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# Research on Operation Strategy of the Pulse Generator Power System Energizing Outer Coil of the 100 Tesla Magnet


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## I Introduction

As an important extreme experimental condition, high magnetic field plays an irreplaceable role in the frontier scientific research. To obtain higher magnetic field, a non-destructive magnet aimed at generating 100 T, which is made up of three coils nested coaxially, is designed at the Wuhan National High Magnetic Field Center. The outer coil will be powered by battery bank and a pulse generator power. Due to the power limitation of the pulse generator, the generator current has reached the maximum value after achievement of 100T. At the same time, the decrease of the peak magnetic field will lead to the rise of the outer coil current because of induced voltage. This poses a challenge to the safety of the coils and power supplies.

In this paper, the main operation stages of pulse generator are studied. Then a proper operation strategy of pulse generator power supply is put forward from the point of power demand of load and safe operation of the pulse generator. Lastly the simulation and experimental results verify the validity of this strategy.

## II 100T Implementing Method

Considering that the outer coil has large radius and energy storage, and requires more energy for its power supply, a combined power supply of battery bank and a 100-MVA/185-MJ pulse generator power is designed to power the outer coil. The discharge sequence is reasonably arranged so that the maximum magnetic field of the three coils is superposed at the same time. The schematic of the power supplies and the magnetic waveforms of the magnet are shown in Fig. 1 and Fig. 2 respectively.

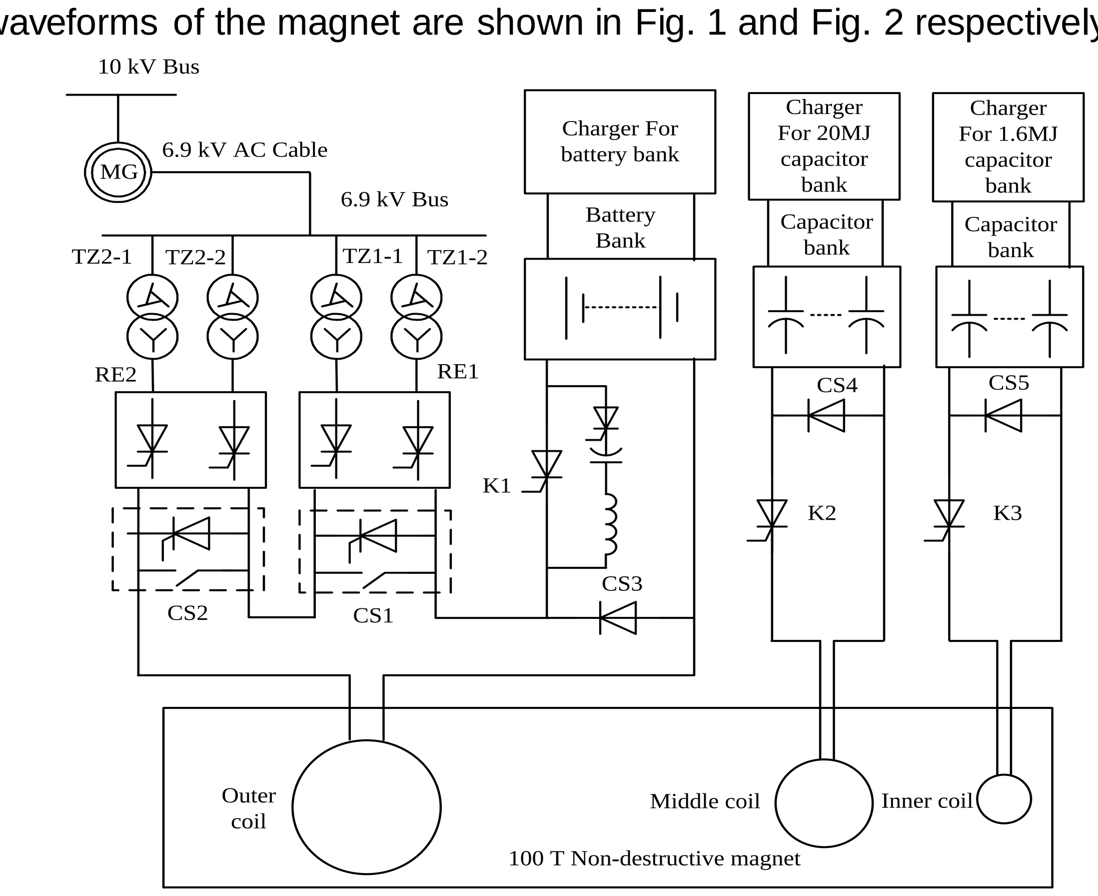


Fig. 1 Schematic of 100T-ND magnet power supplies.

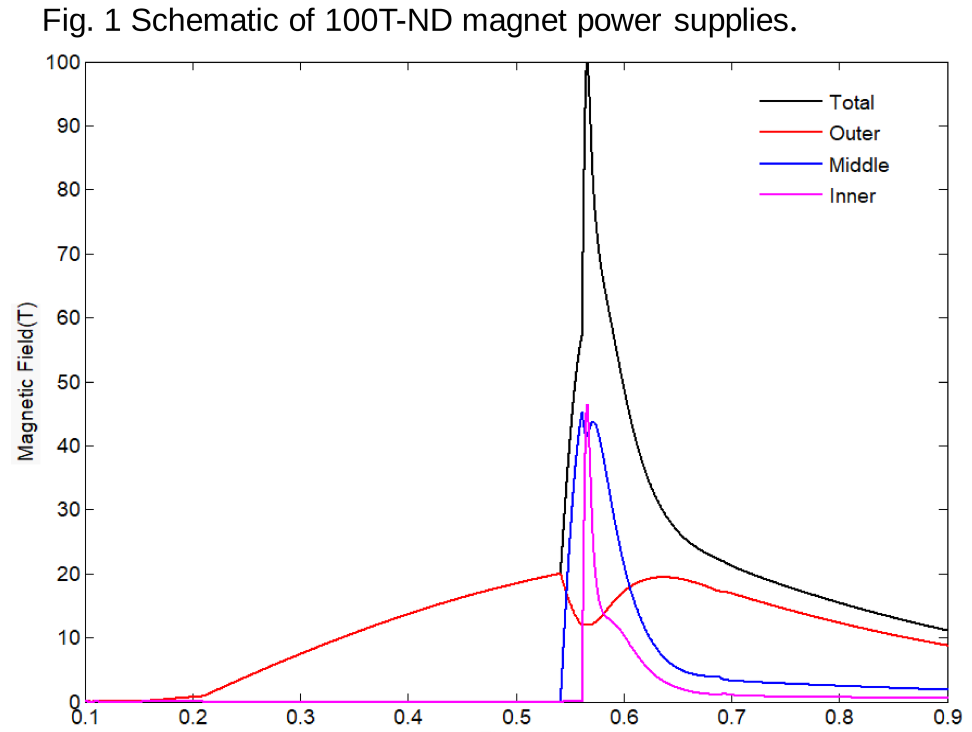


Fig. 2 Magnetic waveforms of the magnet.

## III Operation Strategy

The operation process of pulse generator power supply in 100T experiment is shown in Fig. 3. The process mainly includes rectifier stage, inverter exit, de-excitation and freewheeling.

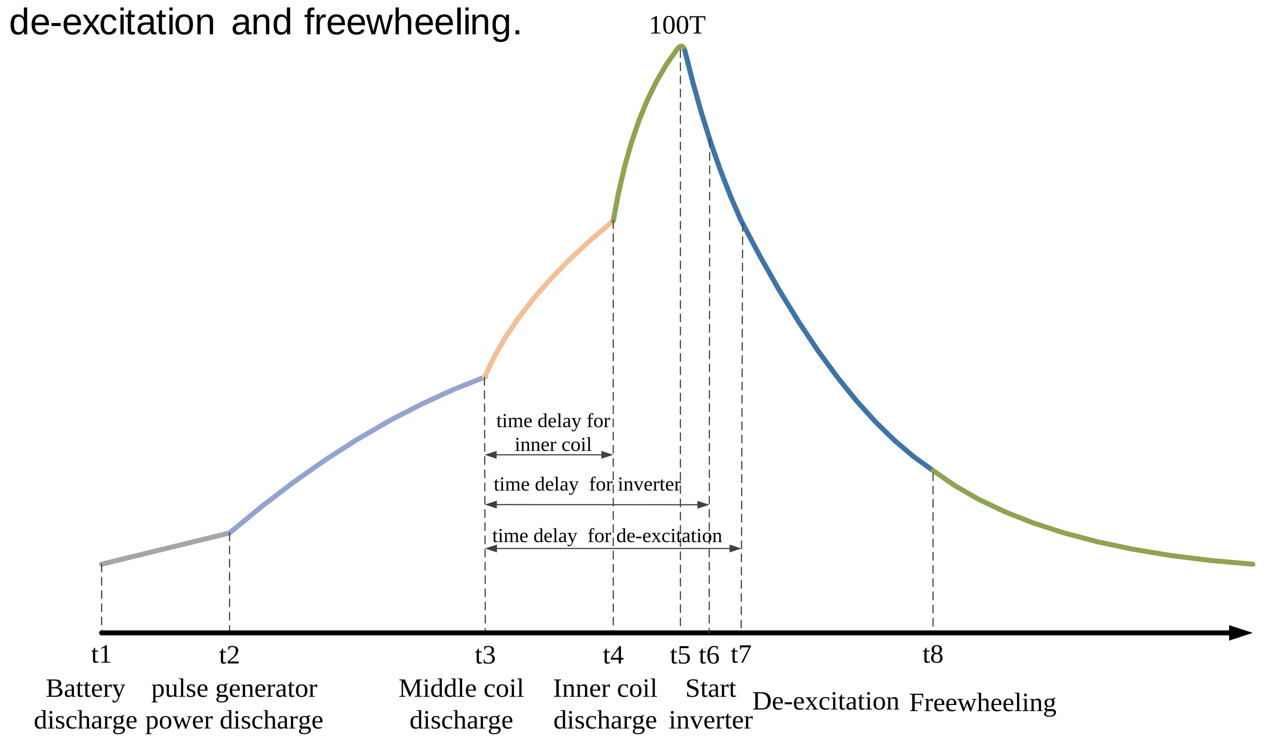


Fig. 3 operation process of pulse generator power supply.

### A. The combined power supply of battery bank and the pulse generator

A proper procedure is needed when the combined power energizes the outer coil. The battery bank discharges first through thyristor switch K1, thyristor crowbars CS1-CS1 and the outer coil, then the two 12-pulse power converter modules get triggered after a few milliseconds when the current in the loop is higher than latching current of thyristor. Two 12-pulse converter modules will be connected in the circuit of outer coil naturally. As a result, the thyristors in power converter modules and in thyristor switch of battery bank will suffer no possible overvoltage at start of the operation. The current path during operation is shown in Fig. 4.

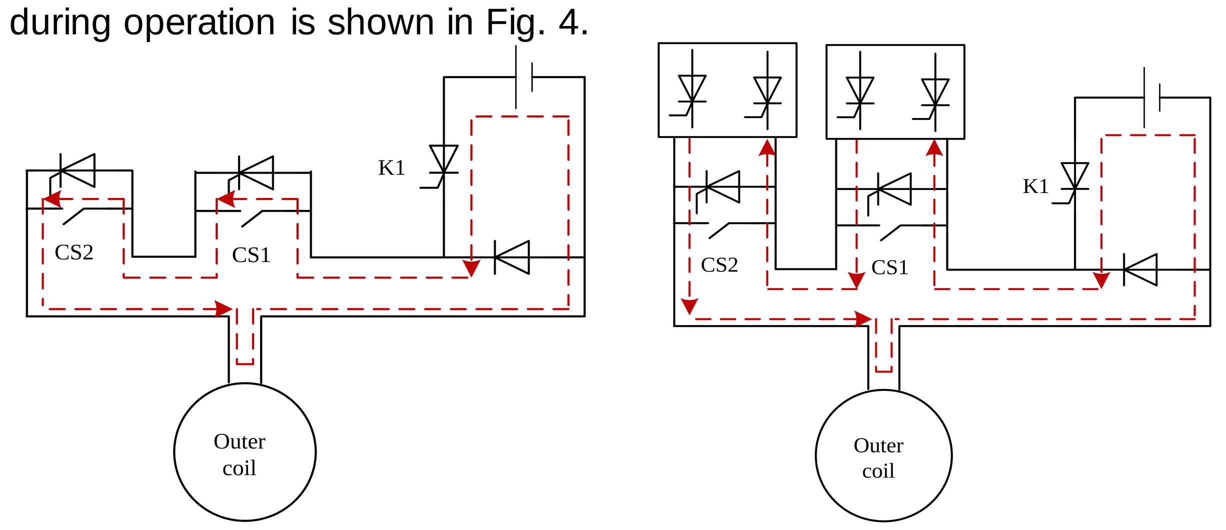

Fig. 4 Schematic of current path during operation.

### B. Inverter exit

To prevent the outer coil from overcurrent, the battery switch K1 is forced to turn off and the rectifier is started to invert after achievement of 100T. Fig. 5 and Fig. 6 give the experimental waveforms of generator output voltage and rectifier output current under two different exit modes. It shows inverter exit is more optimal because of no overshoot voltage.

Because of the serious voltage distortion of the pulse generator and large load current, the commutation failure of the rectifier is prone to occur. Commutation failure may cause damage to switching device and magnet. Therefore, the parameters of inverter operation should be selected reasonably.

1. The maximum inversion angle

Based on the analysis of the pulse generator model, the safe area of the inverter is obtained. As shown in Fig. 7, the left side of the red dotted line is the safe area. From the intersection of the red dotted line with the curve, the maximum inversion angle $\alpha_{max}$ can be obtained easily.

2. Trigger angle change speed

When the system is shifted from rectifier to inverter, the phase of the generator output voltage changes rapidly with the change of triggering angle, which will result in larger errors in phase-locked systems. At last, excessive triggering errors will cause commutation failure. So, the suitable transition speed is needed. The relation between the trigger angle change speed and the phase locking error is expressed as the equation (1):

$$\Delta\alpha = 2.723\times10^{-4}\frac{I_D}{E_0}\frac{d\alpha}{dt} \quad (1)$$

Here Δα is trigger error, so the final trigger angle αfinal is expressed as the equation (2):

$$\alpha_{final} = \alpha_{max} - \Delta\alpha \quad (2)$$

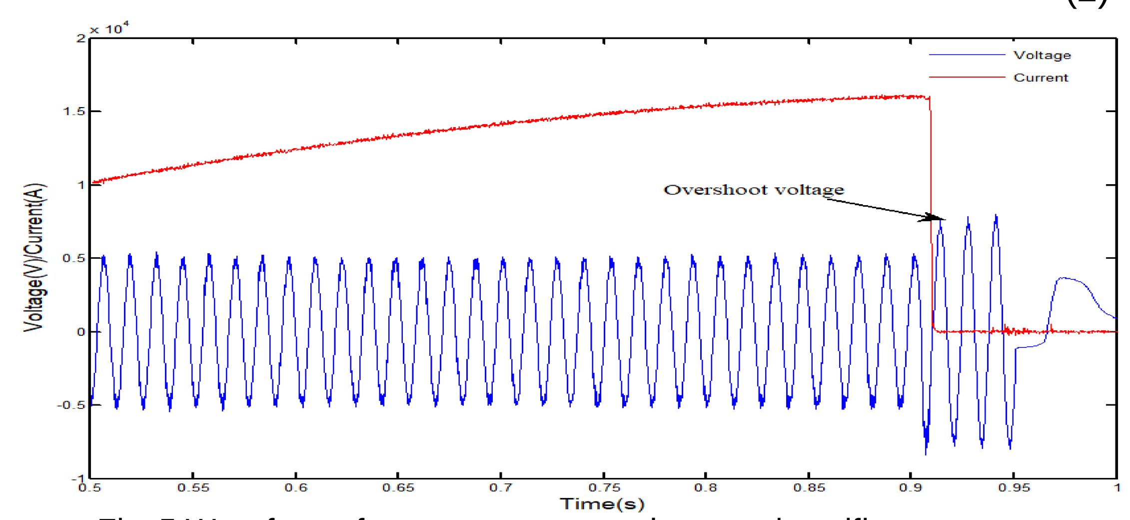


Fig. 5 Waveform of generator output voltage and rectifier output current under freewheeling exit mode.

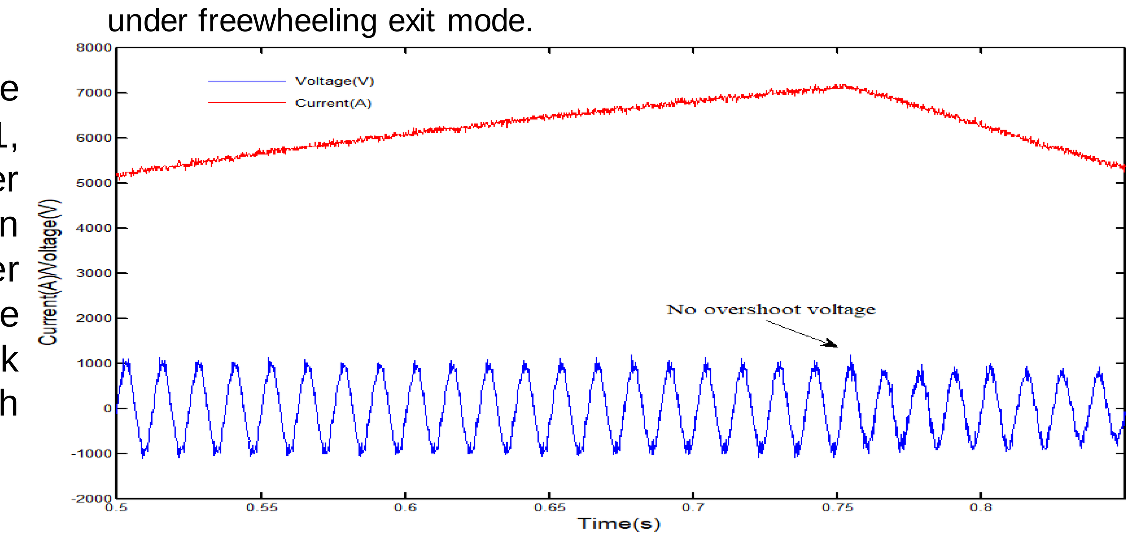


Fig. 6 Waveform of generator output voltage and rectifier output current under inverter exit mode.

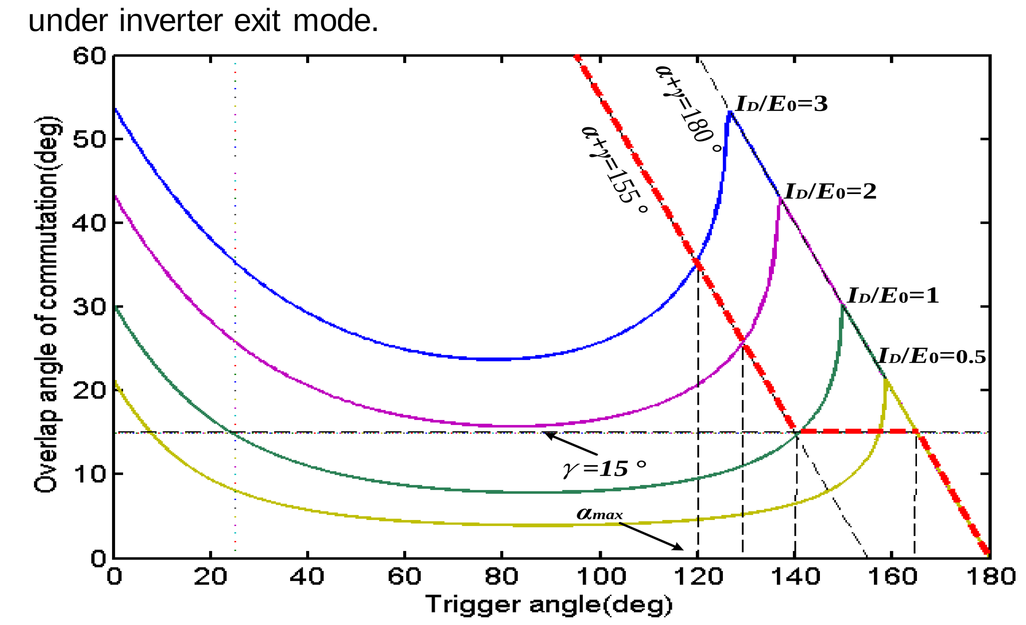


Fig. 7 Schematic of the safe area of the inverter. Here γ , α , $I_D$ and $E_0$ is the overlap angle, α is the trigger angle of rectifier; is current in outer coil; $E_0$ is the generator output voltage.

### C. De-excitation and freewheeling

The schematic of generator excitation system is shown in Fig. 8. After the de-excitation signal is received by the generator excitation system, the energy in the rotor coil is quickly fed back to the power grid by inverting, thereby eliminating the stored energy in the generator rotor and achieving the effect of protection. After a period of time, the rectifier blocks the trigger pulse and trigger the freewheeling thyristor. The rectifier is cut off from the generator.

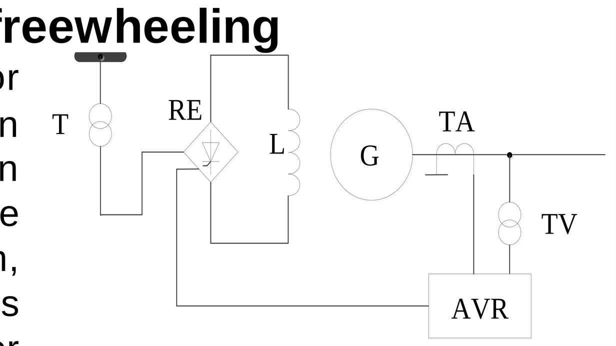


Fig. 8 Schematic of generator excitation system.

## IV Result

To verify the validity of the designed operation strategy of the pulse generator power system, a test experiment aimed at generating 60T has been completed. The combined power supply discharges the outer coil first to generate background magnetic filed. Then the middle coil and the inner coil are discharged in turn. Three coils would generate the highest peak magnetic field when the discharge sequence of the three coils is arranged reasonably. The coil magnetic field waveforms are given in Fig. 9.

The experimental parameters of the pulse generator power supply is as follows : the output voltage of pulse generator is 4.2kV, the maximum current of outer coil is 13kA, the trigger angle change speed is 3 degrees per second, $I_D$ / $E_0$=13 / 4.2=3. According to the safe area of the inverter shown in Fig. 7 and formula (1) and (2), the maximum invert angle is set to 117°. The results are given on the Fig. 10-11.

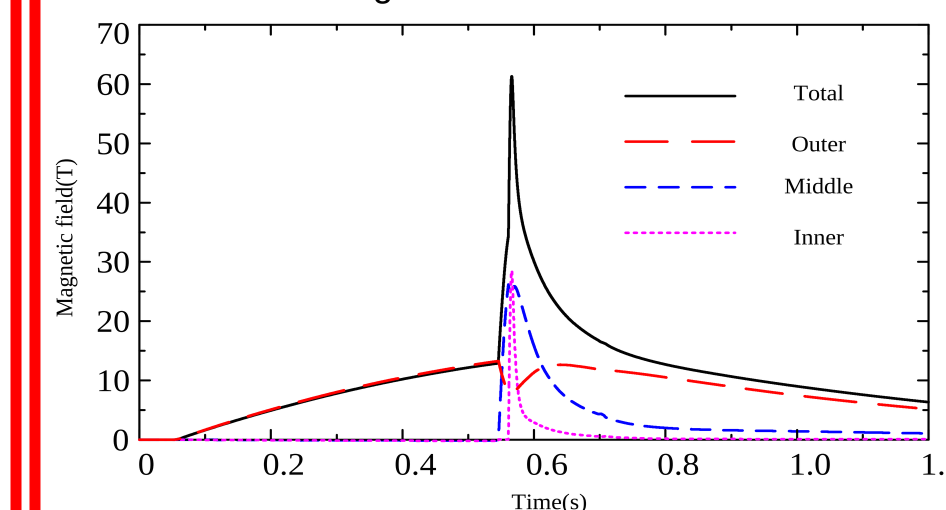


Fig. 9 Coil magnetic field waveforms.

Fig. 10 shows the waveform of trigger angle and de-excitation signal. It indicates that in the rectifier stage, the firing angle is 15°. After 0.6s, the firing angle is increased from 15° to 117°. The system is transformed from rectifier to inverter

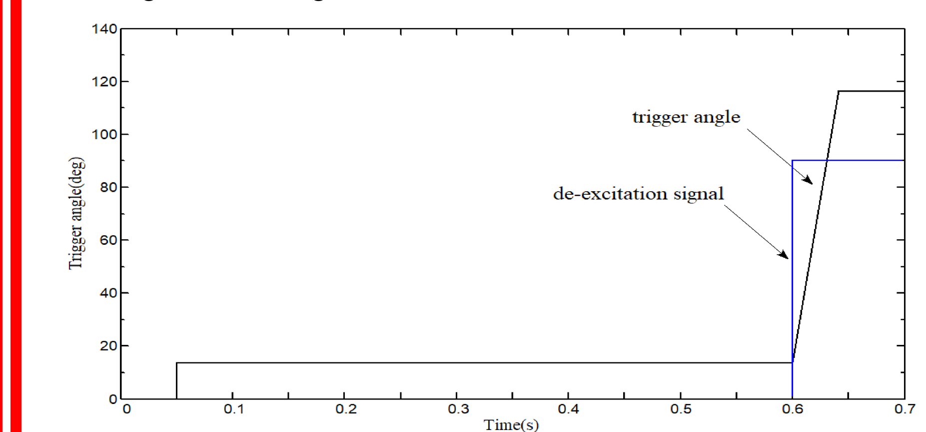


Fig. 10 Waveform of trigger angle and de-excitation signal.

Fig. 11 gives waveforms of the generator output voltage, rectifier output voltage and rectifier output current in whole operative process. The generator output voltage shows the designed operation strategy can effectively solve the voltage overshoot problem. The waveform of rectifier output current shows that after achievement of 100T, the rectifier will enter the inverter state so that the magnet current drops and the magnet overcurrent is avoided. The output voltage waveform of a set of rectifier shows The output voltage is almost constant during rectification, which indicates that the forced excitation is effective.

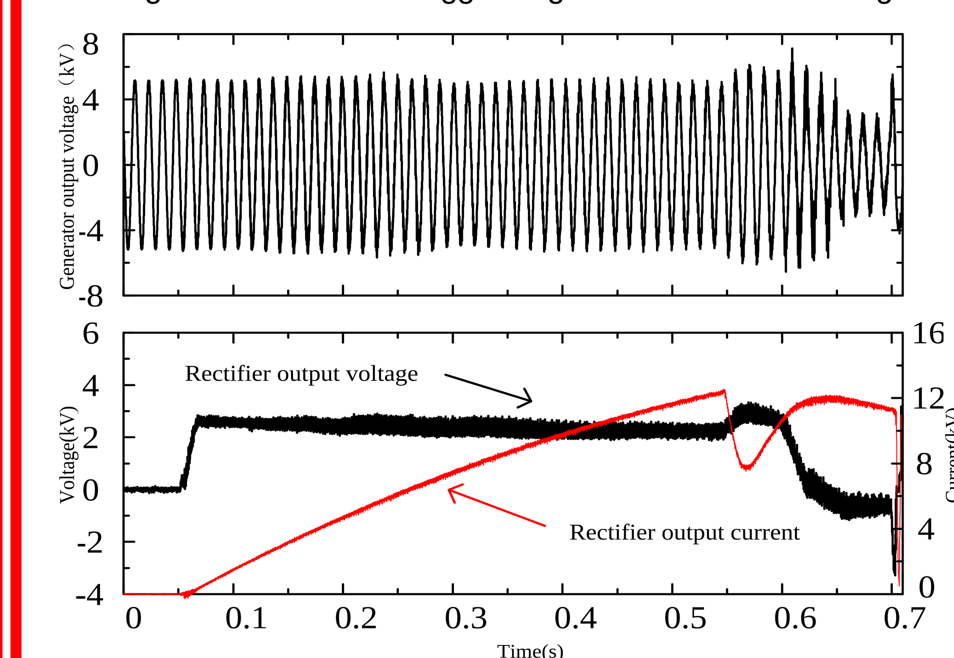


Fig. 11 Waveform of generator output voltage, rectifier output voltage and rectifier output current.

## IV Conclusion

In this paper, the operation strategy of the pulse generator power system which energizes the outer coil of magnet made up of three coils nested coaxially to generate the background magnetic field is studied. From the point of multiple power system coordination and safe operation of the pulse generator power system, an operation strategy consisting of rectification, inverter, de-excitation and freewheeling is designed. The designed operation strategy can effectively solve the voltage overshoot problem and prevent the outer coil of the magnet from overcurrent. Lastly, the test experiment generating 60T magnetic field has been completed, verifying the validity of this strategy.

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