Inverter power supply and control system for high pulse energy laser shock processing

Haiying Xu (许海鹰)[1*], Zhifei Miao (苗志飞)[2], Zhigang Che (车志刚)[1],
Wei Zhang (张 伟)[2], Shikun Zou (邹世坤)[1], and Ziwen Cao (曹子文)[1]

[1] *Science and Technology on Power Beam Processes Laboratory,*
Beijing Aeronautical Manufacturing Technology Research Institute, Beijing 100024, China
[2] *School of Mechanical Engineering & Automation, Beijing University of Aeronautics and Astronautics,*
Beijing 100191, China
* *Corresponding author: xhyxhy@126.com*

Received May 14, 2012; accepted August 13, 2012; posted online December 20, 2012

In order to meet high pulse laser output, the laser shock power supply based on insulated gate bipolar transistor (IGBT) inverter technology, constant current-constant voltage charger mode, high voltage pulse spark, and high pulse current discharger technology is designed. The master oscillator stage and two amplifier stages for xenon flash lamp spark and discharge circuits are designed in this power supply. The voltage of energy storage capacitors can be adjusted from 1 000 to 3 000 V. A variety of measures, such as FREE and Q-switch mode, trigger signal delay, water confining layer control, cooling water control are provided for laser shock processing technology optimization.

OCIS codes: 140.3390, 140.3538, 140.3540, 140.5560.
doi: 10.3788/COL201210.S21418.

Laser shock processing (LSP) technology has been widely introduced in foreign aviation industry and other industrial fields[1−4]. With wide application prospects, LSP technology has been rapidly developed in domestic aviation industry.

In order to obtain intensive pulse energy laser of tens joules or even hundreds joules, Nd: glass laser was usually adopted[1]. Although the operating frequency of Nd: glass laser is relatively low, it still has the obvious advantage in the field of LSP for the high pulse laser energy.

The key technologies of Nd: glass laser for LSP include stable charging technology, xenon flash lamp high voltage trigger technology, large current discharge technology, Q-switch and xenon flash lamp trigger synchronization control technology[5].

Commonly, 50-Hz alternating current (AC) was adjusted by thyristors in early domestic Nd: glass laser power supply, then, the AC was promoted to high voltage by step-up transformer. At the beginning of charge, the large impact current was easy to result in the damage of charging circuit components. Besides the charge noise, the charging efficiency was very low. The charge process was finished at fully charge. For leakage current of energy storage capacitors, output pulse laser energy was different at different moment of discharge trigger. This charge mode made the output pulse laser energy fluctuate.

For the xenon flash lamp trigger circuit was susceptible to electromagnetism interference, the unexpected trigger was always arisen. In addition, actual LSP technique requirements have not been considered in the early domestic laser shock equipment.

Recently, with the emerging of new power parts and control technologies, domestic inverter technology has been rapidly developed. It is possible to manufacture a new type of laser shock equipment with high pulse energy.

With Nd: glass laser introduced from abroad, a new type laser shock power supply with high pulse energy and its control system, which based on the insulated gate bipolar transistor (IGBT) inverter technology, constant current- constant voltage charge technology and high voltage pulse triggering technology, have been developed. Discharge pulse with 500-μs pulse width and 5 000-A peak current is obtained. FREE mode and Q-switch mode are provided in control system. It also provides a series of optimization LSP measures in this control system, such as automatic control of water confining layer and cooling water. By these measures adopted, the automatization level of laser shock processing system has been improved.

The charge and discharge circuits are included in main circuit topology. The number of charge and discharge circuits is related with the number of flash lamps in laser optical system. The Nd: glass laser optical path is showed in Fig. 1. It includes the master oscillator stage and the amplifier stages.

Three Nd: glass crystal rods can be seen from Fig. 1. It means that three charge and discharge circuits are needed to drive three flash lamps respectively. The charge and discharge circuits adopted to spark flash lamp of the Nd: glass rod 1 are known as the master oscillator stage. Those circuits adopted to spark flash lamps for Nd: glass rod 2 and rod 3 are called amplifier stage.

The constant current-constant voltage inverter charge circuit of master oscillator stage is shown in Fig. 2. Those charge circuits of amplifier stage are similar to the circuit showed in Fig. 2.

The rectifier circuit MD$_1$, inductance L_{01}, half-bridge inverter circuit (including capacitor C_{01}, C_{02} and IGBT Q_{01}, Q_{02}), high frequency step-up transformer B$_0$, secondary rectifier circuit (including D_{01}, D_{02} high voltage rectifier diodes) had been introduced in master oscillator stage's constant current-constant voltage circuit. The

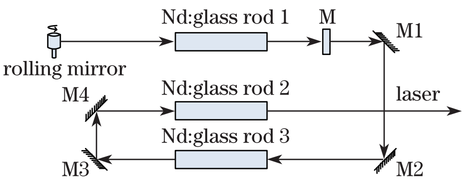

Fig. 1. Optical paths of Nd: glass laser.

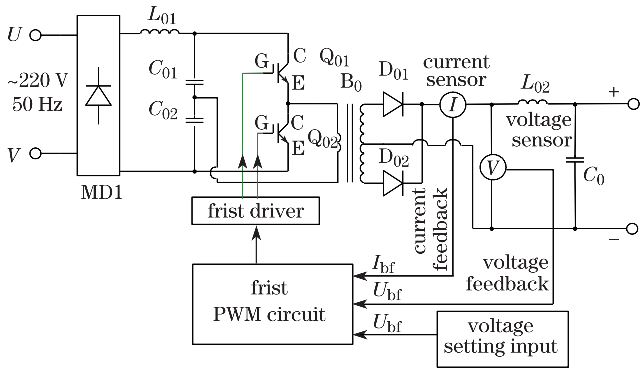

Fig. 2. Constant current-constant voltage circuit topology.

capacity of the storage capacitor C_0 is 700 μF, which is formed by series-parallel 150 μF/1 100 V capacitors.

The circuit operation process is as follows. Through the rectifier filter circuit MD_1 and L_{01}, 220 V/50 Hz AC is changed to 310-V stable direct current (DC). This DC is transformed to 20-kHz square AC by half-bridge inverter circuit (includes capacitor C_{01}, C_{02}, and IGBT Q_{01}, Q_{02}). The 20-kHz square wave AC coupled by step-up transformer B_0 is transformed to high voltage AC with same frequency. This high voltage AC is the input of the secondary rectifier circuit and inductor L_{02}. Through these rectifier and filter parts, DC can be achieved to the need of the storage capacitor C_0 charging. The charge voltage can be continuously adjusted from 0 to 3 000 V. According to the difference between the detection voltage of storage capacitor C_0 and enactment voltage value, the constant current or constant voltage charge mode will be chosen by control system.

The circuit of flash lamp trigger and discharge in master oscillator stage is shown in Fig. 3. Those amplifier stage's flash lamp trigger and discharge circuits are similar to the circuit shown in Fig. 3.

In order to protect the discharge circuit components, a 50-μH hollow inductance is introduced to restrict increase rate of the discharge current. The B_1 is a high-voltage pulse trigger transformer, which can provide tens of thousands volts voltage negative pulse to trigger the flash lamp. The ratio of primary coils and secondary coils is 1:20 in the transformer B_1. When the 1 500-V pulse is inputted in primary coils, 30 000-V high voltage pulse will be inspired in the secondary coils.

The operation process of the discharge circuit is as follows. Firstly, the C_1 is charged to 1 500 V, with R_1 adopted to restrict current peak. When the synchronous trigger signal is valid, switch Q_0 is turned on by drive circuit. The charge stored in C_1 will be discharged by the primary coils of transformer B_1 and switch Q_0. Thus 1 500-V voltage pulse will be produced at the B_1 primary coils. The 30 000-V high voltage pulse will arise at the B_1 secondary coils for the transformer B_1 coupling. It makes xenon in the flash lamp to be ionized. Thus, a narrow conductive channel is attained. The charge stored in C_0 will be discharged by the inductor L, flash lamp, and B_1 secondary coils. With a large number of xenon ionization, electron impact acceleration and xenon rapid heating, conductive channel is increased. After several μs, the entire section of flash lamp is full of arc. A high pulse discharge current is arisen. This discharge process can be considered as a relative steady state discharge, in which the xenon flash lamp can be considered as very small resistance[6].

In order to restrict the impact current at the initial moment of charge and to reduce circuit losses, constant current-constant voltage charge mode was introduced in the control system. In this charge mode, Charge process is divided into constant current charge stage and constant voltage charge stage. At the stage of constant current charge, the energy storage capacitor is charged fast by a constant current, which makes the capacitor voltage increase linearly. In order to avoid overage charge, the constant current charge stage will be stopped until there is a little difference between the capacitor voltage U_1 and initialization voltage U_0. The control system will make the charge process turn to constant voltage charge stage. At this charge stage, the charge current is extremely small. When the capacitor voltage is charged to the set value U_0, the charge current of mA-class is ordered to maintain constant voltage on the energy storage capacitor. Once the discharge trigger signal is received, the constant voltage charge stage will stop.

In order to achieve the constant current and constant voltage output characteristics of the inverter power supply, inner loop of current negative feedback and outer loop of voltage negative feedback controls had been introduced in the control circuit. The inverter power supply output characteristics control sketch map is shown in Fig. 4.

During the storage capacitor C_0 being charged by inverter power supply, the control circuit of current negative feedback closed-loop will be operated at the time of C_0 voltage below enactment voltage. Namely, at the stage of constant current charge, charge current I_{f} as feedback parameter participates in the system proportional-integral-derivative (PID) regulator. When the voltage of the storage capacitor C_0 has been charged to enactment voltage, the control system of inverter power supply will be turned to constant voltage charge mode. In this charge stage, capacitor voltage U_{f} as the feedback parameter is adjusted by PID regulator, which will make the voltage of C_0 preserve enactment voltage.

After the energy storage capacitor has been charged fully, the discharge process starts immediately at the time of discharge trigger signal appearance. This discharge mode is named FREE mode. Generally, this discharge mode is applied to debug the optical paths. The energy is difficult to reach the threshold for laser output at free discharge state. Usually, Q-switch technology is adopted to achieve laser output. It means that some ways are used to make Q value in laser cavity change according to certain time procedures. At the time of pumping startup, the resonance can not be produced for the low Q at cavity or the high resonance threshold. When the Q value is suddenly increased, the laser oscillation is set

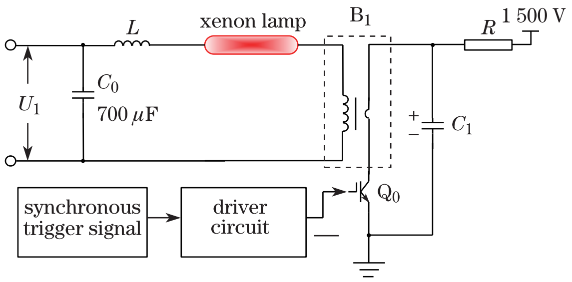

Fig. 3. Flash lamp trigger and discharge circuit.

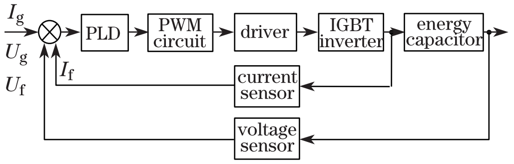

Fig. 4. Control sketch map of charge.

up quickly. In a very short time, a high pulse energy laser is produced at the end of resonance cavity[7,8].

Q-switch operation and FREE operation modes had been designed for high pulse energy laser output and the optical path debugging respectively. For the high speed rotating prism tuning Q technology is adopted, the synchronous discharge trigger pulse should be considered at control system.

Effective time of 'delay time' is named as pulse duty between a active trigger switch signal to the discharge signal. The core integrated circuit (IC) producing the trigger 'delay time' is NE555. A single NE555 circuit is shown in Fig. 5(a). A series of NE555 and logic control circuit have been introduced in the trigger synchronization control circuit, which circuit diagram is shown in Fig. 5(b).

In Fig. 5(a), when the pulse falling edge by C_3 is inputted into the NE555 trigger port, a width-adjustable pulse signal will arise at output port. The output pulse width depends on resistor R_7, VR_1 and capacitor C_6. The duration of the output pulse signal can be adjusted by resistance VR_1. Thus, 'delay time'can be adjusted from 0 to 1 000 μs.

The 2.5-ms discharge button signal duration, 400-μs rotating mirror pulse duration, 0-1 000-μs "delay time", and 20-μs discharger duration signal are designed in this system. The signals of Q-switch control, FREE control and cooling water control are 12-V positive signal.

The Q-switch signal and FREE signal are complementary, which means one signal is "1" state, and the other signal is "0" state.

At the Q-switch state, Q-switch signal at "1", free control signal at "0", the output signal of U1B is positive. When rotating prism signal and discharger button signal are "1", the output of U1A is low. A pulse falling edge is inputted into the NE555 tuning circuit 1, then a delay time pulse, which positive pulse width is determined by delay time of NE555, will arise at the NE555 tuning circuit1 output port. At the end of the delay time, namely the falling edge of the delay time signal is inputted into the NE555 tuning circuit 2. Subsequently, a fixed pulse width positive signal will be produced. When the cooling water control signal is "1", the discharger trigger signal, which is controlled logically by U2A and U2B, will be produced. FREE mode and Q-switch mode trigger sequences had been detected by TPS2024 oscilloscope. These logic signal diagrams are shown in Fig. 6 respectively.

When there is a large pulse current flow, xenon flash lamp without cooling water will be destroyed easily[9]. In order to protect the xenon flash lamp, the protection circuit in the discharge trigger control system, which does not make xenon flash lamp spark without cooling water, had been designed. If the cooling water signal is "0", the discharger signal will always be maintained low signal "0". This measure guarantees flash lamp will not be sparked by high voltage pulse without cooling water.

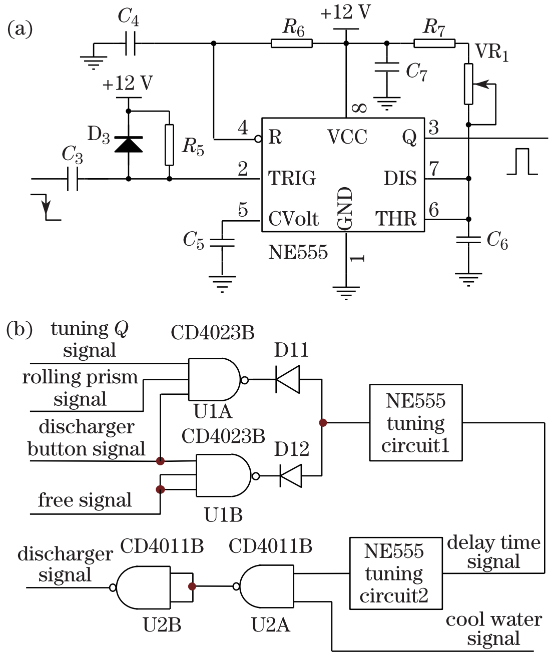

Fig. 5. Trigger logic control circuit. (a) NE555 and its external circuit; (b) trigger timing logic control circuit diagram.

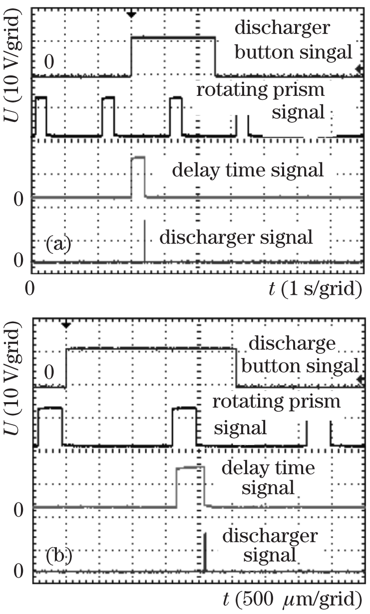

Fig. 6. Discharge trigger sequence. (a) Free mode trigger sequence; (b) Q-switch mode trigger sequence.

In addition, the circuit of water confining layer control based on the NE555 was designed.

At the 2 900-V U_g, the voltage of C_0 was detected. The test results is shown in Fig. 7.

It can be seen from Fig. 7 that charge time of the voltage increased from 0 to 2 900 V is only 7.6 s. This charge rate can meet the need of the 0.1 Hz discharge frequency.

At the same time, the PWM_1 and PWM_2 pulse signals driving Q_{01} and Q_{02} were detected during the constant current charge stage. These signals are shown in Fig. 8(a). At the constant voltage charge stage, PWM_1 and PWM_2 for driving Q_{01} and Q_{02} are shown as in Fig. 8(b).

With 1:1 000 current transformer and 82-Ω current sample resistance, the discharge currents, which storage capacitor charge voltage amplitude was set from 2 000 to 3 000 V, were detected. According to these test results, it can be found that discharge current is increased linearly with the charge voltage of energy storage capacitor increasing. At 3 000-V charge voltage, the discharge current wave form is shown in Fig. 9.

It can be seen that discharge current pulse width is 500 μs in the Fig. 9. The maximal discharge current amplitude is up to 5 000 A.

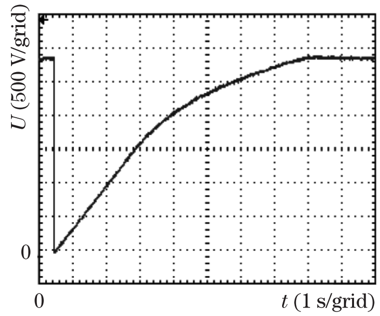

Fig. 7. Charge voltage curve of energy storage capacitor.

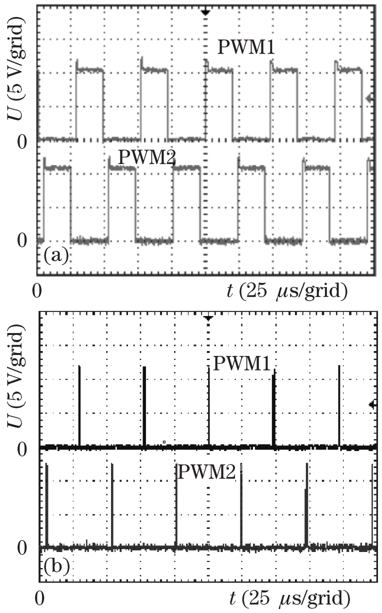

Fig. 8. PWM constant current-constant voltage charge. (a) PWM pulse of constant current charge phase; (b) PWM pulse of constant voltage charge phase.

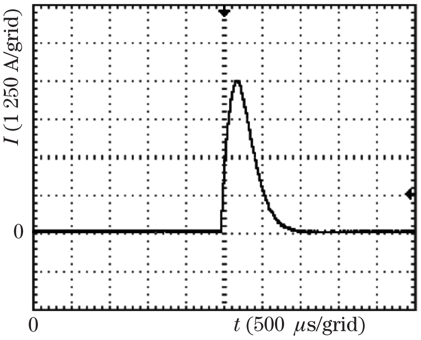

Fig. 9. Discharge current.

Table 1. Relationship Between Amplifier Stage Voltage and Pulse Laser Energy

Master Oscillator Stage U_1 (V)	Amplifier Stage U_2 (V)	Laser Energy E (J)
3 007	2 007	19.97
3 011	2 112	23.08
3 002	2 215	26.85
3 005	2 310	29.13
3 012	2 408	32.09
3 009	2 500	35.23
3 003	2 609	37.07
3 013	2 710	40.83
3 008	2812	44.05
3 010	2 909	47.15
3 002	3 011	49.86

The 3% spectroscope and laser energy test apparatus were used to detect the laser output energy at different charge voltage amplitude. Because the low charge voltage at the master oscillator stage resulted in low pulse laser energy output, the charge voltage of master oscillator stage was set at 3 000 V. The charge voltage of the amplifier stage was increased from 2 000 to 3 000 V, with 100-V increments every times. The different charge voltage amplitudes of amplification stage and its corresponding to laser energy are shown in Table 1. It can be seen from Table 1 that laser energy is enhanced linearly as amplifier stage voltage increases. The laser energy is 49.86 J at 3 000-V charge voltage of amplifier stage.

When the master oscillator stage charge voltage and the amplifier stage charge voltage were set at 3 000 and 2 900 V respectively, the pulse laser energy had been detected 8 times consecutively. The average output laser energy was 47.02 J. The maximum error was 0.5 J between the maximum output energy 47.15 J and the minimum output energy 46.65 J. It is indicated that the power supply performance is relatively stable, which ensures the residual stress on the workpiece surface is very uniform during the continuous operating condition. Thus, the stability of the laser shock quality is enhanced.

In conclusion, constant current-constant voltage charge control strategy and IGBT inverter technology are adopted in this system, which can improve LSP power supply charge speed and stability. The high voltage pulse trigger xenon flash lamp technology is adopted, which not only ensures reliable trigger to the xenon flash lamp, but also helps to improve the life of the xenon flash lamp. Besides, control and protection circuit based on the NE555 can improve reliability and flexibility of control system, it can enhance the automatization level of the LSP system, which helps to the production efficiency.

References

1. Y. K. Zhang, Laser & Optoelectronics Progress (in Chinese) **44,** 76 (2007).
2. B. M. Davis, S. R. Mannava, T. J. Rockstroh, and J. A. Hahn, in *Proceedings of AIAA*, **2062,** 5 (2004).
3. D. W. See, J. L. Dulaney, A. H. Clauer, and R. D. Tenaglia, Surf. Eng. **18,** 32 (2002).
4. Z. C. Che, S. L. Gong, and Z. W. Cao, Rare Metal Materials Engineering **40,** 235 (2011).
5. Y. K. Zhang, H. B. Guan, and Y. X. Ye, "The method and device to improve energy Nd:glass laser repetition rate and stability" (in Chinese) Chinese Patent CN101604816 (2009).
6. J. Chen, H. B. Li, and B. C. Jiang, Laser & Infrared (in Chinese) **39,** 191 (2009).
7. W. Wei, Optical instruments (in Chinese) **30,** 12 (2008).
8. Y. C. Zhang, C. K. Wang, and Z. P. Duan, High Power laser and particle beams (in Chinese) **7,** 352 (1995).
9. G. Z. Tian, Q. F. Ou, and M. Zhong, Laser Technology (in Chinese) **31,** 251 (2007).