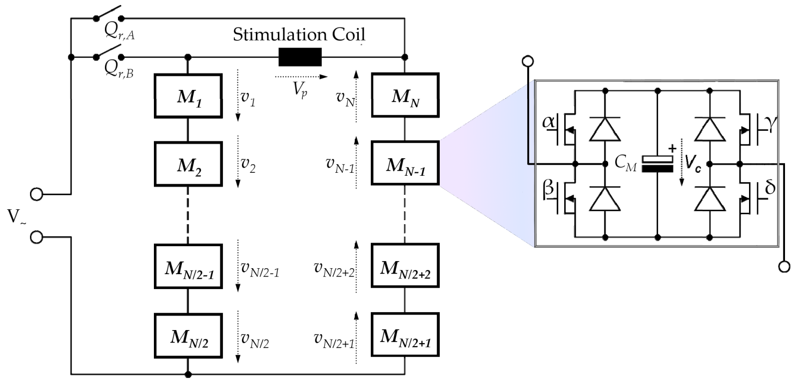

Fig. 1. General topology of the stimulator. The coil and N modules are connected in series. For recharging, the modules are split into two columns that can exchange energy with the outlet (voltage $V_\sim$) using switches $Q_{r,A}$ and $Q_{r,B}$. Each module contains an H-bridge circuit as shown on the right.

II. Technology

The high-voltage pulse shape is generated by adding up relatively small voltage steps. Each step is generated by an independent two-pole module. All of these identical subunits are connected in series. Independence of the single modules is required for the high speed as shown later on.

At any time, each module has to provide only a small portion of the full pulse voltage $V_p(t)$. There are several options for the implementation of the subcircuit in every single module. For simplicity, we propose an H-bridge topology (see inset of Figure 1). Every module contains an electrical energy storage C_M with the voltage V_c, four semiconductor switches and corresponding free-wheeling diodes. The latter entail the side benefit that the capacitor C_M can be a polar element, e.g., an electrolytic capacitor.

Single H-bridges are a common topology for inverters in power electronics. They use the following four switching states: (a) The capacitor is presented to the module terminals in positive polarity (switches α and δ are closed); (b) the capacitor is presented to the terminals in negative polarity (switches β and γ are closed); (c) the module terminals are shorted, i.e., the module enforces $0\,\mathrm{V}$ without connecting the capacitor (either β and δ or α and γ closed); (d) in the *passive mode*, no switch is closed and the diode rectifier which feeds the capacitor is the only available current path. Accordingly, every module can generate a voltage $v_i(t) \in \{-V_C, 0, +V_C\}$.

Due to the combination of a number of such modules, the full pulse source provides in total the voltage $\sum_i v_i$. In the simplest mode, a waveform can be reproduced as a staircase (see Figure 2). This constitutes the basic concept behind this technology. The whole column of modules forms a high-power parallel digital-to-analog converter (DAC). N modules can generate $(2N+1)$ quantization levels.

The voltage in every module, and thus also for all components, is limited to a maximum level defined by the voltage of the capacitor. The capacitors of all modules together in combination with the free-wheeling diodes are a dynamically balanced voltage divider. Additionally they act as a snubber circuitry [18], [19]. The limited voltage level in every module allows the use of common low-voltage power components, such as field-effect transistors (MOSFET). Due to their faster turn-off dynamics, these devices support much higher switching rates than high-voltage semiconductors [20].

Due to the high speed of the circuit, the remaining difference between the staircase and the desired waveform can be reduced by combining the parallel DAC approach with the principles of pulse-width-modulated (PWM) DAC conversion. However, classical sine-triangle digital PWM with fixed pattern length is not optimal for this problem. For very slow parts in the pulse, nonadaptive PWM leads to an unnecessarily high switching rate whereas it is too slow for very sharp slopes. Therefore, a sigma-delta–type modulation scheme is used here instead [21].

Although switching modulation is performed on a single voltage step only, it is not done by a particular dedicated module. The switching load is distributed among all modules. If one module contributes the rising edge of a PWM cycle, another one can perform the next falling edge. Thus, a single module is responsible for just $1/N$-th of the effective switching rate. The selection of the module that has to perform a certain switching operation is implemented by sorted lists for every available state that contain the modules in this respective state. In addition to the module identifier, these lists store the time of the last state change of each module. For every request from the controller for a module state change from a certain 'source' state to another, that candidate from the 'source' state is chosen which has the oldest time stamp. A detailed description will be published at a place that provides sufficient space as soon as the developement of the control methods is completed.

The passive mode is an important state in the context of magnetic stimulation since fully controllable pulse sources entail a new problem. All classical devices, even those with IGBTs [15] only trigger the start of a pulse or a pulse phase. The current of the last phase is always flowing through a rectifying semiconductor, such as a diode or a thyristor. These are automatically turned off as soon as the current direction changes. Exact knowledge of the duration of the full pulse and the moment when the current crosses zero is not required there.

This is different for a pulse source that can fully control

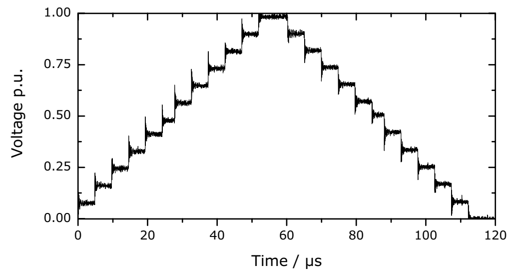

Fig. 2. Recorded voltage steps which reflect the DAC character of the device. The key aim for this evaluation setup (see Section III) has been the control approach. Therefore, we have not optimized parasitic inductances for minimum switching transients, yet.

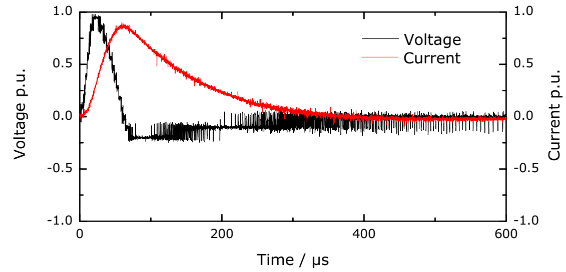

Fig. 3. Classical monophasic pulse generated with the testbench. In contrast to conventional monophasic devices, the decay of the current is not generated by resistive damping, but by controlled extraction of energy from the coil to charge the module capacitors. Accordingly, a significant amount of energy can be recovered and used for the next pulse.

the pulse duration. If the pulse is switched off actively, it is important not to terminate it while the inductance of the stimulation coil is still driving a considerable amount of current. Although the presented topology does not interrupt the current because it is voltage-controlled, it can shorten the coil by switching all modules to 0 V. If this state is kept for a longer duration, the current decays towards zero with a time constant given by the ratio of coil inductance to total inner resistance; all remaining energy of the coil is converted into heat.

However, the exact duration of a pulse cannot be calculated offline before a pulse because this would require comprehensive knowledge of the (frequency-dependent) resistance and inductance values of the coil and also of magnetic field losses due to induction in nearby conductors, such as small metallic objects in furniture or other lab equipment; additional damping slightly prolongs a pulse. If the current—which reflects the energy content of the coil—cannot be measured without phase error during a pulse, the passive mode can be used for draining the remaining energy from the coil and storing it in the module capacitors. Thus, shortly before the end of a pulse is expected, the passive mode (d) replaces the active states (a) and (b). In the passive mode, the module does not control the polarity, but it still determines the absolute value of the voltage due to the integrated rectifier. The direction of the current flow determines the sign of voltage such that the power flow is directed from the coil inductance to the modules. As soon as the current reaches zero, the current flow stops and the pulse energy is retrieved.

The module capacitors can be directly charged from an outlet. An additional transformer or power supply is not required for the topology in Figure 1. This design is a—although not simultaneous with respect to its two terminals—four-quadrant voltage-source converter and therefore a power supply itself. This means that it can generate voltage and current shapes in all four quadrants of the current-voltage plane at the stimulation-coil terminals as well as on the outlet side. Thus, for charging and discharging between pulses, it can exchange energy with the outlet in both directions.

During the pulse generation, the electrical storages in the single modules complement the stimulation coil. This ensures the stability of the system. Furthermore, most of the magnetic energy from a pulse can be retrieved from the coil for every kind of waveform. The circuit does not contain any resistive component for shaping the pulse.

III. Recordings

For a physical implementation, the most complicated and sophisticated part in this new pulse-source design is not the high-power circuit, but the control approach for the distributed voltage-source modules. Due to the underlying design principles, all components in the circuit scale simply with the power rating. According to the required peak voltage, the number of modules may be increased. The number of transistors and capacitors in parallel in every module determines the maximum current. Because MOSFETs have a very good parallel balancing performance and almost linear properties for very low drain–source voltages, the on resistance can be reduced to almost every level. Therefore, we set up a first test bench with reduced power rating for testing the dynamical behavior of the whole pulse source (MOSFETs: CSD16401, Texas Instruments, Inc., TX, USA; Capacitors: 50 µF X5R GRM21BR61, Murata Manufacturing Co., Ltd., Kyoto, Japan; 2 mF 136RVI, Vishay Intertech., Inc., PA, USA). This evaluation device acted especially as a prototype for developing appropriate control strategies.

Figure 3 shows a classical monophasic waveform from a commercial device generated with this test setup. In contrast to sinusoidal biphasic stimuli, classical monophasic devices dissipate the total energy in every pulse. The high power demand limits the achievable pulse rate to approximately one Hertz in commercial devices, although especially this pulse type may be advantageous in neuromodulation (see, e.g., [13]), which requires repetitive stimulation. The presented technology solves this problem as the monophasic waveform can be reproduced such that it includes a virtually damped decay at the end of the pulse. Instead of converting the pulse energy into heat using a resistive free-wheeling circuit, the test setup transfers the magnetic energy of the coil back into the capacitors. Accordingly, repetition rates of more than hundred pulses per second become easily achievable.

In addition, this technology can also generate novel pulses. Figure 4 depicts an example that has intervals with very different properties. The dynamics and the amplitude vary

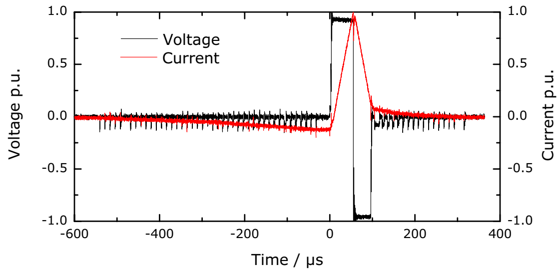

Fig. 4. Energy-efficient pulse shape as derived in [22]. Due to the very slow, but small first phase, this waveform is a good benchmark for the stability of the pulse source. For the efficiency-increasing effect of the first phase, the current in the coils' inductance has to be controlled very precisely. This is reflected by the switching pattern with the amplitude of a single level before and also after the main pulse. Despite that, it is not performed by a single module, but the load is distributed among all these units as described.

by several orders of magnitude and demonstrate the high stability of the topology. The first, very slow phase of the current is almost not visible in the voltage, but has to be controlled very precisely for achieving the correct current profile. This pulse shape was derived in optimization studies with nonlinear neuron models and is supposed to be more efficient with respect to energy loss as it reduces heating of the coil and other components [22].

The recordings show that the deviation and thus the harmonics are very low. No curve was recorded with an additional low-pass filter; the used high-frequency probe has a bandwidth of 300 MHz and a rise time of 1.2 ns. In principle, the harmonics of the coil current fall with $1/N^2$, with the module number N.[1]

For a higher stability and robustness in pulsing, the capacity in every module is oversized, i.e., the stored charge at the beginning exceeds the required charge during the longest phase of a pulse. This is achieved by a combination of ceramic capacitors (for their low series resistance) and electrolyte capacitors (which provide a high energy density). As a consequence, the setup is even able to generate a sequence of pulses without recharging in between. The control setup ensures that the single pulses in the train are not different in shape or amplitude.

IV. Conclusions

The discussed pulse-source technology for magnetic stimulation is the first practically reasonable approach that allows almost absolutely arbitrary waveforms. The pulses are controlled by a synthesizer algorithm and can be changed dynamically without delay, even within a repetitive TMS train.

The design gave up the principle of all TMS device designs for achieving the new flexibility. On the hardware side, the costly high-voltage components are replaced by off-the-shelf low-voltage semiconductors. The additional complexity is mainly an issue of software and can be solved by appropriate control algorithms.

[1]The reduced step size contributes the first $1/N$-factor, the increased effective switching rate for the very same switching rate in every module accounts for the second $1/N$.

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