Evaluation of Total Harmonic Distortion of Input Power between Single- and Three-Phase Flyback Converters in Capacitor Discharge Application

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Abstract—**In this study, we evaluated a three-phase power supply to improve input power quality for the capacitive charging and discharging application. The power supply consisted of three flyback inductors, and microcontroller to generate switching pulses and film capacitor for high-energy charging and discharging. Two of three discrete power switches successively switched on with overlapped 60° of phase to make the current flows continuously. From the computer simulation, we confirmed this method achieves 1.3% of Total Harmonic Distortion (THD) and power factor of 0.96. Also, the input current waveform follows the input voltage waveform. To verify the proposed method, we implemented and tested the prototype system. Through the experiments, we confirmed the total harmonic distortion was 2.7% and the power factor was 0.94 in 50 Hz discharge condition with maintaining 1,200 charged voltages in high-voltage capacitor.**

Index Terms—**Total Harmonic Distortion (THD), power supply, three-phase, dc-dc converter, capacitor discharge**

I. Introduction

Generally, for inducing enough nerve and muscle stimulation at about 10~20 cm apart from the skin surface with magnetic stimulator, a time-varying magnetic field of about over 1~2 Tesla should be generated with a pulsed waveform [1]-[4]. Additionally, depending on the disease, treatment method, affected part and inter- and intra-patient, the stimulation frequency and time should be over a dozens of Hz and hundreds of minutes are needed respectively to elicit nerve and muscle stimulation and therapy [5]-[8].

Most of functions of the body are controlled by electrical or chemical actions and reactions. This kind of actions of the human body occurs in the human body, but it can also be obtained by inducing outside of the human body. Electrical stimulation is usually used for stimulation given in vitro. However, in the specific case where a non-contact method is required to present a stimulus without direct contact with the body, a magnetically induced stimulation method is usefully used. In order to induce a current in a living body by using a magnetic field, it is based on two basic electromagnetic laws (1) and (2).

$$\nabla \times \mathbf{E} = \frac{\partial \mathbf{B}}{\partial t} \tag{1}$$

$$\mathbf{B} = \frac{\mu_0}{4\pi} I \int_C \frac{d\mathbf{l} \times \hat{\mathbf{r}}}{r^2} \tag{2}$$

where **E** is the electric field, **B** is the magnetic field, t is the time, μ_0 is the permeability in free space, I is the electric current, $d\mathbf{l}$ is the vector along the coil path, $\hat{\mathbf{r}}$ is the unit vector, r is the distance in arbitrary point from the coil. When the magnetic field changes with time and the human body is in close proximity, a secondary electric current is induced in the living tissue by electromagnetic coupling. This leads to neuronal depolarization associated with biopotential phenomena and generates action potential.

The induced electric field is obtained from Faraday's law (1). In this case, B is the magnitude of the magnetic field generated by applying the current to the magnetic coil, and the magnitude of the electric field (E) becomes larger as the change of the magnetic field is made more in a short time. For the magnetic field generation, the current flowing through the coil can be estimated using the Bio-Savart's law (2). The current and magnetic potential of the coil can be solved as shown in the following (3).

$$E = -\frac{\partial A}{\partial t} - \nabla\phi = \frac{\mu_0 N \partial I}{4\pi} \int_C \frac{dI}{R} - \nabla\phi \tag{3}$$

where A is the electric current, ϕ is the magnetic flux, N is the number of windings, R is the distance in specific point from the coil. The induced electromotive force is determined by the amount of change of the current flowing in the coil, the winding of the coil, the distance from the coil, and the direction of the coil by (3). Since

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the electrically controllable parameter is the magnitude and rate of change of the current per unit time, it is important to generate a high current in a short time to obtain a large time-varying magnetic field.

Therefore, most magnetic stimulators use high-performance power supplies where the electric energy is stored in a high-capacity and high-voltage capacitor which are capable of providing discharges of over 1,000 amperes of current at over 1,000 volts, instantaneously [3], [9], [10]. The stored energy is discharged momentary from capacitor into the stimulation coil using an electric power switch to generate the time-varying magnetic field; thus, it basically forms an inductor-capacitor (LC) resonant circuit [11]-[13]. Since the energy stored in the capacitor is discharged into the stimulation coil in the form of high-voltage and -current for a short time, much of the stored energy is consumed. After one stimulation is output, the power supply should quickly recharge the capacitor for next stimulation.

To reduce power consumption and allow faster charging, a method to return the injected energy from the stimulation coil to capacitor has been used. However, this method occurs a section the polarity of both ends of the capacitor is inverted. At this time, a short circuit is instantaneously applied between capacitor and power supply, flows a surge current, and transient current generated with high order harmonics. To solve this problem, a switched mode power supply (SMPS) with flyback topology was used to generate high-voltage while limiting the current by using an inductor [10], [11]. Although the inductor also limits the current surge, the power factor is decreased greatly [11], [12]. This is because of the flyback topology itself, phase shift caused by using an inductor and capacitor to utilize in power conversion and energy storage, respectively, and discontinuous usage of output. These three reasons are superimposed. The decrease in the power factor reduces the device's affordability, and causes an increase in the installed capacity of electric power supply system [13]-[15]. Additionally, it has adverse effects on the operation of other electronic equipment using the same power line. When using magnetic stimulation devices, power factor compensation is especially necessary.

In particular, the power factor deteriorates the efficiency of the device and causes overheating, abnormal sound, vibration noise, and malfunction of the device due to the influx of the harmonic current in the device. Therefore, the power factor of electric and electronic devices has important meaning and the magnetic stimulator using high power has more significance. Therefore, international organizations such as the International Electrotechnical Commission (IEC) have established standards for harmonics such as 61000-3-2 (for devices under 16A/phase consumption) and 61000-3-4 (for devices over 16A/phase consumption) are strictly regulated. However, many studies according to magnetic stimulators have been carried out designing a stimulation coil, its applications, and therapeutic methods. Among these, researches for stimulation coil had been mainly performed in terms of the efficiently generation of the time-varying magnetic field and the targeting of constant location in the living body to induce the action potential. For this, it was performed mainly through computer simulation and actual implementation for verification in relation to materials to configure for the coil manufacturing, structure of coil forming part, size, number of turns, channels, shape, heat generation and heat dissipation methods [16], [17]. From this, recently, the shape of round coil, figure-eight, double cone, four-leaf, H-shaped coil is mainly used according to applications [18]-[20].

Application studies using magnetic stimulators were performed mainly in the field of rehabilitation and neurological. When a time-varying magnetic field is generated within 10 to 20 cm of the human body, current is induced in the body by electromagnetic phenomena. In the field of rehabilitation, this is mainly applied to muscle, such as axial symptoms [21], stroke recovery [22], and poststroke dysphagia [23] and urinary incontinence [24]. It has also been studied extensively in the neurological field and is being studied for the purpose of clinical treatment in the areas of depression, psychiatric, aging, dementia, age-related cognitive decline, and addiction treatments [25]-[29].

A study related to system design for generating magnetic fields has also been studied. Since a time-varying magnetic field must be generated at a distance of up to 20 cm from the coil, a high voltage and current must be momentarily applied to the coil. Therefore, it has been performed in terms of safety [30]-[32]. Although the correction of power factor for a system with a capacitive discharge application such as a magnetic field generator has been carried out, it was mainly studied in the field of laser and electro discharging machining for unipolar pulse output. It has been rarely performed in a system that generates a magnetic field while changing the polarity of the output voltage.

In this study, we propose a three-phase switching method, capable of generating high-voltage and -current and improving the total harmonic distortion and the power factor of the power supply for using in magnetic stimulator while taking advantage of flyback topology. This method uses three flyback inductors and the switching pulses for driving each of the gate of primary switches are overlapped with 60° for continuous current flow. A computer simulation was carried out to evaluate the proposed method and calculate the total harmonic distortion and the power factor. After simulation, we also developed the power supply and implement was carried to confirm the total harmonic diction, the power factor, and usefulness.

II. METHODS

To evaluate the method, a computer simulation was carried out for both the conventional one-phase flyback and the proposed three-phase flyback topology for both of the same input and output conditions. From the real implementation, the total harmonic distortion and the power factor was measured and performance improvement was verified. To simulate the two circuits, we used Orcad PSpice software (Cadence Inc., USA). Numerical data obtained from the simulation results were exported to MATLAB software (Mathworks Inc., USA) and calculated the total harmonic distortion and the power factor.

A. Magnetic Stimulation Power Supply with the Conventional One-Phase Flyback Topology

Fig. 1 shows the block diagram of a power supply for magnetic stimulation using the current flyback topology. The inductor used for power generation also plays the role of current limiter. However, the power factor of this type of power circuit is generally low, and many harmonic artifacts are added to the input current.

The Silicon Controlled Rectifier (SCR) is turned-off while the flyback converter operating and the capacitor is charged with high voltage. When the trigger signal turns on the SCR, the energy stored in the capacitor is discharged through the coil, and a magnetic field is produced by the resulting current. After energy discharge, the residual energy in the coil is charged back into the capacitor, and the polarity of the capacitor thus becomes inverted. When the SCR is turned off, the capacitor re-discharged with the opposite polarity into the secondary winding of the flyback transformer and the coil. At this time, the secondary winding of the transformer serves as a current buffer that it absorbs an excessive influx of current. To simulate this topology, the schematic was draw using OrCAD Capture (Fig. 2) and simulated with PSpice software under the parameters as listed in Table I.

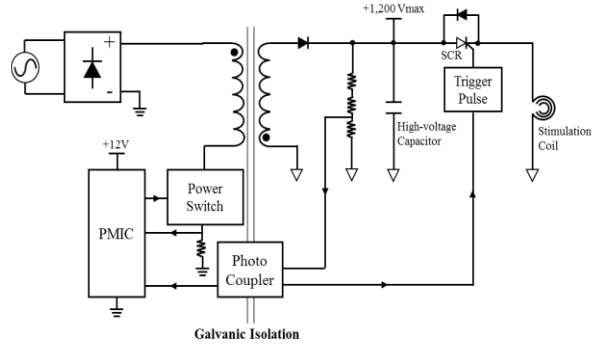


Fig. 1. Block diagram of a power supply for magnetic stimulation using the conventional flyback topology.

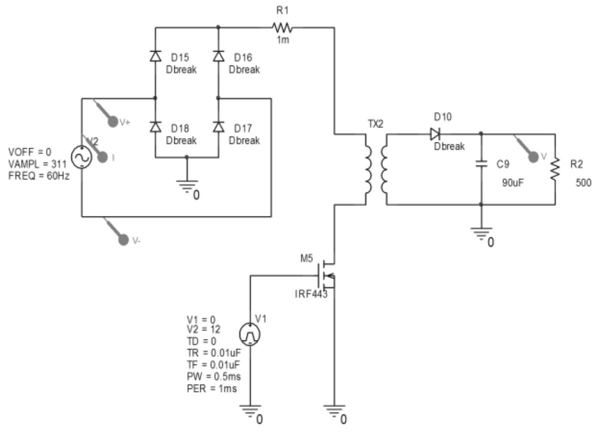


Fig. 2. Simulation circuit of conventional power supply with one-phase flyback converter.

TABLE I. PSPICE SIMULATION INPUT CONDITIONS AND PARAMETERS

Items	Values	Unit
AC input voltage	311	Volts in peak
AC input frequency	60	Hertz
Switching frequency	1,000	Hertz
Duty ratio	0.5	-
Turns ratio (Primary : Secondary)	1 : 2	-

Total Harmonic Distortion (THD) is the ratio of the sum of the harmonic components except the fundamental to the fundamental of the current. It is expressed as (4) and calculated using the root mean square (rms) value of current or voltage. The unit is %.

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2}^{\infty} I_{n(\mathrm{rms})}^2}}{I_{1(\mathrm{rms})}} \tag{4}$$

where I_{rms} is the rms value of input current. Therefore, the larger of the THD value, the higher the distortion of the input signal due to the harmonics. It means that the energy other than the input component superimposed and degrades the quality of the input power source and makes the overall system performance is degraded.

The power factor is the ratio of the effective power to the apparent power in the AC circuit. The harmonic distortion of the fundamental wave of current and the phase difference of the fundamental wave of voltage and current can be expressed as (5).

$$\mathrm{PF} = \frac{\cos\theta}{\sqrt{1+(\mathrm{THD})^2}} \tag{5}$$

where θ is the phase differences between input voltage and input current. From the above expression of THD by (4), it can be seen that the higher the THD, the lower the PF.

B. Proposed Three-Phase Flyback Topology

Fig. 3 shows the block diagram of a power supply for capacitive discharging application using a proposed three-phase flyback topology. In most cases of power converter, continuous input current flow of control method is used to obtain high power factors.

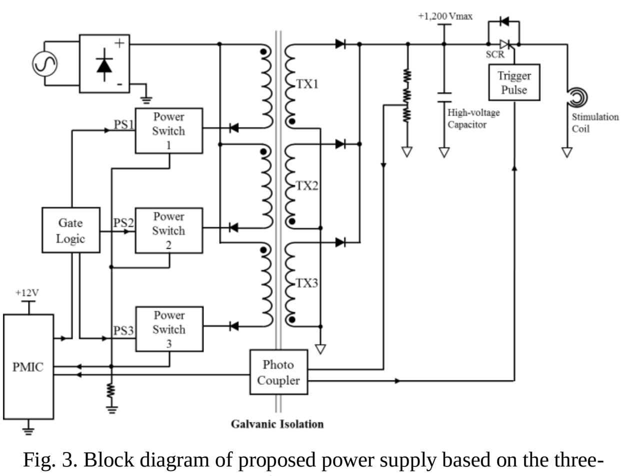


Fig. 3. Block diagram of proposed power supply based on the three-phase flyback topology.

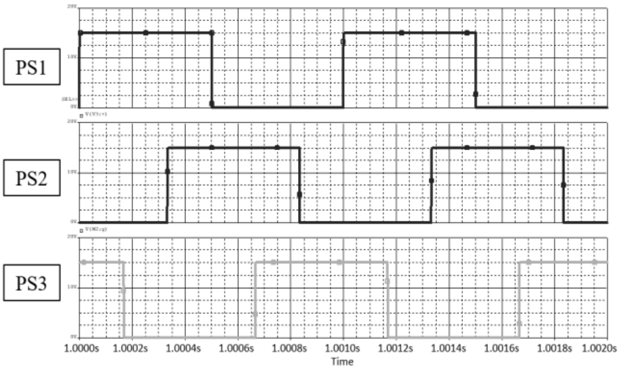


Fig. 4. Three switching signals to drive the gate of FETs for each three flyback inductors.

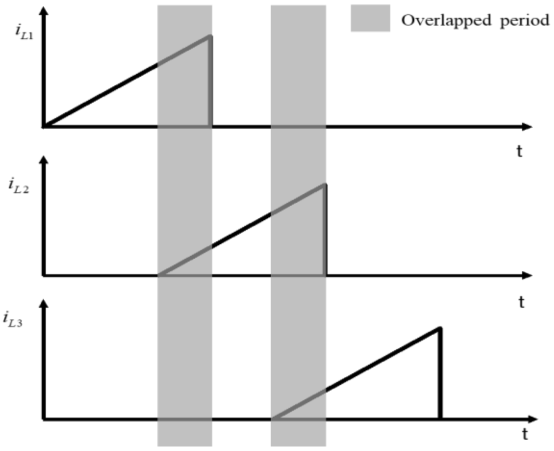


Fig. 5. Current waveform flowing in the primary winding of each flyback inductors.

This method uses high switching frequency with changes the switching time so as to ensure that the current follows the input voltage waveform. Power factor improvement through high frequency switching achieves the benefits of an increased power factor but it creates problems with inductor losses and electromagnetic interference (EMI).

Compared to existing power supplies in capacitive discharging application system, this method uses three inductors to decrease the harmonic and reduce the phase difference between voltage and current waveform. Three flyback inductors (TX1, TX2, and TX3) are used for power conversion and each switching element can be operated at low frequency (Fig. 4). This causes a decreasing in EMI while allowing for continuous current flow and improving the power factor. A transistor-transistor logic (TTL) circuit for gating three power switches (PS1, PS2, and PS3) was designed. Each signal is 120 ° out of phase, thus creating 60 ° wide overlapping sections between gate drive pulses. Because of this overlap, current can be flows continuously.

The current flowing through the primary winding of each inductor designed for flyback operation is determined by the inductance of the winding and is given by (6)

$$i(t) = \frac{1}{L}\int Vdt \tag{6}$$

where i is the current, t is the time, L is the inductance, V is the voltage. At this time, if the inductance value of the primary winding is sufficiently larger than the period of the power switch 10 times or more, a current flows in the form of a sawtooth wave as shown in Fig. 5.

Since the proposed method has a period where the current concurrently flows by 60 degrees, it flows like as shown in Fig. 6 and the current waveform is measured at the input terminal, the continuous current flows is measured. From this, the power factor could be improved.

Fig. 7 shows the schematic for the proposed method to simulate with PSpice software and its operation was analyzed under the same conditions used in the existing flyback topology.

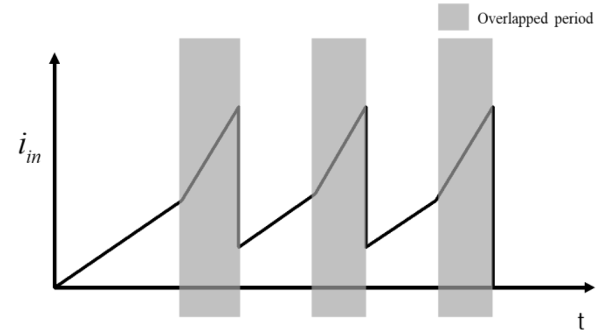


Fig. 6. Input current waveform by 3-phase overlapped switching period.

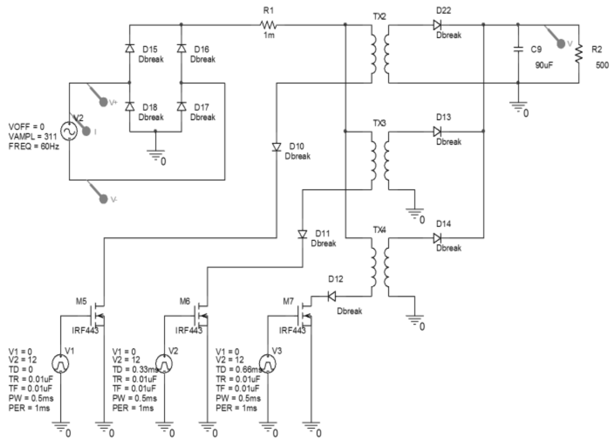


Fig. 7. Simplified circuit for PSPICE simulation of proposed three-phase flyback topology constituted by three inductors.

C. Testing the Three-Phase Flyback Topology

The three-phase flyback topology was evaluated by implementing at a practical scale. For the three flyback inductors, C-type amorphous cores were used (Hill Technical Sales Corp., USA). An IXTQ480P2 (IXYS Corporation, USA) N-Channel MOSFET was used as a power switch to drive each inductor, and a MC33152 (On Semiconductor Inc., USA) gate driver was used to drive the gate of the MOSFETs. The flyback inductors were made with PQ3535 bobbin and PQ type ferrite cores. The windings of primary was used insulated copper wire of 1.2 mm in diameter and inductance was 10.4 mH. The winding of the secondary side was made of the same material as the primary side, but the diameter of the secondary side is set to 0.3 mm in diameter. Inductance was about 20.9 mH. These inductances were measured HP4192A low frequency impedance analyzer (Agilent

Technologies, USA) at 100 kHz. For supplying the microcontroller, control parts, and signal conditioning circuits, a FS10-15 AC-DC (Power Plaza, South Korea) converter with +12 V and +5 V DC outputs was used. To control the overall system and generate the switching frequencies, an 8-bits microcontroller ATMEGA128A1 (Microchip Technology, USA) was used. This microcontroller works at a 4.5 V to 5.5 V operating voltage, 16 MHz maximum operating frequency, 52 General Purpose Input Output (GPIO) ports and it has several capabilities, such as a 10-bit Analogue-to Digital Converter (ADC) with 8-channesl, and two 8-bit and two 16-bit timer counters. To generate three switching signals, two 16-bits and one 8-bits timer/counter was used. A Liquid Crystal Display (LCD) was used to monitor and control the operational modes with 4 tact switches. A 10 film-capacitor was configured to have a 110 μF capacitor banks. A five 10 Ω and 100 Watts power resistors were connected in series to create 50 Ω dummy load.

One Silicon Controlled Rectifier (SCR) SKT551/14E (SEMIKRON, German) was used as a power switch. This SCR has 1,500 Volts of repetitive peak reverse voltage, 390 Ampere of forward current. The SCR was connected between high-voltage capacitor banks and the coil in series.

For the stimulation coil which is load of the power supply, 29 turns of insulated 0.8 cm square copper wire were coiled of 13 cm in diameter. Cooling fan was equipped on the right side of the coil to dissipate the heat generated by Joule's effect during stimulation. The experiment was performed with the same conditions used in the previously referred simulation; the power supply was operated at 1 kHz switching frequencies, and discharged while maintaining a maximum output voltage of 1,200 volts, at a maximum stimulation frequency of 50 Hz. In order to prevent the short circuit between the flyback converter and the coil, for a one high energy pulsed discharge, switching frequencies used for boosting are stopped 100 μs before the every one pulse is output. One pulse is then output from the coil to create a time-varying magnetic field and the converter is allowed to operate again after 300 μs.

III. Results

Fig. 8 shows the simulation results obtained for both the existing one-phase and the proposed three-phase flyback topology power supplies.

In Fig. 8 (a), a discontinuous of input current waveform was shown. It generates harmonic artifacts during the switching operation. This harmonic distortion are the causes of power factor degradation and the calculated power factor was 0.617. Fig. 8 (b) shows the simulation results for the power circuit of the three-phase switching method. A continuous provision of input current waveform was observed. Simulation results show that the power factor was increased to 0.953. Based on these simulation, an improvement in the power factor was obtained with the proposed three-phase switching method.

Fig. 9 shows an actual implementation of the three-phase flyback topology at a practical scale. Power was directly obtained from the alternating 220 V/60 Hz electric power line. The whole configuration was 35 x 22 cm^2, which represents an increase in area by a factor of approximately 2.6 when compared to the currently existing one-phase flyback method. The power factor was measured with a power meter (Model 6300, Kyoritsu, Japan) and achieved 0.94.

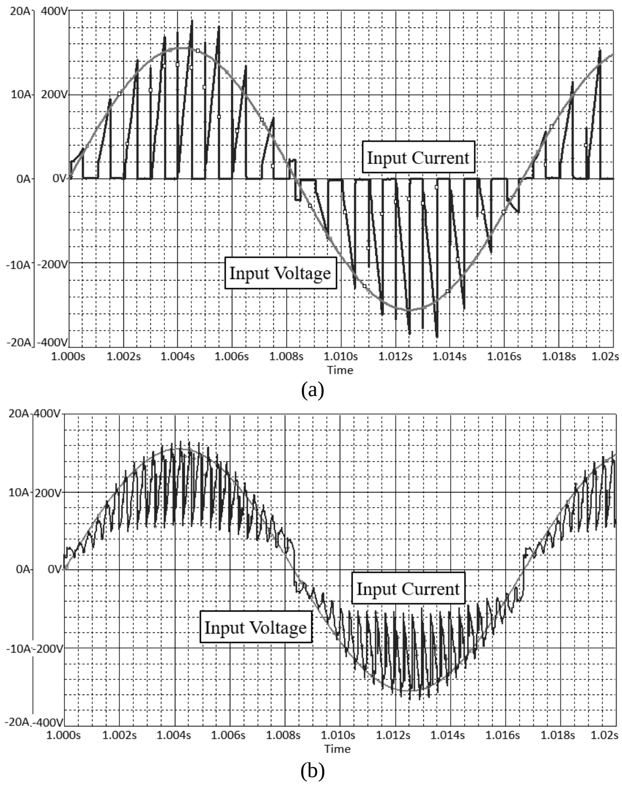


Fig. 8. Simulation results obtained for both (a) one-phase and (b) proposed three-phase flyback topology.

Fig. 10 shows an actual view of the stimulation coil. The stimulation coil for magnetic field generation have an inductance of approximately 87 μH. The size was 14 cm in diameter, the thickness was 0.8 cm, and weight was 270 gram.

Fig. 11 shows the waveform of input voltage and input current. The fluctuation in each waveform is due to the switching actions for boosting. There was almost no phase difference between the input voltage and the current.

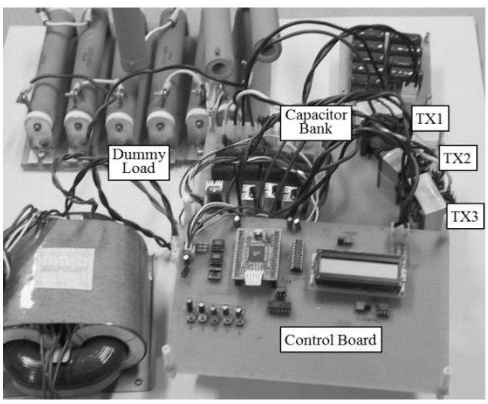
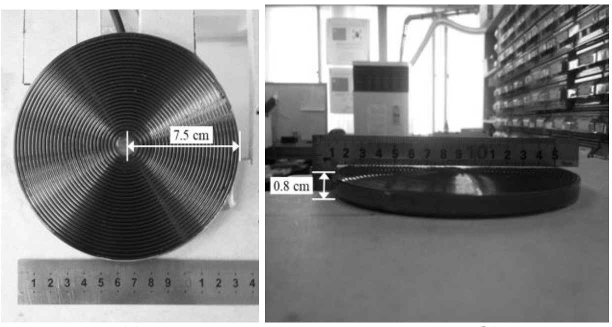


Fig. 9. Actual implementation of the three-phase flyback based power supply.



(a) (b)

Fig. 10. Actual view of the coil; (a) is overview and (b) is side view.

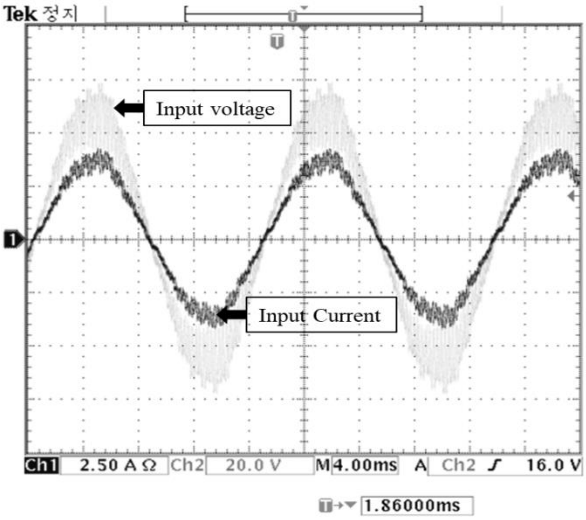


Fig. 11. Waveform of actual input voltage and input current.

Table II shows results of the simulated and measured values for the one-phase flyback topology and the power supply implemented in the three-phase topology proposed in this paper. The THD and the PF were improved in three-phase rather than one-phase topology. The measured values of both the THD and the PF are lower than those of the simulation results because there are influences such as component error, wiring, noise, etc. depending on actual implementation.

TABLE II. A COMPARISON OF THE RESULTS OF CONVENTIONAL AND THE PROPOSED METHOD

		One-phase	Three-phase
Simulation	THD	3.4%	1.3%
	PF	0.617	0.953
Actual measurement	THD	4.3%	2.7%
	PF	0.59	0.94

Fig. 12 shows the charging and discharging waveform of capacitor voltage at 50 Hz stimulation condition. Also, the input current waveform was measured with a current probe TCP305 (Tektronix, USA). The voltage was charged in the form of stairs that is because phase of the input current. The maximum output voltage was maintained stably at about 1,200 volts for continuous stimulation at 50 Hz. There was no discontinuous section to the input current waveform and follows sinusoidal wave. A zero-current flows were shown in order to prevent damage to the power supply in accordance with the short-status between the input and the output, the main microcontroller controls the switching frequencies stops 60 μs before the trigger signal is generated to driver the SCR and after 200 μs for enough freewheeling of the diode.

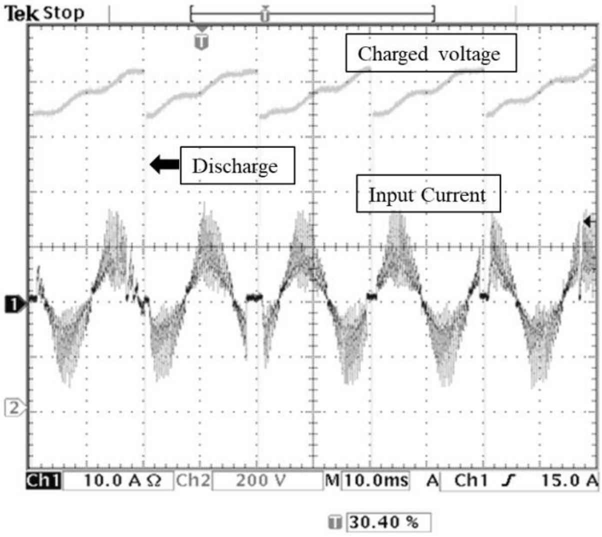


Fig. 12. Capacitor voltage of charging and discharging for stimulation and an input current waveform.

IV. CONCLUSIONS

In this study, a high power factor power supply for used in magnetic stimulator was designed and evaluated through real implementation. A three-phase interleaved switching method was suggested to improve the power factor. Spice simulations and an actual experiment were carried out to verify the method. In both cases, results show that the proposed three-phase flyback power circuit generates a continuous flow of current waveform which follows the input voltage. The power factor reaches value of 0.94 was a high performance than existing power supplies for using magnetic stimulators.

Unlike power supplies in other electrical and electronic equipment, a magnetic stimulator for used in medical fields must be capable of suppling high power and should not have adverse effects on the operation of other medical electronic devices using the same power line. The proposed three-phase switching method has current flowing in two of the three inductors at every switching time, and the input current thus flows continuously which allows for power factor improvement. Also, a particular advantage of the method lies in the fact that, by using three inductors, each power switch can be operated at low switching frequency. This allows for power factor enhancement with low frequency, improvements in electromagnetic interference, and reduce stress on the inductors and switching elements. Although the circuit size is approximately 2.6 times larger than one-phase method, it guarantees higher power factor and efficiency, improvement of performance such as stimulation frequency, strength, time, and it has a lower price than specially designed high power supplies for use in other capacitor discharge equipment such as laser, magnetic stimulator, electrical discharge machining.

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