펄스포밍의 스위칭 제어기술을 적용한 경두개 자기자극장치

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Pulse forming's switching control adopted a Transcranial Magnetic Stimulation Biomedical engineering, Dongju College University

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요 약

본 연구에서는, 펄스포밍 제어기술과 펄스 성형을 가지는 자기 자극장치에 대해 언급 하고자 한다. 자기자극장치는 5-100초 사이에 펄스성형 기술적용과 순간적 방전코일 전류 6kA까지 상승되므로 스너버 회로를 가지는 IGBT 전력소자를 사용하였다. 57-67%의 열손실을 줄였고, 2-34%의 적은 에너지를 사용한 유도전계펄스로 전형적인 코사인 펄스와 매칭 되는것을 알수가 있었다. 자기자극장치는 펄스성형하는 기술 증가와 함께 한계 펄스진폭의 예측되는 감소인 20- 100초 사이에서 펄스성형 기술을 운동신경에 활발한 자극하기 위하여 사용된다. 자기 자극장치 프로트 타입에서 이용된 기초과학 기술에 의하여 기능을 확장할 수 있고, 전력소비를 줄일 수 있었고, 자기자극장치의 열손실에 대해서도 축소할 수가 있어, 더 나은 연구와 치료에 통해 응용할 수가 있다.

ABSTRACT

In this study, a magnetic stimulation (MS) device with controllable pulse forming technology and pulse shape (MS) is described. The MS device uses an IGBT with appropriate snubbers to switch coil currents up to 6 kA, enabling pulse forming technology control from 5 s to over 100 s. The induced electric field pulses use 2% - 34% less energy and generate 57% - 67% less coil heating compared to matched conventional cosine pulses. MS is used to stimulate rhesus monkey motor cortex in vivo with pulse forming technology of 20 to 100 s, demonstrating the expected decrease of threshold pulse amplitude with increasing pulse forming technology. The technological solutions used in the MS prototype can expand functionality, and reduce power consumption and coil heating in MS, enhancing its research and therapeutic applications.

키워드

경두개, 자기자극장치, 펄스포밍, 한계펄스, 유도전계

Key word

transcranial, magnetic stimulation, pulse forming, threshold pulse, induce electric field

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Ⅰ. 서 론

With non-invasive magnetic stimulation the stimulating coil acts as the first coil, air as the medium for the flow of the magnetic field, and the electrically conductive living body tissue as the second coil. Magnetic stimulation(MS) is a noninvasive tool for the study of the human brain that is being investigated as a potential therapeutic agent in psychiatry and neurology.

A pulsed current sent through a coil produces a magnetic field that, in turn, induces electric field in the brain, which can cause neurons to fire. Available MS devices induce damped cosine electric field pulses. The pulse forming technology can be adjusted over a wide range, whereas control over the pulse width is nonexistent or very limited. We have developed a novel MS device which induces near-rectangular electric field pulses with pulse forming technology over a wide range.

Fig. 1. Strength-duty curves linking pulse forming technology to electric field strength E and coil energy W for threshold stimulation of neuron with membrane time constant of = 150 us. Curves are normalized to one at PW = 100 s. pulse forming technology adjustment, the pulse shape reduces power consumption and coil heating. Thus, MS can expand the functionality and improve the efficiency of MS as a clinical and research tool. Pulse forming technology control of the MS stimulus enables response characterization of different neuronal populations and optimization of the pulse forming technology for various research and clinical applications. For example, the strength-duty curve relates the pulse amplitude or energy for threshold stimulation with the pulse forming technology. The strength-duty curve of a neuronal population can be derived empirically by delivering MS pulses with different pulse forming technology while the amplitude to yield threshold stimulation. The strength-duty curve can be used to estimate neuronal membrane time constants [2]. MS with adjustable pulse forming technology could also be used to study and selectively target distinct neuronal populations that overlap in space. Similarly, it has been suggested that the ratio of cortical motor threshold to scalp sensory threshold is lower for brief pulses than for long stimuli [5].

Therefore, using briefer pulses could improve the ability of MS by reducing unpleasant scalp sensations. The effect of MS pulse forming technology on neuronal activation in the brain and the scalp has not been fully explored due to the relative difficulty in modifying pulse forming technology in conventional MS machines. The basic circuit topology of a general Magnetic Stimulation is given in Fig. 2. In particular, once an SCR is turned on by applying a current pulse to the gate terminal, it can be turned off only when the anode current reaches zero [8].

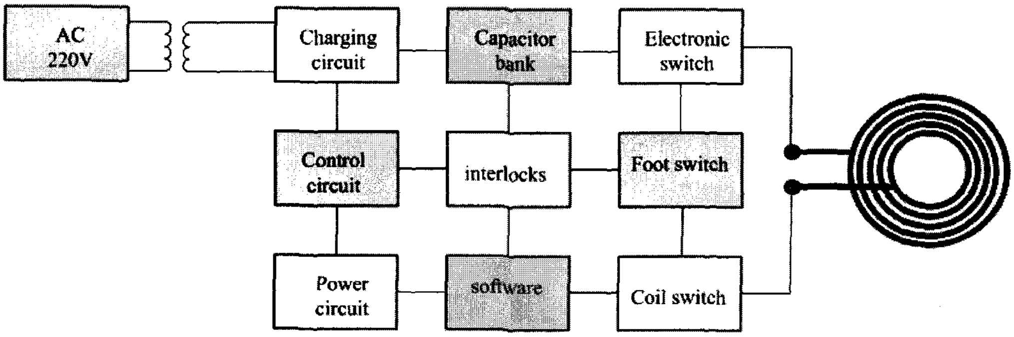

그림1. 전형적인 경두개 자극장치
Fig.1 Diagram of a Transcranial Magnetic adjusting Stimulation

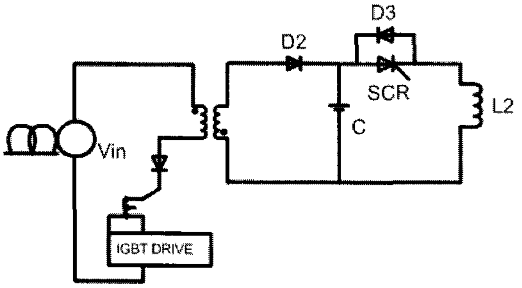

그림 2. 일반적인 자기자극장치
Fig.2 Schematic of a general Magnetic Stimulation

Thus, the SCR switch can only initiate the pulse but cannot control its pulse forming technology. In this case, the pulse forming technology is determined by the resonant period of the capacitor and the coil. two capacitor configurations resulting in two discrete pulse forming technology settings [9]. However, besides the limitation of only two pulse forming technology choices in these devices, the pulse forming technology range is very restricted. This approach still provides only discrete pulse-width adjustment, and requires powering down the system to manually insert connectors configuring the capacitors. Further, implementing this system with electronically controlled switches would be impractical since it would require the use of seven high-power semiconductor devices and/or relays, with up to three switches connected in series in some capacitor configurations.

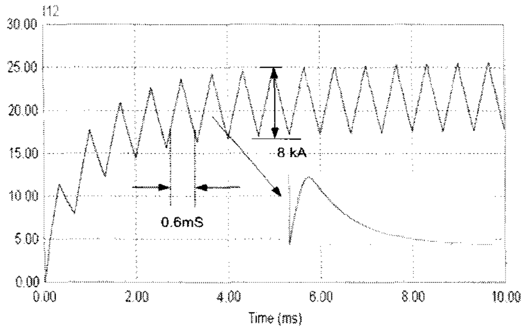

그림 3. 일반적인 자극장치 출력파형
Fig.3 waveform output of a general Magnetic Stimulation

Fig 3 presented waveform output of a general Magnetic Stimulation. The use of rectangular pulses can substantially benefit high-frequency, high-power MS applications such as in magnetic seizure therapy, where excessive power consumption and coil heating are presently major limitations. In this paper, we present the circuit topology, implementation, and test results of a MS device which, in contrast to existing MS machines, allows easy pulse forming technology adjustment over a wide continuous range and produces near-rectangular electric field pulses that improve the electrical efficiency and reduce coil heating.

Ⅱ. 하드웨어 설계

The basic circuit topology of the MS device is given in Fig. 2. It is similar to a conventional monophasic MS stimulator with the main difference that the switch is implemented with a semiconductor device such as an insulated gate bipolar transistor (IGBT) which, unlike an SCR, can be turned off from the gate terminal. Switch connects the stimulating coil to the energy-storage capacitor, causing the coil current to ramp up, which, in turn, induces electric field in the brain proportional to the coil current rate of change. Fig 4 Proposal of a Transcranial Magnetic Stimulation. To date, circular coils with a mean diameter of 80-100mm have remained the most widely used in magnetic stimulation. The pulse forming technology is limited to a quarter resonant period, which corresponds to complete discharge. For brief pulse forming technology's , the coil current rise is approximately linear and the induced electric field pulse is near. In conventional MS stimulators, only pulse amplitude can be adjusted, while in MS device both pulse amplitude and width can be controlled. MS pulse shape results in less power consumption and coil heating. Through the device controller, the user specifies the voltage of capacitor which determines the amplitude of the induced electric field, and the on-time of switch which sets the pulse forming technology of the positive phase of the induced

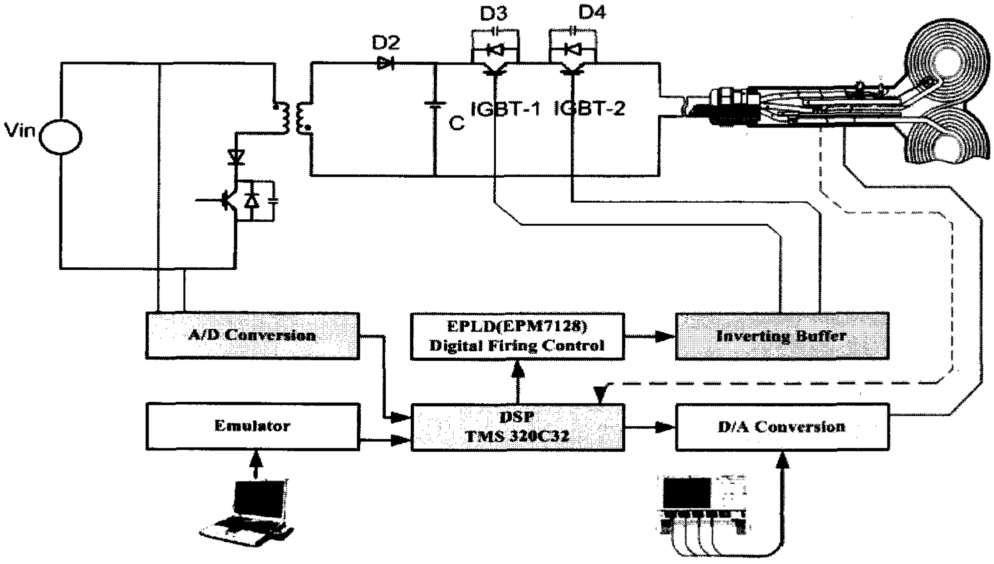

그림 4. 제안하는 경두개 자극장치
Fig.4 Proposal of a Transcranial Magnetic Stimulation

pulse. Mathematically, the initial positive phase of the MS coil current is an under damped oscillatory response, and the subsequent negative phase is an exponentially decaying response. The use of the correct coil side is particularly important in cortical stimulation as the human motor cortex is more sensitive when the induced current is flowing from posterior to anterior.

$$\Delta E_{\in} = \Delta E_{L_m} + \Delta E_C + \Delta E_{Load} \tag{1}$$

where is the amount of energy that has been drawn from the input power source during the considered switching period. is the difference of the energy stored in the magnetizing inductance of the transformer and is equal to zero because de-energizes at the end of each switching period. is the change of the energy stored in the output capacitor during the same switching period and can be described as

$$\Delta E_C = E_{C,(n+1)T} - E_{C,nT} \tag{2}$$

And finally, is the amount of energy delivered to load during the same period. Output capacitor provides the load current; hence, we can write

$$\Delta E_{Load} = \frac{1}{R} \cdot \int_{nT}^{(n+1)T} V^2_C \cdot dt \tag{3}$$

In (1), using the trapezoidal rule instead of integration, we can approximate as

$$\Delta E_{Load} \cong \frac{T}{2R} (V^2_{C,(n+1)T} + V^2_{C,nT}) \tag{4}$$

Moreover, the energy stored in a capacitor at each instant is equal to the squared value of the voltage that appears across the capacitor divided by twice the value of the capacitor can be rewritten as

$$\Delta E_{Load} \cong \frac{T}{RC} (E_{C,(n+1)T} + E_{C,nT}) \tag{5}$$

Substituting (2) and (4) into (1) and solving for the energy stored in the output capacitor at the end of the desired switching period, one obtains

$$E_{C,(n+1)T} = M \bullet E_{C,nT} + \frac{1}{1+\frac{T}{RC}} \triangle E_{\in} \qquad (6)$$

where

$$M = \frac{1-\frac{T}{RC}}{1+\frac{T}{RC}} < 1 \qquad (7)$$

Equation (8) shows the recursive relation of the energy stored in the output capacitor. Power consumption and coil heating The power consumption of a Magnetic Stimulation device can be expressed as

$$P = \frac{f_{train} \quad (\Delta \ Wc \quad)}{\eta} \qquad (8)$$

Where f_{train} is the pulse train frequency, ΔWc is the energy dissipated per pulse, and η is the capacitor charger efficiency. The energy per pulse can be measured by subtracting the energy on all n capacitors in the power circuit before and after the pulse

$$\Delta Wc = \frac{1}{2}\sum_{i=1}^{n} CiV_{Ci}^{2}(t=0) - \frac{1}{2}\sum_{i=1}^{n} CiV_{Ci}^{2}(t \geq tp) \qquad (9)$$

Ⅲ. 실험결과

the right side of the body; with Side B visible the right motor cortex is stimulated and the response will occur on the left side of the body. While the basic circuit topology of MS devices is simple, the circuit implementation requires careful component selection, layout, thermal management, and transient suppression, due to the very high operating voltages and peak currents. These values are within the range of commercial monophasic MS devices, however the MS circuit presents additional implementation challenges due to the forced coil current commutation which enables pulse forming technology control. To enable pulse forming technology control, the turn on and turn off of switch have to be controllable from its gate terminal. Implementation schematic of MS device. Snubber circuits in parallel with capacitor bank C and switch Q suppress voltage spikes associated with Q turn off and reduce power dissipation in Q. A custom-made controller sent triggering pulses to the gate drive via an optic cable, with pulse forming technology set by the user. Fig 5 presented waveform current of a pulse forming switching 20 khz , Fig 6 waveform current of a pulse forming switching 10khz, fig 7 have 5khz.

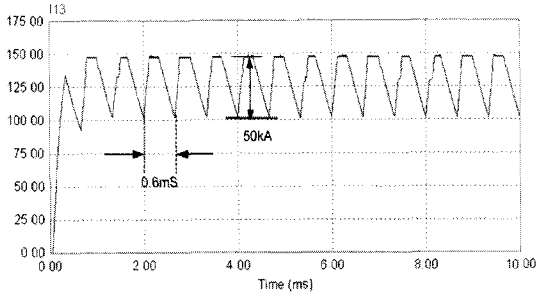

그림 5. 펄스포밍 스위칭의 전류파형(20khz)
Fig. 5 Waveform current of a pulse forming switching (20khz)

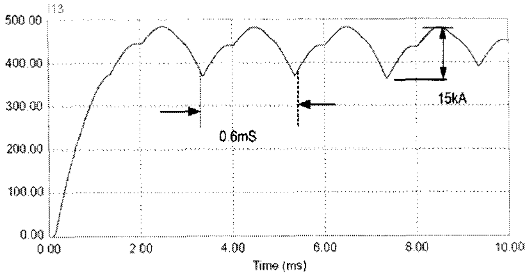

그림 6. 펄스포밍 스위칭의 전류파형(10khz)
Fig. 6 Waveform current of a pulse forming switching (10khz)

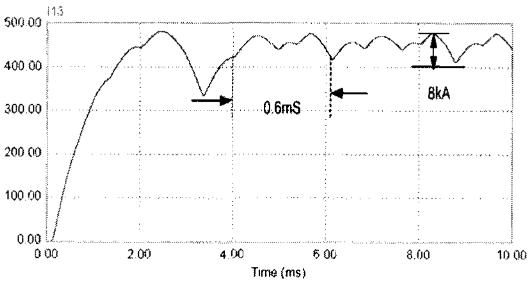

그림 7. 펄스포밍 스위칭의 전류파형(5khz)
Fig. 7 Waveform current of a pulse forming switching (5khz)

Free-wheeling diode was implemented with two series-connected fast 1800 V /105 A diodes. To allow pulse forming technology control over a significant range and to produce close to rectangular induced current pulses, the MS energy-storage capacitors have to be larger than those in conventional stimulators. The maximum capacitor voltage should be chosen to allow supra threshold stimulation of the targeted neuronal population at the shortest desired pulse forming technology. The capacitance value should be chosen based on the upper limit of the desired pulse forming technology range. In MS, the coil current is forced to commutate between the energy-storage capacitor bank and the free-wheeling diode when the coil current is at its peak. Therefore, the wiring and component placement in the MS device were arranged so as to minimize the stray inductance. Still, stray inductance cannot be completely eliminated. For example, capacitor bank series inductance of 150 nH with 6kA current stores magnetic energy sufficient to produce a 23kV spike on an IGBT switch with 10nF collector capacitance. Therefore, snubber components were installed in parallel with the energy-storage capacitor bank and the switch to handle the turn-off transient. Capacitor is mounted tightly between the collector and emitter terminals of to suppress high-frequency high-voltage spikes. Diode consists of three series-connected fast-recovery 1200 V/60 A diodes Snubber capacitors utilize high-voltage, high-current polypropylene, and paper film/foil capacitors. These capacitors have to be large enough to hold the peak switch voltage below its rated limit.

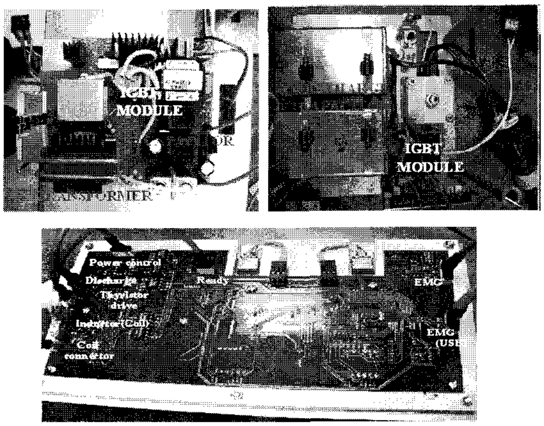

그림 8. 실험장치(IGBT & Discharge Module)
Fig. 8 Experimental tool (IGBT & Discharge Module)

The MS device was tested with capacitor voltages up to 1.65 kV and peak coil currents up to 6 kA. The pulse forming technology range of the initial electric field phase was 5 to 160 s. The experimental measurements of key MS switching waveform are given in fig 5,6,7. The waveform associated with pulse forming technology of 20, 40, 60, 80, 100, and 120 s are overlaid for comparison. As expected, the positive phase of the induced pulse comprises a portion of a cosine wave, which is close to rectangular for brief pulse forming technology. Finally, from the emulated neuronal membrane potential it can be seen that longer pulse forming technology produce more membrane depolarization. As expected, turn off causes a voltage spike and ringing at collector due to the parasitic inductance of the energy-storage capacitor bank and its wiring. Due to the snubbers, collector-emitter voltage never exceeds about twice the initial capacitor voltage, and is, thus, well below the 4,500 V rating of the IGBT. The power consumption of a MS device can be expressed as (6) where is the pulse train frequency, is the energy dissipated per pulse, and is the capacitor charger efficiency. The energy per pulse can be measured by subtracting the energy on all capacitors in the power circuit before and after the pulse. In expression, it is assumed that the capacitor charger is turned off or contributes a negligible amount of charge during the pulse. The stimulating coil temperature is proportional to square of the coil current integrated over the pulse duration, which is sometimes called the load integral. For all four capacitor configurations, the initial capacitor voltage , which is directly proportional to the pulse amplitude, was adjusted to obtain equal peak filter voltage, corresponding to equal neuronal membrane depolarization. Coil heating is directly proportional to load integral I dt. Note that all data points correspond to TMS configurations that yield same amount of neuronal depolarization, and, therefore, pulses with larger amplitude have briefer pulse forming technology phase, therefore, not significantly affecting the energy measurement.

Finally, the capacitor charger efficiency is not included in the power consumption estimate for either configuration. However, it is reasonable to expect that a properly designed charger supplying a more narrow output voltage range close to the peak voltage, as is the case in MS, will have better efficiency than that of a conventional monophasic MS device where the capacitor is charged up from zero after every pulse.

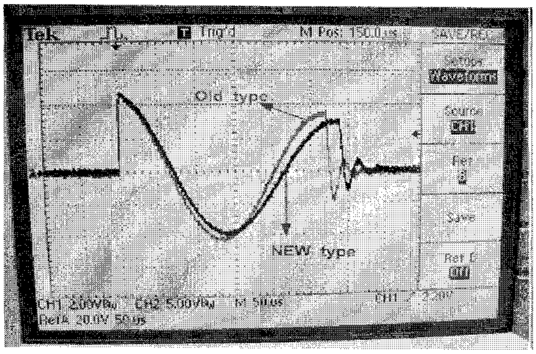

그림 9. 구형과 신형 출력파형 비교
Fig. 9 Waveform of old & new compared

Ⅳ. 결 론

The Magnetic stimulation proto type successfully demonstrated pulse forming technology control by forced commutation of currents up to 6 kA between the IGBT and the free-wheeling diode. The design could be further optimized to reduce the turn-off voltage overshoots and ringing, while keeping the snubber capacitors in parallel with the IGBT and, hence, the switching losses, reasonably small. For the near-rectangular Magnetic stimulation pulse, the power consumption and coil heating are reduced by 20% - 31% and 57% - 67%, respectively, compared to matched conventional cosine pulses. The reason for this substantial performance improvement is that the progressive discharge of the capacitor during the cosine pulse deteriorates the electrical efficiency since lower voltages are associates with inefficient energy transfer to the coil. Consequently, the Magnetic stimulation electric field remains at near-peak value during the positive pulse phase. We have successfully developed the first TMS device capable of inducing near-rectangular pulses with PW adjustable from 5 to over 100 s. Coil currents up to 6 kA were force-commutated by an IGBT switch with appropriate snubbers, while the resulting transient voltage spikes did not exceed power-train component ratings. The key safety parameters of the MS device are within the range of existing commercial products. The rectangular pulses use 22% - 34% less electrical energy and contribute 67% - 72% less coil heating compared to a matched conventional cosine pulses.

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