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Repetative Transcranial Magnetic Stimulator (rTMS) Characterization and How to Develop the Functionalities for Treating Neural Disorders

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Abstract

Background: Repeated transcranial magnetic stimulation (rTMS) is an important non-invasive technique with several protocols to treat a wide variety of neural disorders. This method utilizes a strong power supply to discharge high currents in a single or dual flat spiral coil with specific characterizations. It makes a magnetic field that promotes neuroplasticity by applying the field distribution on the appropriate brain zone and requires adjusting time and frequency relating to intervention protocols.

Aim: This study investigates components of an rTMS machine to describe development approaches to increase performance, specifically in the binary mode of recovering proportionally with brain and heart signals.

Methods: The proposed method achieves an rTMS and probe-set coil prototypes whose performance is approved with some statistical modelings and experiments analysis.

Results: Results show that the physical properties of the coil are proportional to the power supply effect and the magnetic field distribution in front of the probe set.

Conclusion: By clarifying the mechanism of oscillator switching modes and the location of the processing unit in rTMS, this paper is directed to utilize external sensors to create a smart stimulator with touch EEG or ECG signals through the most accurate intervention.

Conflicts of Interest: The Authors declare no conflicts of interest.
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Introduction

Electric stimulation traditionally could induce neurophysiological changes in the nervous system by varying the stimulation parameters and delivery methods (1). With the development of electrical automation technologies in recent years, the use of radiofrequency-RF magnetic fields in biomedical applications has increased dramatically for both diagnosis and therapy (2, 3). Repetitive transcranial magnetic stimulation (rTMS) is a feasibly established related technique for non-invasive brain stimulation that has been broadly expanded in basic clinical neurophysiology for the treatment of various neuro disorders (4). Analysis of the level and duration of the rTMS perturbations combined with electroencephalography (EEG) shows varying neural activations due to neuroplastic effects after interventions over the brain (5).

The rTMS consists of a high-current pulse generator to produce a discharge current of several thousand amperes that flows through a

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stimulating coil and generates a brief magnetic pulse with field strengths up to several Teslas. Thus, this magnetic field that is created undergoes little attenuation by extracerebral tissues and depolarizes superficial axons to activate neural networks in the cortex (6). Stimulation in a certain pattern, with repetitive protocols, can have both excitatory and inhibitory effects (7). Low frequency-rTMS (HF) may increase the rate of seizure and low ق (LF) was found to suppress, but both facilitate reorganization in the affected hemisphere and due to cortical excitability leads to effective organization processing within the functional network that leads to more strengthening the synaptic activity of surviving neurons (8). The most beneficial right or left hemisphere (RH/LH) and rate of recovery vary widely between kinds of protocols from patient to patient. As a specific sight, LF-rTMS cause inhibition of RH-language homologs may be due to transcallosal disinhibition or decreased overactivation in RH that promotes increased LH-perilesional activation and function (9, 10). J. Woong Park, et al. (2004) by finding the best switching frequency considering duty ratio has proposed a half-bridge ZCS resonant and Cockroft-Walton circuit using two separate transformers for each one to prepare high voltage as discharging source of the electrodes (11). Also, W. Young Kim and G. Hwang Bo (2009) utilized such an inverter, but only used a low-voltage transformer, which could decrease switching loss and control output energy precisely. They could obtain the desired magnetic stimulation by the control of pulse repetition rate and switching the number of charging cycles simultaneously (12). Through investigating how to improve coil efficiency, studies on circular flat spiral coils showed that besides the power transfer efficiency, adjusting the coil design variables including inner and outer radius, channel width and some turns affecting the coil impact, and inductance as physical characteristics can help for optimizing output power (13-15). Most recently, Vincent Leung, et al. (2022) described how to design an inexpensive compact battery-powered rTMS prototype that could generate a 10 Hertz magnetic pulse train with a peak flux density of 100 (mT) at 2 (cm) distance from the coil (16). For an important issue, treating sessions with LF-rTMS (<1 Hz) by peak flux density didn't produce certain changes in the cerebral cortex (17). The rTMS effect on electrophysiology properties of PNs could be detected by recording the mini excitation postsynaptic current (mEPSC) of projection neurons (PNs). Furthermore, calcium channel activities from PNs by varying frequency, intensity, and time show the potential cellular activity of rTMS-induced neural plasticity activity to treat different neural and psychiatric disorders. (18). Uma R. Mohan et al. detected 10-50 (Hz) direct current stimulation in the neocortex (temporal, frontal, parietal, and occipital lobes) compare to TMS with specific power caused the greater rate of high-frequency activity (HFA) decreases than 100-200 (Hz) stimulation in the MTL (medial temporal lobe, hippocampus, and limbic area), and also different gamma band oscillation was observed. These results suggest that neuronal activity changes depend on suitable frequency, location, and intensity of stimulation for designing stimulation protocol (19). Since the syndromic classification of some neurological disorders like epilepsy is highlighted with long interictal arrhythmia (20, 21), there are some algorithms to predict an attack and prevent a rapid attack to increase convenience (22, 23). For this reason, both acute and delayed rTMS facilitate rehabilitation by maintaining enough energy behind the coil at least for 30 minutes necessarily to attain other efficient modulations with delayed protocols (24, 25). One proof is the study on OCD patients with possible frontal lobe involvement that showed rTMS is a good therapeutic tool for compulsive urges, but not obsessions decrease with right lateral 30-minute stimulation protocol and 8 hours after stroke (26). Another proof is some significant changes in blood

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serum levels 1- or 2 hours after intervention which make some limitations which are offered on the stimulation to reduce high-risk positions according to rTMS principles (27, 28). In a principle of neurophysiology, with m-n frequency modulation (m<n, and n as a harmonic ratio of m) that m-phase can cover faster phase, phase coupling as a signal architecture can predict heart rate, breathing frequency, and fluctuation in BOLD signal with brain signals that could be beneficial to determine stimulation frequencies. Therefore, rTMS has good potential for treating syndromic disorders with the qualified signal prediction (29). During future development, using sensors in chronic data collection for modulating by the specific algorithms, translating data into stimulation parameters can convert rTMS to a closed-loop mechanism control system with high accuracy in treating wide neurological diseases (30, 31).

This study describes how to create an rTMS with only one transformer and an H-bridge inverter in a power supply unit, with some differences from older prototypes like utilizing inductors on the path of a capacitor charging circuit that saves capacitor energy for charge and discharge continuously. Field distribution was investigated by varying the voltage and relating currents comparing an air core cylindrical- and two circular flat spiral-coils with different cross-section areas. Simulations and test experiments revealed how it can improve magnetic field strength with specific frequency and duty cycles within the switch master power supply and oscillators. It seems complex, but this study prepares a route to utilize all required information to develop performable functionalities and stratification of the process.

Methods

The rTMS includes four or five fundamental units consisting of a power supply with a transformer that in traditional models would be more and an inverter charging unit to supply main capacitors; a switching circuit that controls the charging and discharging frequency and pulse duty ratios under specific modulation protocol controlled with an external processing unit; a probe-set utilizing desired flat spiral coils; and finally, a foot switch to control stimulation by the operator.

In this study, the H-Bridge is utilized to reach enough electric potential for the charging capacitor and it is designed as a multi-purpose circuit not-necessarily with a three-phase structure. This inverter can supply the electric potential up to 1.5 kV, but only three principal voltages of 150, 300, and 450 (V) are investigated by frequency and duty cycles within statistic modeling and experiments. Duty cycles can be adjusted with feedback about 3-4 seconds time intervals for changing of capacitors, and square wave pulses current discharge through the coil.

Energy Maintenance

Two types of coils are utilized in experiments. The flowing current (I) creates the energy through a coil as an inductor with an inductance of (L) that the energy can be calculated as below for different topologies:

(1) $$E_{cylandrical} = \frac{1}{2} LI^2$$

(2) $$E_{flat\ spiral} = \frac{1}{8} \mu_0 (\frac{NI}{\pi r})^2$$

where, permeability coefficient of conductor (μ0) equals to 4π × 10-7 (H/m) for copper.

According to probe-set characteristics and capacitor energy (1/2 CV^2), the energy ratio of the coil clarifies the number of capacitors requires in the capacitor bank. Utilizing the eight capacitors of 250 (V) and 1200 (μF) could achieve the needed energy when each four paralleled capacitors are connected in series. There are also two distinct inductors with that complete the role of the capacitors as the energy reservoirs to maintain continuous current in the path of charge and discharge. Inductions of these two reservoirs are directly related to the functionality of oscillators and stimulation frequency variation.

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Coils Structure

Circular flat spiral coils provided by two distinct wire diameters of 16 and 12-AWG 1.29 and 2.05 millimeters, and low line spacing (s). According to Ampere's law:

(3) $$\oint BdA = 2B\pi r$$

(4) $$B_t = \frac{\mu_0 NI}{2\pi r}$$

The B value relates to the radius (r) that is proposed as Wheeler's modified formula in equation (5). Then for any flat spiral coil with any shape, except a low number of turns coil (N) and wire diameter smaller than line spacing (w << s), inductance can be calculated proportionally to the outer diameter (Do) as mentioned below with conversion factors of 39.37 (in/m) and 10-6 of micro-Henry (μH) to (H) for coil induction.

(5) $$r = \frac{a + N(w+s)}{2}$$

(6) $$L = \frac{N(D_0 - N(w+s))^2}{16D_0 + 28N(w+s)} \cdot \frac{39.37}{10^6}$$

Due to the line spacing and insulating layer, a capacitive coefficient (C0) forms in each loop that reveals the line spacing should be decreased as it would be possible.

(7) $$C_0 = \frac{8.85 \times 10^{-12}}{4\pi s} \equiv (kA)$$

Furthermore, total magnetic flux density (N.φ) or (LI) would be obtained by solving equation (8) and considering inner and outer radiuses for boundary conditions.

(8) $$\iint BdA = \int_a^b \left(\frac{\mu_0 NIw}{2\pi}\right)\frac{1}{r}\,dr$$

(9) $$LLI = \frac{\mu_0 N^2 Iw}{2\pi} ln\left(\frac{b}{a}\right)$$

Basic physical characterizations of air core cylindrical coil experimentally were also investigated using an inductometer for better analysis of current excitation comparing the coils. The inner radius is considered as 33 (mm) at the same inductance (L = 17μH), and the same number of turns (N=16) of flat spiral coils. Peak amplitude from the top surface of the coil (z) is notable while the B value has been calculated as equation (10). However, It doesn't vary too much with coil height, though total magnetic flux density (φB) is crucially proportioned to the number of turns, as mentioned below:

(10) $$B = \frac{\mu_0 I_{peak}}{2r} . (1 + \frac{z^2}{r^2})^{-3/2}$$

(11) $$\varphi_B = NAB$$

Cross-sectional area (A) substitutes considering the difference between inner and outer diameters as mentioned before. However, current excitation through both types of coils according to the proposed RLC circuit and frequency modulation (f) within duty cycle (T) would be estimated accurately as is brought up below:

(12) $$I_{peak} = \frac{V_{supply}}{\sqrt{L/C}}$$

(13) $$f = \frac{T}{2\pi RC}$$

Considering (√(L/C)) for inductor resistance (R), then:

(14) $$I_{peak} = 2\pi f C . V_{supply} . (T)^{-1}$$

The schematic of Figure 1a. shows processing unit controls charging capacitors with appropriate time intervals according to frequency and pulse generator modulations in the back of the coil. Fast charging of the capacitor to attain fast repetitive discharge through the coil is possible with an H-Bridge inverter. Before pulse generation with square wave oscillation, the current frequency should be adjusted according to rTMS principles which are related to the threshold of stimulation. Therefore, high alternative current discharge with high frequency should be converted to a DC using a high-power rectifier board behind the coil. Relating to the basic topology of rTMS, two steps of data analysis are followed:

1. Statistical modeling considering physical properties of a coil in probe-set;
2. Test experiment of rTMS prototype with different coils.

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The first step is followed by simulations of magnetic field distribution on the coils with mentioned physical properties. The second step is more complex, but oscillography tests and calibration methods with inductometer processing could prove electromagnetic field induction through designed coil prototypes.

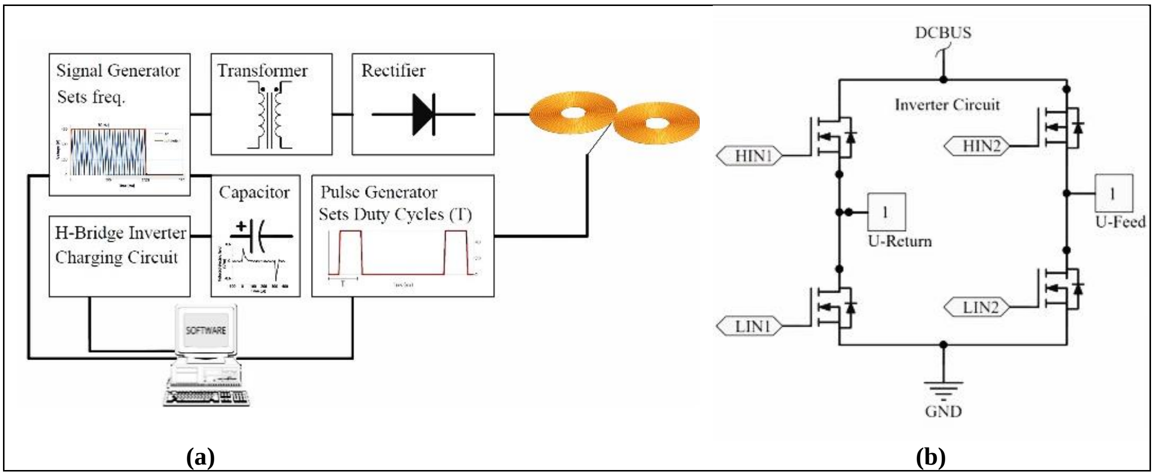

Figure 1. (a) Topology of rTMS machine and processing unit; (b) Schematic of H-bridge inverter circuit.

Results

To characterize the functionalities of the proposed platform, field distribution and the magnetic flux density on the coil would be investigated most importantly by some analysis methods.

There are some data sets, collected with modeling, and investigated through physical experiments to prove observations as described. First, a review of frequency and duty cycle to prepare desired field distribution shows that according to the threshold potential of the neocortex, at least 10 (Hz) current modulation within 70-200 (μs) cycles could create a suitable magnetic flux for neural stimulation. In addition, 2.2 to 7 teslas can be considered as desired magnetic field strength for creating the neuroplasticity effect.

Though statistical modeling shows the 30 (Hz) for 100 (μs) modulation attains 7 teslas and higher to know how fast they should be designing the prototype, making a rapid setup depends on the electronic component's quality. However, 450-500 (μs) was approved through manuscripts, and magnetic flux certainly depends on current discharge relative to the electric potential of capacitors and the discharge mechanism on the coil.

Fundamental Regularization

By regulating a DC-current after H-bridge to charge the capacitors as the main source of energy, the mechanism of two switches of S1 and S2 as they are shown in Figure 2 is important to adjust ton/off. The S1 switch will be closed when the charging of the capacitor was completed, and S2 will be closed to recharge. Note that when S1 is open, S2 is closed and reversely. However, the adjusted frequency after Q1 was led into the coil, and the S3 switch will be authorized for current discharge within desired time domain relating to the S1 and S2 switches.

The inductor after the capacitor therewith regulating the adjusted frequency reserves the current behind the coil as the inductor after the inverter, which regulates the current on the back of the capacitor relating to the charging time intervals. Noticeably, the first inductor regulates the signal amplitude with a defined frequency behind the coil. The reverse current is too important to increase the lifetime of the circuit specifically for capacitors, IGBTs, and Mosfets immunity.

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Since the current discharge would be boosted up to thousands of amperes, therefore the rectifier should tolerate high electric potential with a high inducted current that is possible using a high-power bridge structure. Moreover, convenient insulation of connectors and capacitors is another factor to decrease high-risk positions. Even, insulating the machine from induced electromagnetic fields can improve component functionalities during the performance of rTMS with strong magnetic field flux density.

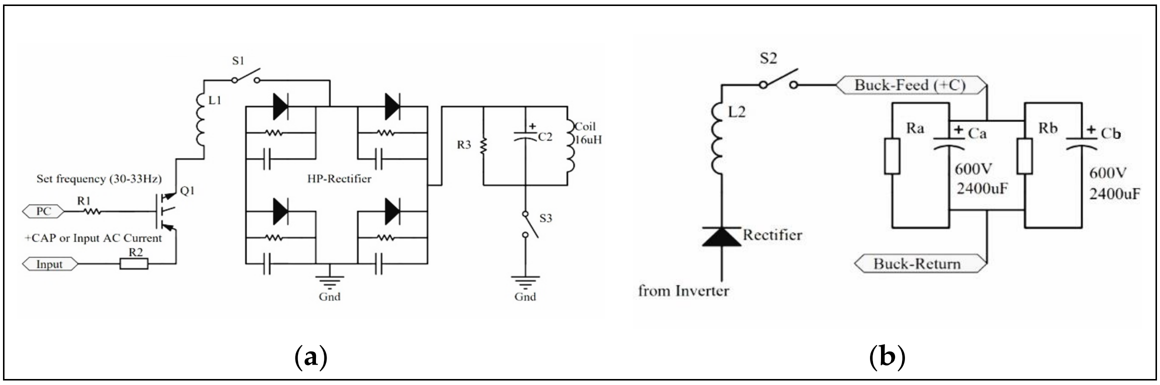

Figure 2. Switch Master Power Supply (SMPS) including (a) Adjusted frequency and time domain oscillator, and (b) Main capacitors charging unit.

Modeling and Simulations

The coil as the main part of the probe set was statistically characterized with the field distribution analysis. The probe set functionality would be better when the magnetic field distribution could be touched far from the core with the required strength due to facilitating the pulse stimulation efficiency. It can be observed on 3D plots that a magnetic field of about 7.5 (T) could be touched far from the core of the flat spiral coil. The field distribution has also a special shape relating to field strength variation toward the z-direction, while as it can be seen in Figure 3 the peak amplitude decreased with flat distribution on the top surface of the cylindrical. Although the stronger field can be created by a cylindrical even with lower voltage excitation, it is clear that this field couldn't be touched in-depth of the air core but conversely for flat spiral due to physical structures. Therefore, an impossibly conductive core is needed to touch a stronger field on the top surface of the cylindrical. According to 2D plots, a stronger field was created vertically on x-z or y-z cross sections that were only distributed on the coil body surface and it was weakened far from the center. For this reason, the probe set should be installed on a stand to increase safety features for the patient and operator.

A comparison by varying the electric potentials (Table 1) reveals a cylindrical coil at Vmax, could create a field strength three times stronger than a circular flat spiral. On the other hand, increasing the cross-section with the wire diameter of the flat coil strongly affected the B-field at the maximum voltage, which proves that the total conductive surface specifically the cross-section area proportional to electric potential affects the magnetic flux density on the coils.

This is highlighted the point that in a flat spiral coil, each layer plays the role of a conductive core for the outer layer that intensifies magnetic flux. Whereas the cross-section area under the B-field increases with the wire diameter, and field strength intensifies with the electric potential as can be seen in Table 2, peak magnetic flux density obtained at the higher voltage with higher wire diameter. Though the cylindrical coil attained maximum magnetic flux, field distribution makes it no suitable choice.

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Table 1. Electromagnetic field strength proportional to voltage and wire diameter.

Coil type	Wire diameter (mm)	450 V		300 V		150 V	
		Min	@ Core	Min	@ Core	Min	@ Core
Flat Spiral	16AWG - 1.29	0.819	1.189	0.578	3.978	0.263	0.353
Cylindrical	12AWG - 2.05	7.381	10.340	0.672	1.981	0.691	1.341
		11.704	31.064	8.698	28.698	5.648	10.648

Table 2. Electromagnetic field characterization versus Input voltage variation.

Coil type	Wire	U (V)	Matrix. L (Inductance) (uH)	Mag. Flux (Wb)
Flat Spiral	12AWG	450	0.190809	0.194219
		300	0.049489	0.033582
		150	0.051842	0.017590
	16AWG	450	0.056104	0.057107
		300	Non	Non
		150	0.056117	0.019040
Cylindrical	12AWG	450	Non	Non
		300	12.142630	8.239795
		150	12.141540	4.119527

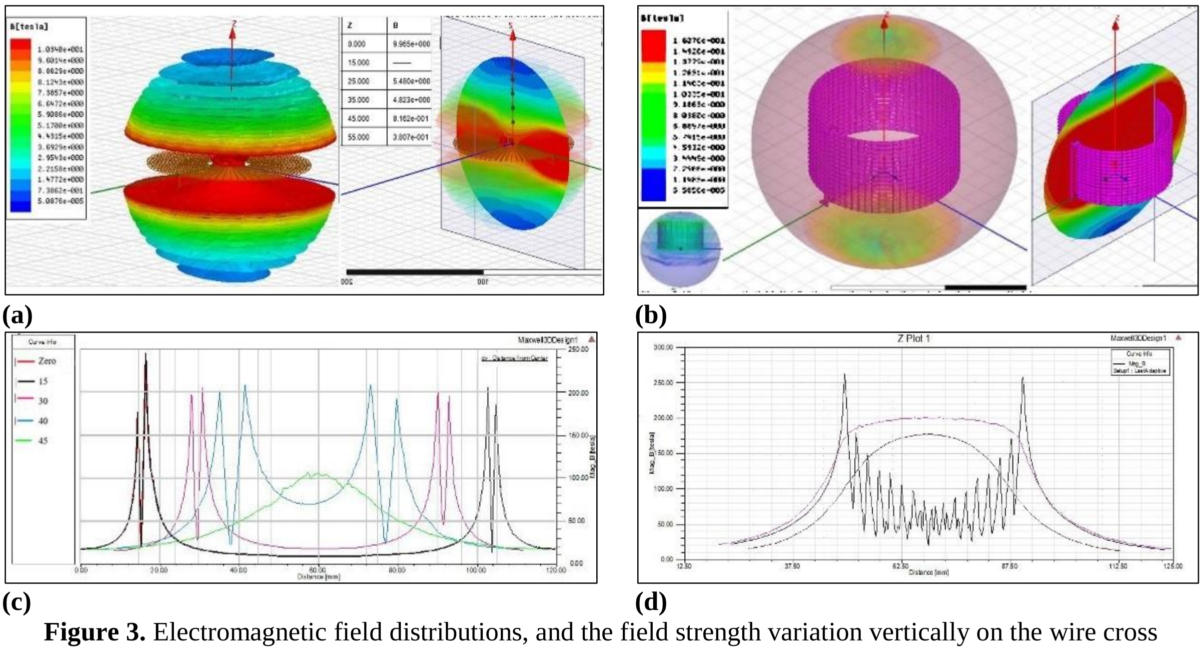

Figure 3. Electromagnetic field distributions, and the field strength variation vertically on the wire cross sections of (a, c) circular flat spiral and (b, d) air core cylindrical coils.

Discussion

Test experiments on the platform with the components as shown in Figure 4 proved the performance of the prototype. Components qualification is not negligible to increase efficiency. Though adjusting frequencies between the power supply and pulse generator according to time domains is important, frequency modulation between inverter Mosfets is considerable too. Whenever and how fast the inverter unit could supply the required electric potential on the capacitors to continue charging even by reserving the energy within an inductor is suitable to increase the accuracy for long-term application as described before. Oscillography tests also reveal some lapse

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between current amplitude after signal generator with square wave pulse generator due to converting alternating current to DC-current after rectifier board and the brief current discharge through the coil which takes some microseconds left.

After adjusting the main characteristics like amplitudes and frequencies, specifically for repeated stimulation, despite utilizing high tolerable components trying to reduce the negligible faults is another point to increase efficiency, for instance utilizing the least number of supper high voltage capacitors to facilitate the current discharge with high immunity through current transmission process. Subsequently, stratification to adjust variables by the processing unit in a closed-loop mechanism is another method. This aim will be achieved by some external sensors and suitable interfaces, but more importantly, these sensors shouldn't be affected under the magnetic field stimulation noticeably near the coil and probe set. If the stimulation effect could be controlled by brain or heart signals monitoring, time gaps between stimulation and monitoring systems can be adjusted efficiently. Moreover, sensors insulating from the external magnetic field due to electrostatic effects are important. However, the process would be possible by optimizing the coil characterization too. As described previously, high magnetic field strength could be touched on the body surface and at the center of the core, but when the field distribution on the coil has a suitable shape and accurate penetration relating to desired magnetic flux far from the core, the immunity of touch response signals far from the body surface would be increased. Therefore, for instance, utilizing butterfly- or quad butterfly-flat spiral coils can achieve desired field distribution. By adjusting the axial angles between coils depth penetration would be more possible without affecting or at least affecting the scalp with external electrodes to touch response signals. Finally, through a brief time gap between stimulation and the signal recording by EEG or ECG method, also in repeated mode would be attaining smart stimulation.

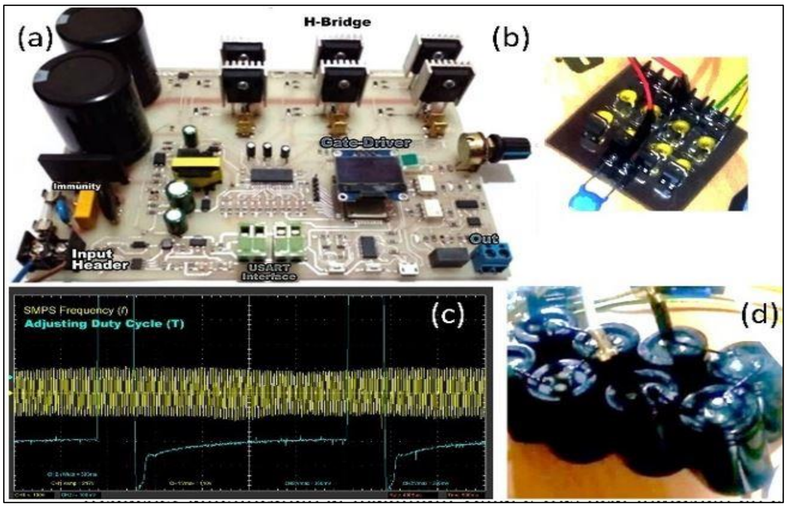

Figure 4. Prototype components: **(a)** Inverter and charging unit; **(b)** Rectifier bridge; **(c)** Adjusted frequency and square wave pulse stimulation with SMPS; **(d)** Capacitor bank.

Conclusion

Repeated transcranial magnetic stimulation (rTMS) as an important noninvasive technique, generates a magnetic field with high current discharge through a circular flat spiral coil. The neuroplasticity effect with neural network activation and also some significant changes in blood has been approved by different stimulation protocols. Therefore, it has the potential to treat wide neural disorders by

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monitoring both the brain and the heart signals. This study has investigated rTMS components to find how to create an efficient magnetic field. The mechanism was investigated by performing two types of coils through some statistical simulations before test experiments on the designed rTMS prototype. Physical characterizations of the coil were reviewed to find how to optimize the field distribution and magnetic flux for adjusting further fundamental variables like frequency and stimulation time domains through regularization of the voltage and current. Although both flat spiral and cylindrical coils could generate a strong magnetic field, the maximum field strength only could be touched at the core center of the flat spiral which approves the structure.

Results show that time gaps between pulses and the frequency have created serious changes in the magnetic flux in addition to the coil cross-section area. Though a strong field distributed on the body surface can affect the external sensors near the coil, the pulse regularization with brain and heart response signals seems beneficial to adjust time and frequency. According to this study, by optimizing the physical structure of the coil it is possible to create field distribution with suitable penetration like performing butterfly or quad-butterfly H-coils even by adjustable angles. Also, using the external electrodes increases stimulation quality with perfect adjusting frequencies, time, and gaps between stimulation pulses during the intervention through monitoring the body response signals. This method can optimize functionalities to create efficient magnetic field stimulation.

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Conflicts of Interest

The authors declare no conflicts of interest.

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Ethics

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