Development of a Long-lifetime Spark Gap Switch and Its Trigger Generator for 2.0 MJ Capacitive Pulsed Power Supply Module

Lee Li, Bao Chaobin, Feng Xibo, Qi Xiangdong, Lin Fuchang
State Key Laboratory of Advanced Electromagnetic Engineering and Technology
Huazhong University of Science and Technology, Wuhan, China

Abstract—Starting from the updated requirements of an advanced laser system, a switch-trigger system for a 2.0 MJ pulsed power supply module has been developed. This paper discusses the design, construction and testing of this switch-trigger system. The two-electrode construction for the spark gap switch was selected due to the superiority in long working life, high peak currents and fast rise-time of currents. The trigger generator based on resonant charging of pulse transformer was constructed. A magnetic isolator and a pressure controller were the auxiliary equipments of this system. In the section about the mathematical principles, the equations of the lifetime and stability of this spark gap switch with graphite electrodes are given. These expressions can be regarded as the design basis of the same type switch. As for the trigger generator, the analysis states that an appropriate ratio can be obtained when using the resonant charging based on core-type pulse transformer. The charging time is dependent on the leakage inductance and the capacitance of the primary and secondary capacitors. Extensive testing has proved the operating parameters of the switches and trigger generator. The measured discharge current waveform of 2.0 MJ capacitive pulsed power supply module is demonstrated to be over 500 kA peak-current and 500 μs pulse-width. And the life test has proved that the switch-trigger system can support more than 200 kC transfer charge. Via replacing the electrodes, the lifetime of this switch can be extended more.

Keywords **— pulsed-power supply; spark gap switch; graphite electrodes; pulse transformer; resonant charging**

I. INTRODUCTION

The motivation of this work related with this paper is to develop a kind of high performance closing switch and its auxiliary devices for an advanced special facility. According to the recently updated requirements, this facility requires the synchronization operation of hundreds of capacitive pulsed power supply (PPS) modules. For each module, it needs an individual switch which supports over 1.8 MJ transfer energy in 400~500μs impulse duration (10%-10% power points). And the useful lifetime of this switch should be long as possible.

For this purpose, we have made various experiments and developments. The rotating arc-gap switch cannot support the short impulse duration due to its big self-inductance [1]. Several types of triggered vacuum switches (TVS) always have the lifetime problem in high-current [2-4]. The solid-state switch even was a candidate too. But the electrical performance of an individual semiconductor wafer is limited. Consequently, the stack assembly with series-parallel connection has to be adopted for high voltage, high current and high energy transfer. This brings about the high cost and low integrated reliability. Thus, we have to turn to the traditional two-electrode spark gaps. In 2009, we have developed a switch-trigger system with 300-kA peak current and 1500-shot lifetime for a 1.2 MJ PPS module [5]. However, for updated requirements, we have to further develop a more compact, more reliable high-energy switch-trigger system.

In this paper, we will represent an updated switch-trigger system which supports up to 2.0 MJ energy transfer per shot, or 150 coulombs charge transfer per shot. The updated spark gap switch is better in smaller size and lighter weight. The trigger generator has eliminated the Marx generator whose replacement is a magnetic core pulse transformer with compact structure and high stability. The veridical experiments show that the lifetime of the spark gap switch is at least 200 kC with a fixed air pressure. If the dry air pressure in the switch can be reduced, the lifetime may double. And the worn electrodes of the switch can be replaced quickly, so the switch lifetime is recyclable. The pulse transformer has the lifetime of 50000 shots, and its max operating frequency is 0.2 Hz. The design approach and achieved performance of this switch-trigger system will be shown in the paper. And the mathematical principle of designing this switch and its trigger generator will be reported too.

II. SWITCH-TRIGGER SYSTEM

A. Two-electrode Spark Gap Switch

The superiority of spark gap switch is appeared in high peak currents and rise time of currents. Moreover, the stability and the maintenance cost of this kind switch are acceptable. The structures and parameters of the previous spark gap switch with graphite electrodes have reported in [5]. Fig.1 reveals the 3-D perspective drawing of the updated switch. Graphite Rogowski-shaped electrodes are used. The upper and lower electrode-holders can resist the thermal damage which caused by high pulse energy transfer. Therefore the graphite electrode tips are replaceable. In the aspect of mechanical structure, this updated switch removes the nylon rods and adopts a novel fastening ring method, and the simplified electrode fixture uses the better alloy materials and the stronger construction. The insulating pressure envelope adopts a new surface coating material. This makes the surface hold off voltage level of the envelope increase by 15% in

978-1-4673-0305-7/12/$31.00 ©2012.IEEE

the ambient humidity and pressure. Finally, the overall dimension of the switch is greatly reduced by 50%; the manufacturing and maintenance cost is decreased by 30%. The technical performances are better than the previous.

Extensive testing of this spark gap switch in a 2.0 MJ, 25 kV capacitor bank yielded the demonstrated operating parameters as summarized in Table I.

TABLE I

MAIN OPERATING PARAMETERS OF THE SPARK GAP SWITCH

Operating Voltage Range	0-60kV
Maximum Peak Current	> 500 kA
Charge Transfer	> 150 C per Shot
Electrode Tip Life*	> 200 kC
Insulating Gas	Dry Air
Weight	11.4 kg
Size	225mm diameter×278mm high

* The lifetime is in a fixed air pressure.

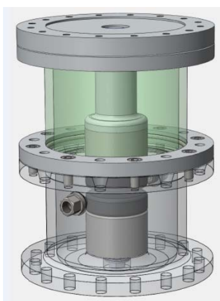

Fig.1 3-D perspective of the updated two-electrode switch

B. Trigger Generator Based on Pulse Transformer

Two-electrode spark-gap switch must be directly over-volted by an external triggering pulse with high voltage, short rise time and low jitter. Several types of trigger generators are candidates. The main drawback of the previous Marx generator previously is the complex structure [5]. A Marx generator always comprises a large amount of separated elements and mechanical parts. Thus, it is not an effective choice for a large-scale application. And the complex generator also leads to the low reliability. The spiral generator always has the switch resistance loss, spiral line resistance loss and coaxial capacitor leakage loss so that its actual ratio always is not high [6]. Especially, the insulating treatment of its output end is difficult for high-voltage requirement. Finally, we decided to use the trigger generator based on a pulse transformer as an alternative.

In several types of transformers, air core transformer (Tesla transformer) has no saturation problem, and is lightweight. However, its coupling coefficient k is low (normally less than 0.8). The energy transmission of Tesla transformer is high in dual resonant mode (k =0.6), the energy transmission efficiency is highest, but the ratio always is low and the charging voltage is bipolar [7]. As for magnetic core transformer, the output voltage can reach the peak value within only half a primary oscillation cycle in single resonant mode. In this mode, the energy transfer time is greatly reduced and the breakdown field of dielectric materials used in the pulse transformer is enhanced. Furthermore, magnetic core transformer has a large coupling coefficient (more than 0.99), small size, and lowest cost [8-9]. But the magnetic core transformers should be worked without saturation of the core.

Fig.2 shows the circuit scheme of this trigger generator. Fig.3 demonstrates the main components of this trigger generator. Fig.4 provides the 3-D perspective of the trigger generator. The resonant charging circuit based on a pulse transformer is composed of the primary capacitor C_L , the thyristor (SCR), the transformer and the secondary capacitor C_H , which are contained in the dashed frame. Diode D1, which is in parallel with SCR, provides the reverse current to reset the core of the pulse transformer. For obtaining the sharpening pulses, SG is a self-breakdown three-electrode peaking gap whose structure is shown in Fig. 5. The trigger electrode is connected to be ground through a resistor R_1 with the resistance of several MΩ.

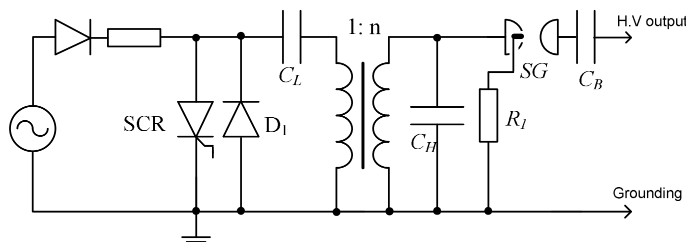

Fig. 2 Scheme of the trigger generator based on pulse transformer

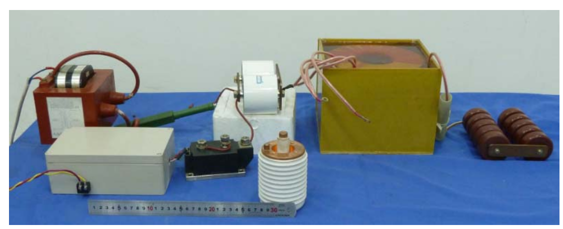

Fig.3 Main components of the trigger generator

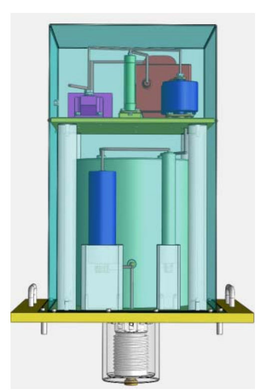

Fig.4 3-D perspective of the designed trigger generator

The primary capacitor C_L is charged to approximately 2 kV in design. SCR is used as the controllable switch, pulse-charging the secondary capacitor C_H through the pulse transformer. The secondary capacitor C_H and blocking capacitor C_B, which are both capable of withstanding 175 kV, are formed from a series set of high voltage ceramic capacitors. The peaking gap SG breaks down at approximately 120 kV.

Fig.6 represents the output pulse voltage waveform of this trigger generator in the switch-trigger system. And the main operating parameters are summarized in Table II.

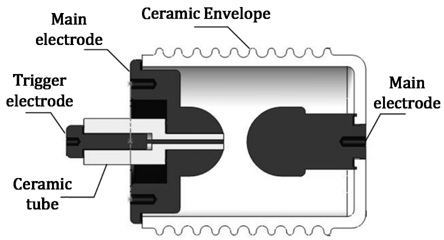

Fig.5 Structure of three-electrode peaking gap

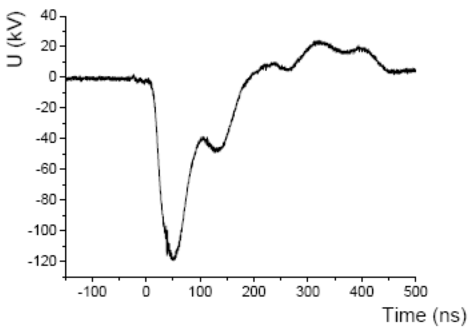

Fig.6 Output triggering voltage waveform (open circuit)

TABLE II

MAIN OPERATING PARAMETERS OF THE TRIGGER GENERATOR

Output Peak Voltage	120 ±3 kV
Rise Time of Output Voltage	≈30 ns
Output Pulse Width	> 100ns
Weight	18.5 kg
Size	380mm x 350mm x 740mm

C. *Magnetic Isolator*

The effect of the magnetic isolator is to block the triggering pulse produced by the trigger generator. The magnetic isolator should represent high impedance during the rise time of the triggering pulse, but when the spark gap switch is turned on, it would become like a conductor wire in the falling process of triggering pulse. We still use the ring-shaped low-remanence magnetic isolator which is made by Fe-based nancrystalline alloy as before [10].

D. *Pressure Controller*

The spark gap switch with graphite electrodes requires auto air blowing after one or several discharging shots. And according to its operation voltage, this switch requires that the inner pressure is adjustable. The pressure controller provides these features. As shown in Fig.7, It involves two actuators, one pressure transmitter, one intelligent regulation meter and one assistant communication circuit board.

Fig.7 Main components of a pressure controller

III. MATHEMATICAL PRINCIPLES

A. *Pre-fire Probability*

Pre-fire is the incidental self-breakdown before triggered. The microscopic surface roughness of eroded graphite electrodes has a major impact on pre-fire. According to a lot of testing, we have found the pre-fire probability of the gaps with the uniform field and graphite electrodes obey the following Weibull distribution:

$$F(\eta)=1-\exp\left(-2\cdot\eta^{18}\right) \tag{1}$$

where η denotes the under-voltage ratio, $\eta=U_w/U_b$. U_w is the working voltage of the switch, and U_b denotes the self-breakdown voltage of the spark gap. When the upper limitation requirement of pre-fire probability of a facility with N switches is assumed as Δ, the following expression is obtained:

$$F(\eta)\leq 1-\sqrt[N]{1-\Delta} \tag{2}$$

Thus, it should be given that:

$$\sqrt[N]{1-\Delta}\leq \exp\left(-2\cdot\eta^{18}\right) \tag{3}$$

Table III gives a series of suggested under-voltage ratio values related to several typical N when Δ=0.1%.

TABLE III

RECOMMENDED η IN DIFFERENT NUMBER OF SWITCHES

N	10	100	1000	10000
η	57%	50%	44%	39%

B. *No-fire Probability*

No-fire means the breakdown failure when triggered. When the rise time of the triggering pulse is with tens nanosecond, and the gap distance is in 2 centimeters, the gap breakdown still obeys the streamer criterion [11]. According to the experimental results, when the breakdown occurs in the rise time, the empirical equation of the 50% breakdown voltage is gotten as:

$$U_{50\%} \approx 1.14U_b + 0.38\sqrt{Pd} \cdot \upsilon$$
$$\text{subject to} \begin{cases} 1.5\times10^2 < Pd < 3.5\times10^2 \text{ kPa}\cdot\text{cm} \\ 2 \le \upsilon \le 6 \text{ kV/ns} \end{cases} \tag{4}$$

where U_b is the static breakdown voltage of the gap (kV), P is the inner air pressure (kPa), υ is the rise rate of the triggering pulse (kV/ns), d is the gap distance. If U_P denotes the peak voltage of the triggering pulse, the no-fire probability of the spark gap with graphite electrodes can be written as:

$$G(\kappa) = 0.5 \cdot \kappa^{-15} \tag{5}$$

where κ is the overvoltage coefficient, $\kappa = U_P / U_{50\%}$. When the upper limitation requirement of no-fire probability of a facility with N switches is assumed as Θ, the following expression is obtained:

$$G(\kappa) \ge \sqrt[N]{\Theta} \tag{6}$$

Clearly, the requirement of no-fire probability will determine the peak voltage U_P of the triggering pulse.

C. Switch Lifetime

In the whole switch-trigger system, the lifetime of the spark gap switch is the shortest piece on board. And the lifetime of the spark gap switch depends largely on the worn electrode tips. Luckily, the lifetime of the spark gap switch with Rogowski-shaped graphite electrodes can be theoretically estimated. When the transfer charge per discharging shot is over 25 C, the sublimation process of graphite caused by the arc heating is sufficient. In this case, the average erosion rate of graphite cathode and anode is close to a constant. Thus, the mass loss of a graphite electrode is linear to the amount of charge transfer. The maximum lifetime equations of the switch in transfer charge [12]:

$$\begin{aligned} & 24.5\times d\cdot\chi + 6.4\times\sqrt{d\cdot\chi} - \frac{U_w}{\eta} = 0 \\ & d = d_0 + \frac{2\delta_m Q_L}{S\rho} \\ & \chi = 2.89P/(273+\theta_T) \\ & \text{subject to } P \ge 101.3 \text{ kPa} \end{aligned} \tag{7}$$

where χ is the air relative density; θ_T is the air temperature in Celsius, d_0 denotes the initial gap distance (cm); δ_m, ρ and S indicates the average erosion rate (g/C), the electrode tip area (cm^2) and the density (g/cm^3) of the graphite electrode tips, respectively. As the lifetime index, Q_L is the cumulative transfer charge.

In practical, the gap distance d of the switch is always increasing over Q_L. When d become the gap distance become great enough, the pressure have to decrease so as to keep triggering reliability. Considering the triggering ability, which may be estimated by no-fire probability, the lifetime of this switch follows:

$$\begin{aligned} & 24.5\times d\cdot\chi + 6.4\times\sqrt{d\cdot\chi} - U_{bX} = 0 \\ & \text{subject to} \begin{cases} \kappa_X = U_P / U_{50\%}(U_{bX}) \\ G(\kappa_X) \ge \sqrt[N]{\Theta} \end{cases} \end{aligned} \tag{8}$$

where U_{bX} denotes the self-breakdown voltage of the switch gap when Eq.6 cannot be met, clearly, $U_{bX} < \frac{U_w}{\eta}$. Thus, the lifetime from Eq. 8 is smaller than one from Eq.7.

Since the designed trigger generator is strong enough, i.e., U_P is over 120 kV, the pressure don't have to change in 200 kC basic lifetime.

D. Magnetic Core of Pulse Transformer

A pulse transformer is the key element of the trigger generator. Ignoring the stray capacitance of the pulse transformer, the equivalent Γ type circuit of the pulse transformer is shown in Fig.8. n represents the winding ratio of the pulse transformer; M is the mutual inductance between the primary winding and the secondary winding; i_M represents the exciting current; n^2C_H is the commuted inductance of C_H from the secondary side to the primary side. i_1 and i_2 represent the primary current and secondary current respectively. The initial voltage across the primary capacitor C_L is V_0 . R_S and L_S represent the stray resistance and leakage inductance of the resonant charging circuit respectively.

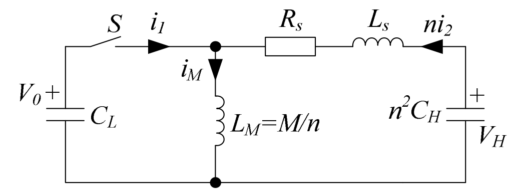

Fig.8 Equivalent circuit of the resonant charging based on pulse transformer

When the magnetic core has no saturation, the magnetizing inductance is large and M/n approaches the infinite. The circuit differential equation and the initial conditions are

$$\begin{aligned} & L_S\frac{di_1}{dt} + R_S i_1 + \left(\frac{1}{C_L} + \frac{1}{n^2C_H}\right)\int i_1 dt - V_0 = 0 \\ & i_1(0_-) = 0, \quad di_1/dt\big|_{t=0} = -V_0/L_S \end{aligned} \tag{9}$$

When $C = n^2C_LC_H/(C_L + n^2C_H)$, $R_S < 0.5\sqrt{L_S/C}$, the inherent frequency of the circuit is $\omega_0 = 1/\sqrt{L_SC}$, the attenuation constant is $\alpha = R_S/(2L_S)$, the working frequency is $\omega = \sqrt{\omega_0^2 - \alpha^2}$. Usually the winding resistance is small, there is $\alpha \ll \omega$. Thus the output V_H across n^2C_H is deduced as

$$V_H(t) = \frac{CV_0}{n^2C_H}\left(1 - e^{-\alpha t}\cos\omega t\right) \tag{10}$$

The transformer ratio n_a, and energy transmission efficiency ζ_a are deduced as

$$n_a = \frac{2C}{nC_H}\left(1 - \frac{\pi R_S}{4}\sqrt{\frac{C}{L_S}}\right) \tag{11}$$

$$\zeta_a = \frac{4C}{C_L + n^2C_H}\left(1 - \frac{\pi R_S}{4}\sqrt{\frac{C}{L_S}}\right)^2 \tag{12}$$

The volt-second product of the magnetic core should obey

$$\int_0^{t_m} V_H(t)\,dt \le N_1 S_M \cdot \Delta B_m \tag{13}$$

where ΔB_m is the maximum swing of the flux density, N_1 is the turns of the primary winding, S_M is the effective section of the magnetic core. The total leakage inductance of the pulse transformer can be expressed as [13]

$$L_S = L_{S1} + \frac{L_{S2}}{n^2} = \frac{\mu\mu_0 N_1^2 S_M}{l}\cdot\frac{1-k^4}{k^2} \tag{14}$$

where L_{S1}, L_{S2} are the leakage inductances of primary and secondary winding respectively, k is the coupling coefficient, μ_0 is the free space permeability, μ is the relative permeability of the core material, l is the mean length of the magnetic path. The volume of the magnetic core should satisfy

$$[S_M l] > \frac{\pi^2\mu\mu_0 C^3 V_0^2}{n^4 C_H^2 \Delta B_m^2}\cdot\frac{1-k^4}{k^2} \tag{15}$$

IV. EXPERIMENTAL EVALUATION

An equivalent testing circuit for 2.0 MJ PPS module was set up as shown in Fig.9. The capacitor bank includes 120 parallel capacitors. Each capacitor has 55 μF capacitance. Thus, the total capacitance is 6600 μF. When the charging voltage is 25 kV, the total stored energy is about 2.06 MJ and the transfer charge per shot is 165 C. Each capacitor connects one damping steel inductor, which has 75 μH inductance and 131 mΩ resistance. The analogue load is 16 parallel resistors. Each resistor has 0.5 Ω and 3.9 μH. The current transformator (CT) uses Pearson 4427 (including an attenuator).

In testing process, by aid of Pearson 4427 CT, the discharging current in the 1/2 load is measured. After being converted to the whole load, the typical current waveform is illustrated as Fig.10. The total pulsed peak current was about 530kA. Simultaneously, the pulse width was about 550 μs (10%-10%). This discharging current is regarded as a reference output current of 2.0 MJ PPS module. In practical, in ordering to improve the energy utilization efficiency of PPS module, the shorter pulse width is mandatory. In the ideal pulse width, even if the energy-storage reaches 1.8 MJ, the PPS module can meet the requirement. Thus, the impedance of the main discharge circuit should further be reduced, so that the pulse width can be smaller than 500 μs.

In the experiment, when the lifetime achieved over 200kC, i.e., 1200 shots, in a fixed operating pressure, the gap distance became from initial 0.8 cm to 1.3 cm. If the switch pressure reduces by 50 kPa per 50 kC in the next, the switch still can operate normally. After the worn electrodes are replaced, the lifetime will be refreshed.

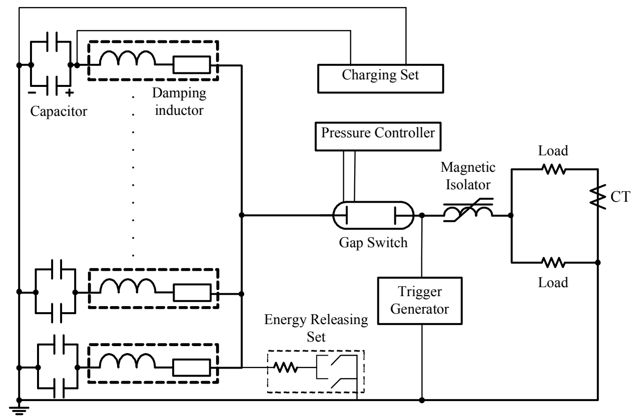

Fig.9 Test circuit for the switch-trigger system

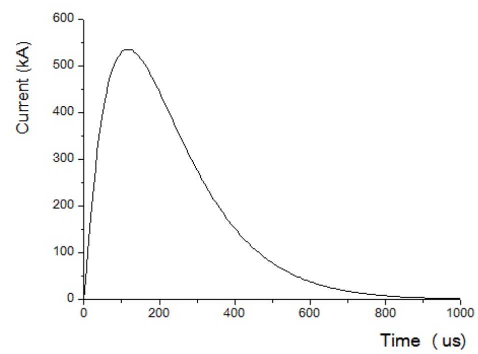

Fig.10 typical discharge current waveform across the gap switch

V. CONCLUSIONS

In this paper, a switch-trigger system for a 2.0 MJ pulsed power supply module has been developed. This system involves a spark gap switch, a magnetic isolator, a trigger generator and a pressure controller. Comparing with the previous reported in 2009, the updated spark gap switch is better in smaller size and lighter weight. The trigger generator is a magnetic core pulse transformer with compact structure and high stability. Several mathematical principles about this system design, e.g., the switch lifetime, the stability and the transformer core design are given. The equivalent test of 2.0 MJ PPS module demonstrates to be over 500 kA peak current and 550μs pulse width.

ACKNOWLEDGMENT

The authors gratefully acknowledge the support of the National Natural Science Fund, China, Grant No. 51107049, and the Independent Innovation Fund, Huazhong University of Sci. and Tech., Grant No. 2011QN093.

REFERENCES

[1] R. Guo, J. He, C. Zhao, L. Chen, and Y. Pan, "A new type rotating arc gap switch and its arc velocity characteristics," *IEEE Trans. Plasma Sci.*, vol. 38, no. 10, pp. 2663–2668, Oct. 2010.

[2] Z. Zhou, X. Duan, M. Liao, H. Dong and J. Zou, "Operational Characteristics of a Field-Breakdown Triggered Vacuum Switch", *IEEE Trans. Magn.*, vol. 45, pp.564–567, 2009.

[3] D. F. Alferov, V. P. Ivanov, and V. A. Sidorov, "High-current vacuum triggered switching devices", *IEEE Trans. Magn.*, vol. 39, no.1, pp. 406-409, Jan. 2003

[4] Z. Zhengyang, D. Xiongying, L. Minfu, D. Huajun and Z. Jiyan, "Plasma stability in a triggered vacuum switch", *IEEE Trans. Plasma Sci.*, vol. 37, no.4, pp. 555-559, Apr. 2009

[5] L. Lee, G. Liu, H. Zeng, G. Hu, N. Liu, L. Cai, and F. C. Lin, "Design, construction and testing of switches and trigger generator for 1.2 MJ capacitive pulsed power supply module," *IEEE Trans. Plasma Sci.*, vol. 39, no. 1, pp. 294–299, Jan. 2011.

[6] R.A. Fitch, V.T.S. Howell, "Novel principle of transient high-voltage generation", *Proc. of the Institution of Electr. Engineers*, vol. 111 no. 4, pp. 849–855, Apr., 1964

[7] Marco Denicolai, "Optimal performance for Tesla transformers," *Rev. Sci. Instr.,* vol. 73, no. 9, pp. 3332–3336, Sep., 2002.

[8] P. M. Ranon, " Compact pulsed transformer power conditioning system for generating high voltage, high energy, rapid rise time pulses," *IEEE Trans. Magn.*, vol. 25, no. 1, pp. 480–484, Jan. 1989

[9] Z. Liu, G. J. J. Winands, K. Yan, A. J. M. Pemen, E. J. M. Van Heesch, "A high-voltage pulse transformer with a modular ferrite core," *Rev. Sci. Instr.*, vol. 79, no. 1, pp. 1-5, Jan. 2008

[10] G. Liu, L. Li, F. C. Lin, Y. Liu, H. Zeng, G. Hu, Q. Y. Tan, N. Liu, L. Cai, "Analysis and realization of magnetic switch in pulsed power conditioning system," *IEEE Trans. on Dielectr. Electr. Insul.*, vol.18, no.14, pp. 1143-1150, Aug. 2010

[11] Y. Kawada, T. Hosokawa, "Breakdown phenomena of gas-insulated gaps with nanosecond pulses," J. Appl. Phys., vol.65, no.1, pp. 51-56, Jan. 1989.

[12] L. Li, F. C. Lin, L. Cai, G. Hu, N. Liu, Z. Y. Zhou, "Analysis on Useful Lifetime of High-Power Closing Switch With Graphite Electrodes," *IEEE Trans. Plasma Sci.*, vol. 39, no. 2, pp. 737–743, Feb. 2011.

[13] R. H. Wang, *Design of Pulse Transformers*. Beijing, China: Science Press, 1996.