DESIGN a High Precision Uni-polar Power Supply as an Electric Discharges for Superconducting Devices

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Abstract—*Taiwan Light Source (TLS) was established in 1993, it has many researchers conduct cutting-edge research, and technology has been in progress the current TLS instrument beam lines haven't enough users with a more cross-generational study. Therefore, Taiwan government decided in 2007 to build TPS (Taiwan photo light source) to improve research instrument hardware. This paper is study TPS magnet power supply (unipolar power supply) performance; it has high stability and reproducibility 、 low ripple and low noise characteristics. Using a high-precision unipolar power supply will improve the new generation of synchrotron radiation light source. Additional paper also discussed the release of energy in the superconducting, using a set of circuits with energy release unipolar superconducting power supply to replace the TLS bipolar superconducting power supply increase the discharge slew rate of superconductivity. Finally, through the measured data to verify unipolar power supply features, the test circuit used in the superconducting energy release discharged mode. It will greatly improve the discharge performance and stability refers to testing data. Uni-polar power supply electric discharge circuit will become TPS superconductivity system in the future and Taiwan's national Synchrotron Radiation research center hardware strengths.*

Keywords : *Superconductivity, Unipolar power supply, Bipolar power supply*

I. INTRODUCTION

Superconductivity was discovered on April 8, 1911 by Heike Kamerlingh Onnes, who was studying the resistance of solid mercury at cryogenic temperatures using the recently produced liquid helium as a refrigerant. At the temperature of 4.2 K, he observed that the resistance abruptly disappeared. In 1913, lead was found to superconductor at 7 K, and in 1941 niobium nitride was found to superconductor at 16 K. The important step occurred in 1933, when Meissner and Ochsenfeld discovered that superconductors expelled applied magnetic fields, a phenomenon which has come to be known as the Meissner effect. In 1935, Fritz and Heinz London showed that the Meissner effect was a consequence of the minimization of the electromagnetic free energy carried by superconducting current. [1~7]

Superconductivity is a property whereby a material loses all resistance to the flow of electrons within it. Hence, a current, once started in a superconductor, will continue to flow indefinitely. Until 1986, physicists had believed that BCS theory forbade superconductivity at temperatures above about 30 K. In that year, Bednorz and Müller discovered superconductivity in a lanthanum-based cuprate perovskite material, which had a transition temperature of 35 K. It was soon found that replacing the lanthanum with yttrium raised the critical temperature to 92 K. This temperature jump is particularly significant, since it allows liquid nitrogen as a refrigerant, replacing liquid helium. This can be important commercially because liquid nitrogen can be produced relatively cheaply. In 1999, the Taiwan Synchrotron Radiation Research institutions independently developed superconducting wigglers magnet system. After three years of preparation time to complete, has now completed four superconducting wigglers magnet, and has three in operation. [8~14]

II. SUPERCONDUCTIVITY MAGNET OPERATION THEORY

Figure 1 are shown super-conductor circuit structure, this structure includes a set of main power supply, side trimming power supply, resistive leads, HTC leads. Protection assembly (diodes and resistors) and magnet coil. Magnet coil can be divided into upper center coil, upper right coil, lower right coil, lower left coil, upper left coil and lower center coil. Thermal intercept part of 70k and 4k can be divided into two regions, 70k separation zone is between resistive leads and HTC leads, 4k region between each coil.[15~17] Superconductivity magnet includes two protection assembly, protected in each group were working around coil. Each protection assembly includes six diodes, three for the positive connection, and the other three for the reverse connection and the combination of the two regions in parallel diodes, each diode of parallel net will link a 5.0m ohm resistor. Normally operation main power supply and side trimming power supply will supplies energy to the coil.

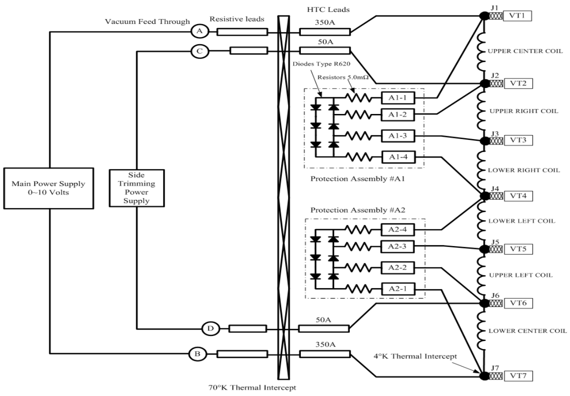
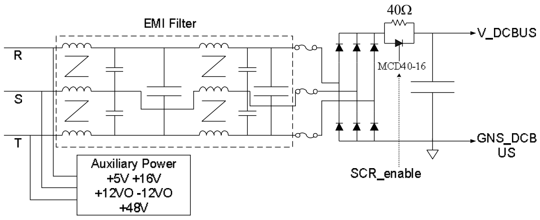


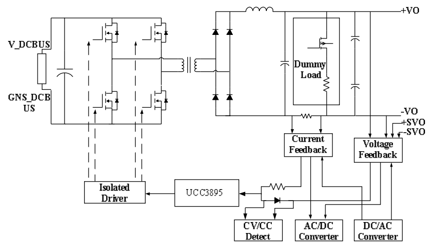
Fig1. Superconductivity magnet circuit structure

III. UNIT-POLAR POWER SUPPLY OPERATION THEORY

Figure 2(a) and (b) show the power-supply input and the output state. Circuit can be divided into two parts, the first part of the AC to DC circuit, DC bus through a bridge rectifier with a large capacitor to an AC voltage to DC which also includes auxiliary circuit, auxiliary circuit respectively generate 5V, 16V, 12V,-12V and 48V. operating mode for the three-phase AC power input, the flow EMI Filter through the diode to the large energy storage capacitor DC bus, DC bus of the two ends points were V_DCBUS and GNS_DCBUS. This terminal voltage will become the second part DC to DC input terminal. The second part is a DC to DC structure, load magnet is a low voltage high current requirement, so the output state will be designed into a DC-to-DC high-voltage low-voltage, DC bus voltage flow into full-bridge architecture will take advantage of the energy transferred to the secondary side of the inductor and output capacitor, the transformer turns ratio of 10:1. Output capacitor in parallel with a dummy load, to ensure that no load in the case of this circuit can quickly discharged. Controller contains are current feedback control and voltage feedback control. Current and voltage feedback control function is to ensure the output current or output voltage value by user's setting. Feedback value sends to the UCC3895 for analysis and compare to a pulse width modulation (PWM) to turn on or turn off the power element. Expect for current and voltage feedback control also includes CV / CC detect, detect the current mode or voltage mode when connected to an inductive load, it will detect the current mode; connected resistive load will be detected as a voltage mode. Protection functions include over-current protection (OCP), over-voltage protection (OVP) and over-temperature protection (OTP). Power supply will automatically turn off when the power supply voltage or current and temperature exceeds the rating of the power supply to avoid damage to the machine ensure the safety of personnel.[18-30]



(a) Input state



(b) Output state

Fig2. Power-supply circuit (Chroma 62075H-30)

Table 1 shows specifications of the Unit-polar power supply. Input voltage is three phase 380 voltage 60Hz, input torrent are 342V~418V (±10%). Power factor at full loading is up to 85%. It is a current mode with two loops control, providing rapid response of stable output and setting output voltage or current slew rate. Current mode control the output current range is 0~250 Ampere; Voltage mode control output voltage range is 0~30 Voltage, maximum output power is 7.5 kW. Internal control chip contains 24 bit ADC and 20 bit DAC, can provide excellent resolution measurement and output settings. Current accuracy within ±10mA, current stability are within ±6.25mA p-p (0~30minutes) and within ±12.5mA p-p (0~8hours); current reproducibility with ±10mA, current ripple within ±100mA p-p (1Hz~1 kHz).

Table 1. Specifications of the power supply.(62075H-30)

Specification	**Uni-polar Power Supply**
Input voltage	Three-phase 380 V ±10%
Current control range	0~250 A
Voltage control range	0~30 V
Maximum output power	7.5 kW
Current stability	±6.25 mA p-p (0~30 min) ±12.5 mA p-p (0~8 h)
Output noise (p-p)	60 mV
Voltage ripple (rms)	15 mV
Current ripple (rms)	100 mA
Range of voltage slew rate	0.001 V~5 V/ms
Range of current slew rate	0.01A~1 A/ms or INF

IV. LONG TEAM STABILITY AND CURRENT RIPPLE TESTING

Figure 3 are testing Uni-polar Power Supply characteristics to use a quadrupole magnet in constant temperature laboratory loading test, the load is an inductive loading, magnet induction 23.5 mH and 81.6 mΩ, set the output current of 250A test time of 8 hours, the initial output current 250.0016Ampere after four hours reduce to 250.0000Ampere and keep the output current 250.0000A to 8 hours. Excluding the first two-hour burn-in time had not stable at power supply that are output current variation is 250.0005 ~ 250.0000Ampere (±5ppm) at 2~8 hours. Figure 4 has shown current ripple and frequency relationship. Using dynamic analysis instruments scanning current ripple of frequency, its current setting at 250A and scanning frequency of 1Hz ~ 100Hz, the maximum current ripple is 1.003mA at 60Hz.

For TPS magnet current specifications, Uni-polar Power Supply must also be connected in parallel to provide a high current to dipole magnet. This experiments are long team testing when the output current is set to 750A, loading is dipole magnet at store ring and magnet inductors are 5.8 mH and 43.8 mΩ. Testing waveforms shown in Figure 5, the initial output current is 750.4300 Ampere, the current reaches a steady value 750.4500 Ampere at 2 hours and output current value within are 750.4500A~ 750.4600A, its current ripple less than 10ppm. Additional, testing the frequency response of the power supply, respectively, scan the frequency of current output 250A, 500A, 750A and 1000A at 1Hz ~1600Hz.

Output current ripple and frequency relationship is shown in figure 6; all the output current and frequency curve maximum ripple at 60 Hz. According to the data, the peak current ripple is 3.319 mA (output current 250 A), 1.976 mA (output current 500 A), 1.274 mA (output current 750 A) and 0.817 mA (output current 1000 A) at 60 Hz, with a smaller current ripple at other frequency.

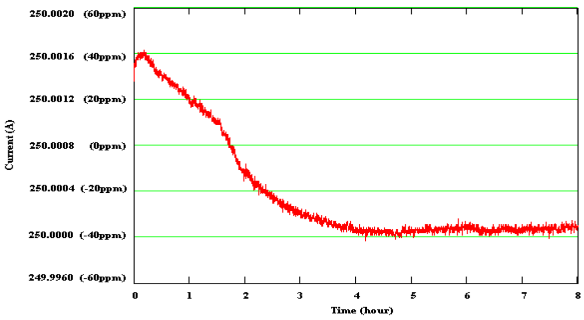


Fig3. Output current ripple (250 Ampere)

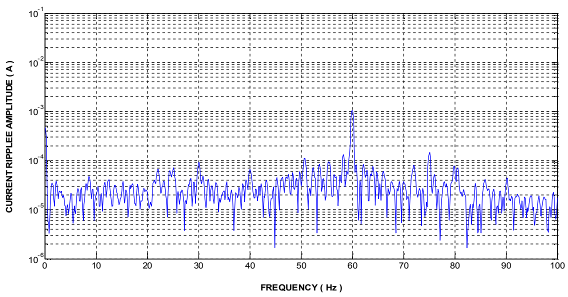


Fig4. Output current ripple by frequency (250 Ampere)

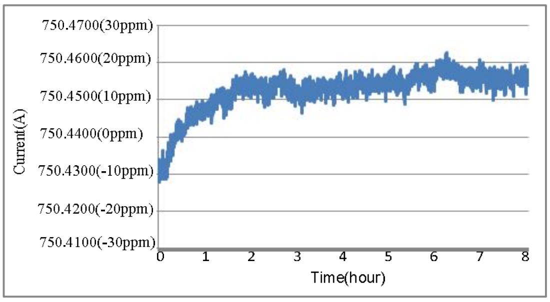


Fig5. Output current ripple (750 Ampere)

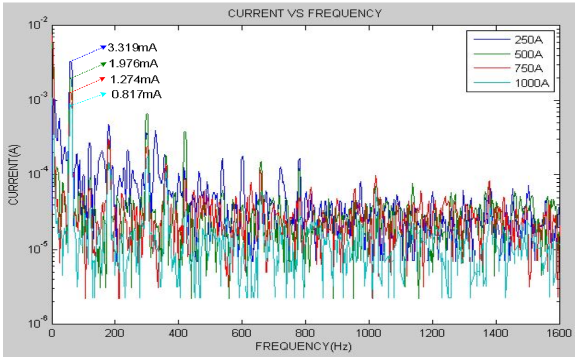


Fig6. Output current ripple and frequency (250 ~ 1000 Ampere)

V. TESTING EXTERNAL CIRCUIT DUMP ENERGY OPERATION THEORY

External dump energy circuit equivalent shown in Figure 7, for this circuit can be divided into four parts: (1) Power input stage, (2) superconducting protection level, (3) superconducting and (4) Release energy circuit. (1) The input stage is unit-polar power supply, connect the anode to the first group of superconducting diode anode and the second group of diodes cathode; and link superconducting inductance anode and cathode relay; cathode is connected to the ground node. (2) Superconducting protection part: using two parallel diode to composed of a group; a group of forward phase, another set of reverse phase. (3)Superconducting is mainly composed of the inductor, resistor value is approximately zero. (4)Energy release circuit part: To increase the speed of superconducting release energy when uni-polar power supply turn off for quick release of energy on the superconducting completed. External dump energy circuit operation theory can be separate of the turn on and turn off mode in this circuit. Turn on and turn off mode shown as figure7 (a) ~(c). The key waveforms of the proposed discharge circuit by a cycle are shown in Figs.8.

Mode1 [t_0~t_1]: Uni-polar power supply energy transferred to superconducting, the voltage across of forward diode is higher than voltage across of the superconducting, therefore input current wouldn't flow through the forward diode and relay. I_{in} current equation to I_L ; D_B 、 D_A 、S_1 turn off , so that I_{dA}=I_{dB}= I_{EL}=0A. the voltage V_{in} across the inductance and resistance of the superconducting $V_{in}=V_L=V_d=V_{s1}$, maximum across voltage of superconducting is given by

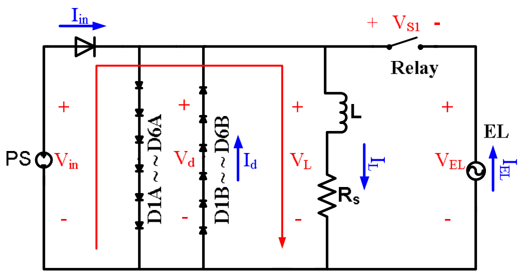
$$V_{L(max)}(t) = I_{L(max)}(t) * R_s \quad (1)$$

Mode2 [t_1~t_2] : Detection signal on relay will be start and turn on S1 relay when uni-polar power supply power off or superconducting current higher than power supply output current. Part of two route release energy stored in the superconducting, electronic load and uni-polar power supply dummy load. Inductor voltage reserves bias, so that relay will turn on and V_{s1}=0V. According the electric load setting value to discharge inductor energy until the current equation to electric load setting current I_L=I_{EL}. At this moment, inductor voltage and current are given by

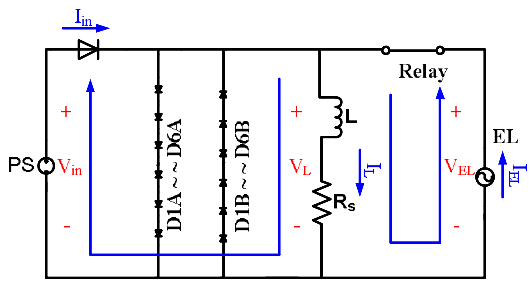
$$V_{L(max)}(t) = -I_{L(max)}(t) * R_s \quad (2)$$

$$I_L(t) = I_d(t) + I_{EL}(t) \quad (3)$$

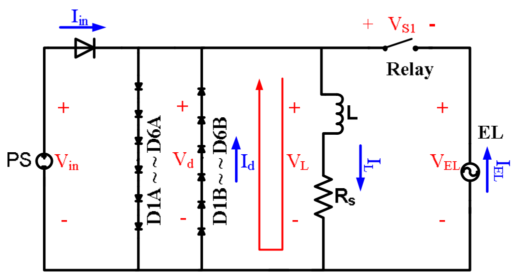
State3 [t_2~t_3]: Inductor energy release to D1B~D6B when the Relay turn off. I_L=I_d reduce the current until inductor energy release complete.



(a) Inductor stored energy [t_0~t_1]



(b) Inductor release energy to electric load [t_1~t_2]



(c) Inductor release energy to protection diode [t_2~t_3]

Fig7. External dump circuit operation mode

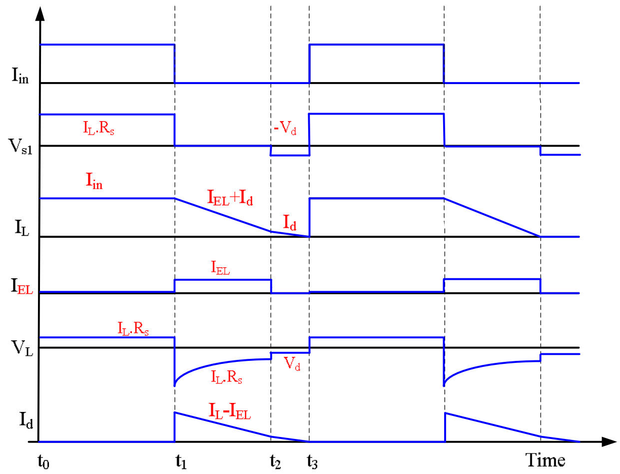


Fig8. Theoretical waveforms of circuit

VI. DUMP ENERGY CONTROL LOOP FUNCTION BLOCK AND DESIGN

Uni-polar Power Supply rear panel of the machine there is a group of APG circuit, its function is to allow users to input small signal voltage 、 current or resistance to control the power supply input current or voltage. Additional, convenient user detection would the power supply output voltage and current values are converted to a small signal voltage and current are transferred to the pins of the APG. The control loop signal use APG in (AIO_MEAS) to measure. APG is shown in Figure 9. APG output analogy voltage is 0 ~ 10V corresponds to the actual current is 0 ~ 300A.

External dump energy control board shown in Figure 10. APG's (AIO_MEAS) anode terminal connected to a diode, the cathode of the diode is connected to the anode of the RC circuit This RC circuit functions as a delay time. delay time of the signal as Va, Va as the positive input of the comparator; comparator input is another one of AIO_MEAS real time signal, this signal directly into the cathode of the comparator, therefore, the comparator are two input signals to cause AIO_MEAS signals one for the delayed signal, one for the real time signal. Through these two signals can be detected real time current value and the previous value of the current. Compare V_+ and V_- use by compactor can make a control signal V_c. The switch (S1) will turn on when the V_+ higher than V_-, Inductor energy will discharge to R2. Opposite, Compactor will provide the low level signal when the V_- lower than V_+, switch (S1) will turn off and discharge circuit is open. The circuit delay time constant is given by

$$\tau = \frac{1}{R_1 C_1} \quad (4)$$

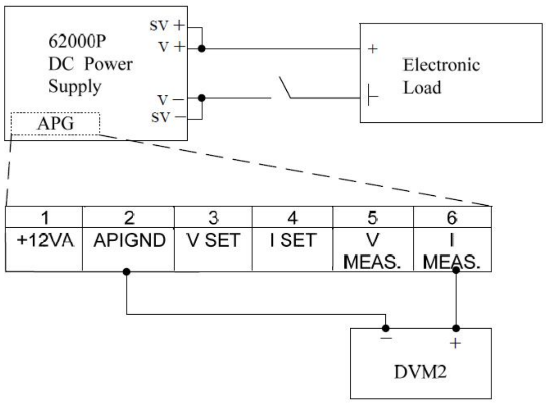


Fig9. Chroma 62075H-30 function block

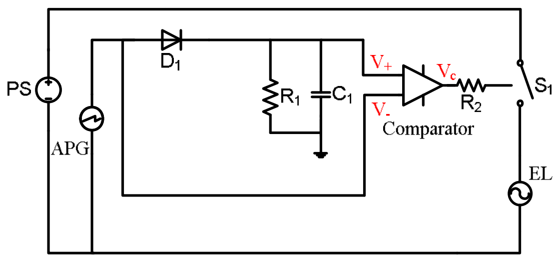


Fig10. Control function block

Figure 11 has shown use by Simplis simulation software testing APG control circuit, selected Diode (D1) 1N4148 forward voltage is 0.3V, R_1=820kΩ and C_1=10uF. D1 components function is ensure V_- voltage can be greater than V_+ when output current stable state that will pull low level of the switch S1 and relay will be turn off. Compare the V_- and V_+ to order high level (15V) or low level (0V) at the control signal V_c. Figure 12 has shown power supply setting initial output current value 120A reduce to 80A at 1s, APG's AIO_MEAS pin will be corresponds to show 3V reduce to 2V. V_+ voltage will be higher than V_- as has a delay circuit at this moment. V_c control signals will be pull high level and S1 turn on. V_c pull high time at 1s~3.1s, V_+ voltage will less than 2V and V_- voltage keep to 2V, comparing the voltage value V_c will be pull low, forcing the S1 switch turn off after at 3.1s.

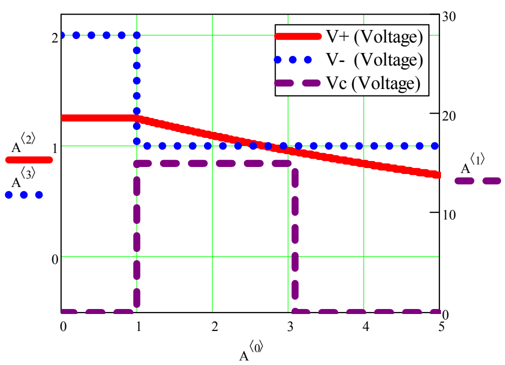


Fig11. Control function simulation waveform

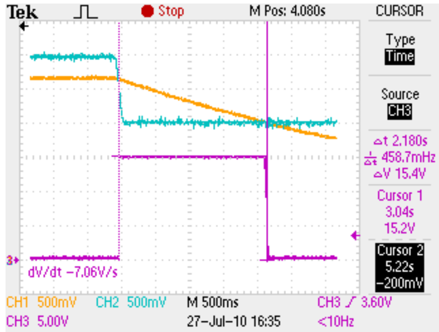


Fig12. Control function waveform

VII. TESTING WAVEFORM AND RESULT EXPERIMENTS

Figure 13 has shown Taiwan and Thailand national synchrotron radiation centre co-work to testing superconductivity. In cooperation mode measurements with superconducting unipolar power supply external dump energy circuit. Turn off the Uni-polar power supply and measure the superconducting energy release route and discharge time when the energy of the superconducting magnet to stabilize after. The experiments selected Chroma 62075H-30 with external dump energy circuit of the proposed circuit can be tested. Initial current is set to 310A, due to power supply maximum output current is 250A, 2 units must be connected in parallel experiments began the first step a superconducting instrument poured into the liquid helium and turn on the power supply to provide energy. Each unit 50A gradually increasing output current value until the current reaches 310A target value. Output voltage is 0.1242V when stable output current 310A. Superconductor resistance is 0.4 mΩ cause of the more voltage as a superconducting cable.

Figure 14 has shown superconducting current and time relationship, superconducting change time: output current from 0A increased to 310A at 0 ~ 1500 seconds and steady-state output current is 310A at 1500~8250 seconds. Testing uni-polar power supply circuit combine to external dump energy circuit discharge energy at 8250s and electric load setting is 0.3A/second. Output current initial 310A reduce to 100A that variation is 210A from T2 to T3 region. For this region reduce output slew rate are consistent with our setting value for electric load, total discharge time is 700s (8250s~8950s). T3~t4 region superconducting current is keep to 100A and the circuit will be cut off to release the test decreased 100A to 0A does not release energy in this case. T4~T5 region output current initial current is 100A reduce to 0A, its output current variation is 100A and discharge time 10000s to 12500, discharge slew rate is 0.04A/s. According to the experimental data, if no external energy releases circuit 310A down to 0A from the discharge time required for the 7750s; Opposite, if the energy release is used the circuit from 310A to 0A and electronic load slew rate is 0.03A / s, its required time will be only 1033second. Additional energy release circuit can effectively increase the discharge rate of superconductivity. Enable superconductivity can be completed in a short time be able energy release.

Fig13. Superconductor testing environment

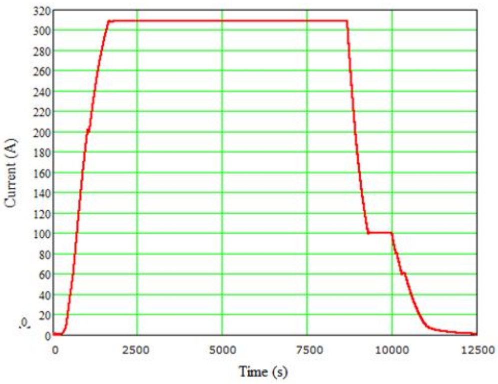


Figure14. Superconductor rising and falling output current

VIII. CONCLUSION

For this research paper, a low voltage, high current dual-mode (CC Mode / CV mode) of the new unipolar power supply is produced. Its internal control chip contains 24 bit ADC and 20 bit DAC, can provide excellent resolution measurement and output settings of high stability and reproducibility with accelerator magnets can provide excellent current source. Low current ripple and low noise is the main function of this power supply, the current value for the stability of the electron accelerator is extremely important, noise and current ripple will cause electrical shift direction, causing the loss of electron beam energy of the electron. Additional external energy release circuit, to achieve the effect of superconductivity release energy and doesn't affect the superconductivity properties. This circuit includes has advantage of simple structure, low cost, easy operation and high efficiency. Combined external dump energy circuit, bipolar power supply will be replaced by a unipolar power supply at the superconductivity when the energy release.

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