Transient Response About the Cathode in the Gyrotron Discharge

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Abstract

The gyrotron is the most important device in the ECRH system. The cathode power supply is one of the most important ancillary devices for gyrotron. Some interesting transient phenomena about the cathode voltage and the cathode current was found in the gyrotron operation. In order to explain these phenomena, an equivalent model of the magnetron injection gun was proposed. The equivalent circuit is composed of parallel resistors and capacitors, and it can explain the test results very well.

Full Text

Transient Response of the Cathode in Gyrotron Discharge

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Abstract—The gyrotron is the most important device in the ECRH system, and the cathode power supply represents one of its most critical ancillary components. During gyrotron operation, interesting transient phenomena were observed in both the cathode voltage and cathode current. To explain these phenomena, an equivalent model of the magnetron injection gun is proposed. The equivalent circuit, composed of parallel resistors and capacitors, can explain the experimental results very well.

Index Terms—Transient response, Gyrotron, Cathode, Gun, Equivalent model.

I. Introduction

A 140 GHz/4 MW electron cyclotron resonance heating (ECRH) system consisting of four gyrotrons is being built for EAST at ASIPP. Up to now, the first two gyrotrons have been established, and the third gyrotron is being set up and commissioned. Robust control and protection systems, data acquisition systems, and power measurement systems have been built for the gyrotrons. During commissioning of the first two gyrotrons, extensive research related to gyrotron operation has been conducted. Currently, many studies on gyrotrons such as beam-wave interaction theory, gyrotron design, and transient millimeter-wave signal analysis have been performed worldwide. However, there is little research on transient analysis of the cathode voltage, cathode current, anode voltage, anode current, and related parameters. We have discovered some interesting phenomena during gyrotron operation, and this paper proposes an equivalent model of the magnetron injection gun to explain the experimental results.

The details of the transient analysis of voltages and currents are discussed in the following sections. Section II presents the architecture and schematic of the gyrotron and its ancillary systems along with the gyrotron timing sequence. Section III describes the negative high voltage power supply for gyrotrons. Section IV provides measurement and analysis of the transient response of the cathode current and cathode voltage. Finally, conclusions are presented in Section V.

II. Ancillary Systems and Timing Sequence of the Gyrotron

The gyrotron cannot operate without its ancillary systems, which include the superconducting magnet and its power supply, collector power supply, cathode power supply, anode power supply, ion pump power supply, filament power supply, and others. The ancillary systems and their connections to the gyrotron are shown in Fig. 1 [Figure 1: see original paper]. Current limiting resistors are used to restrict the maximum current flowing through the cathode and anode (50 kΩ for the anode and 20 Ω for the cathode). DC shunts, which are actually resistors with small resistance values, are used to measure the anode current and beam current (500 mΩ for the anode current and 1 mΩ for the cathode current). Because the filament floats at the cathode high voltage, an isolation transformer is used between the filament and its power supply to protect the filament power source.

The gyrotrons must be operated with the correct timing sequence; otherwise, they may be damaged. The proper timing sequence is shown in Fig. 2 [Figure 2: see original paper]. The PLC_Ready signal is an interlock signal from the PLC (Programmable Logic Controller). The TriggerIn_-60 signal is sent from the EAST central controller; when the timing controller detects its rising edge, it changes the NegHVPre_-60 signal to high level. This signal is sent to the cathode power supply, and when NegHVPre_-60 is at high level, the switchgear of the cathode power supply closes. Once the cathode power supply switchgear is closed, the power supply sends a NegHv_Ready signal to the timing controller. Sixty seconds after detecting the rising edge of TriggerIn_-60, a rising edge of the TriggerIn_0 signal is sent to the timing controller. The timing controller then immediately turns the NegHv_OnOff signal to high level (within several nanoseconds). The IGBTs of the cathode power supply close according to the set time. If the output voltage of the cathode power supply exceeds 30 kV, the NegHV_OutputState signal goes high. Fifty milliseconds after the NegHv_OnOff signal changes to high level, the timing controller turns the PosHV_OnOff signal high to activate the anode power supply. One millisecond after the anode power supply turns on, the Wave_OutputState signal (RF signal) is activated to implement part of the RF protection. If the Wave_OutputState signal goes low, the shutdown procedure initiates: the NegHv_OnOff and PosHV_OnOff signals are set low successively (with a 2 ms interval) to shut down the power supplies and protect the gyrotron. During gyrotron discharge, if the Ip_D signal (plasma current signal from the EAST central controller) goes low, the shutdown procedure starts to protect the EAST tokamak from damage by the millimeter wave output from the gyrotrons. For safety, if any of these signals—PLC_Ready, NegHv_Ready, NegHV_OutputState, Wave_OutputState, or Ip_D—goes low, the shutdown procedure begins.

III. Negative High Voltage Power Supply for Gyrotrons

We have developed two cathode high voltage power supplies for four gyrotrons. The cathode high voltage power supplies use PSM (Pulse Step Modulation) technology, which overcomes the shortcomings of traditional high voltage power supplies such as large single volume, low efficiency, net-side low harmonics pollution, lower power factor, larger output ripple, and slower dynamic response. The power supply topology is shown in Fig. 3 [Figure 3: see original paper]. To protect the gyrotrons, it is necessary to ensure that the stored energy of the power supply system is small enough. The energy is mainly stored in the output filter and stray capacitances for PDM modules. The stored energy is very small (<10 J) in our power supply system. To verify the protection effectiveness, we conducted a short circuit test. A fuse with a fusing energy of 10 J, connected in series in the loop, remained intact when the load was shorted, proving that the stored output energy of the power supply is less than 10 J. Therefore, this power supply can be used for gyrotrons without a crowbar.

If the high voltage source receives a turn-off signal or protection signal from the gyrotron control system, the IGBTs shut down within several microseconds, cutting off the connection between the power supply and the gyrotron. A test was performed to verify that the shutdown time of the cathode power source was within several microseconds. A dummy load with a resistance of 304 Ω was connected to the power source, and a turn-off signal was sent to the power supply. The waveforms of the voltage and current of the cathode power supply when the IGBTs shut off are shown in Fig. 4 [Figure 4: see original paper]. As can be seen, the shutdown time of the cathode power source is about 5 s, which is short enough to protect the gyrotrons.

IV. Measurement and Analysis of the Transient Response of Cathode Current and Cathode Voltage

The measurement block diagram for the cathode voltage and cathode current is shown in Fig. 5 [Figure 5: see original paper]. A high voltage probe connected in parallel with the cathode high voltage power supply measures the cathode voltage, while a rapid response current probe measures the cathode current. Both probes are connected to the same oscilloscope, which is primarily used to measure the transient response. Additionally, a shunt with a resistance of 1 mΩ measures the cathode current for slow overcurrent protection and steady-state cathode current measurement.

Fig. 6 [Figure 6: see original paper] and Fig. 7 [Figure 7: see original paper] show the cathode voltage and cathode current displayed on the oscilloscope during gyrotron shutdown. The response time of the cathode voltage differs between normal shutdown and overcurrent protection scenarios. During normal shutdown, the cathode voltage drops to about 10% of its original value in approximately 25 s. In the overcurrent case, the cathode voltage drops to about 10% of its original value in approximately 90 s. In both cases, the cathode power supply shuts down with the same operation within 6 s. Therefore, we can infer that some gyrotron parameters change when overcurrent occurs, and this parameter change causes the variation in cathode voltage drop time. We propose an equivalent model of the gyrotron gun to analyze this phenomenon.

The equivalent circuit of the gyrotron gun and auxiliary power supplies is shown in Fig. 8 [Figure 8: see original paper], where Rrb is the cathode current limiting resistor (20 Ω); Rra is the anode current limiting resistor (50 kΩ); Rsb is the shunt for measuring beam current (1 mΩ); Rsa is the shunt for measuring anode current (500 mΩ); Rb is the equivalent resistor of the electron gun between cathode and ground (body); Cb is the equivalent capacitor between cathode and ground (body); Ra is the equivalent resistor between anode and cathode; and Ca is the equivalent capacitor between anode and cathode.

The resistance of Rb is related to the voltage across Cb, the voltage across Ca (the sum of the absolute values of cathode voltage and anode voltage), and the filament power supply power. For the normal shutdown process of the cathode voltage, the anode voltage has been reduced to 0, so the value of Rb is only related to the voltage across Cb (the cathode voltage) and the filament power supply power. Table I shows example values.

We analyzed the relationship between Rb and the cathode voltage ub when the anode voltage is zero and the filament power is 1097.65 W. The relationship between Rb and the absolute value of cathode voltage ub is shown in Fig. 9 [Figure 9: see original paper]. The exponential fitting function is:

$$R_b = -359.6 + 1005.5 \cdot \exp(1.6 \times 10^{-5} u_b)$$

where the unit of u_b is volts and the unit of R_b is ohms.

When the cathode power supply shuts down, a capacitor discharge circuit is formed by Cb and Rb, representing a zero-input response. Assuming the initial voltage across capacitor Cb is U_b (a positive value in volts), the Laplace transform equivalent circuit is shown in Fig. 10 [Figure 10: see original paper]. The voltage across capacitor Cb is:

$$u(s) = \frac{U_b}{s(1 + sC_bR_b)}$$

Using inverse Laplace transform, we obtain:

$$u(t) = U_b \cdot \exp\left(-\frac{t}{C_bR_b}\right)$$

where $u(t) = u_b$. By solving the equations and assuming $u(t) = u_b = u_t$, we get:

$$u_t = U_b \cdot \exp\left(-\frac{t}{C_b(-359.6 + 1005.5 \cdot \exp(1.6 \times 10^{-5} u_t))}\right)$$

Taking the natural logarithm of both sides and simplifying:

$$\frac{t}{C_b(-359.6 + 1005.5 \cdot \exp(1.6 \times 10^{-5} u_t))} = 359.6(\ln u_t - \ln U_b) + 1005.5(\ln U_b - \ln u_t)\exp(1.6 \times 10^{-5} u_t)$$

Let $U_b = 41000$ V and $u_t = 4100$ V; we can calculate the time for the cathode voltage to drop to about 10% of its original value:

$$t \approx 1644.2C_b$$

As shown in Fig. 6, during normal shutdown, the cathode voltage drops to about 10% of its original value in approximately 25 s. Therefore, the equivalent capacitance is:

$$C_b \approx 15.2 \text{ nF}$$

For the current flowing through Rb, assuming the direction shown in Fig. 10 is positive:

$$i(t) = -C_b\frac{du}{dt} = \frac{U_b}{R_b}\exp\left(-\frac{t}{C_bR_b}\right)$$

Since Rb varies with voltage u_t, substituting the equation for Rb yields the relationship between current $i(t)$ and voltage u_t:

$$i(t) = \frac{U_b}{-359.6 + 1005.5 \cdot \exp(1.6 \times 10^{-5} u_t)} \exp\left(-\frac{t}{C_b(-359.6 + 1005.5 \cdot \exp(1.6 \times 10^{-5} u_t))}\right)$$

The value of $i(t)$ is always positive, indicating that the actual current direction is the same as shown in Fig. 10, i.e., the same as the direction at time 0-. The relationship between $i(t)$ and u_t is shown in Fig. 11 [Figure 11: see original paper]. When $u_t = 41000$ V, $i(t) \approx 26$ A $= i(0-)$; when $u_t = 30000$ V, $i(t) \approx 24$ A; when $u_t = 20000$ V, $i(t) \approx 20$ A; when $u_t = 0$ V, $i(t) \approx 0$ A. The value of $i(t)$ decreases with decreasing u_t, and the drop time is almost the same. It should be noted that the current $i(t)$ is the current flowing through resistor Rb; it is not the same current measured by the current probe shown in Fig. 5 and is difficult to measure directly.

When an arc occurs in the gyrotron gun, the cathode current increases suddenly, which is dangerous for the gyrotron. Therefore, if overcurrent occurs, the protection system shuts down both the anode and cathode power supplies simultaneously. As seen in Fig. 7, the voltage begins to turn off about 5 s after overcurrent occurs. The energy transmitted to the gyrotron after overcurrent is:

$$W \approx \int p\,dt \approx \int ui\,dt \approx 41 \text{ kV} \times 35 \text{ A} \times 5\mu\text{s} \approx 7.2 \text{ J}$$

In the overcurrent situation, the anode voltage starts to decrease simultaneously with the cathode voltage, meaning the anode voltage is not zero when the cathode power supply shuts down. However, as shown in Table I , the value of Rb is less affected by the anode voltage. For simplicity, we ignore the anode voltage in the overcurrent situation. As seen in Fig. 7, the cathode voltage drops to about 10% of its original value in approximately 90 s, which is much longer than in the normal situation. The equivalent capacitance is:

$$C_b \approx 54.7 \text{ nF}$$

The increase in equivalent capacitance Cb may be due to discharge between the cathode and ground, thus increasing the cathode voltage drop time.

To further verify these assumptions, we attempted to add a crowbar short-circuit switch across the cathode voltage source. When the cathode voltage source turns off, the crowbar short-circuit switch automatically closes, and the equivalent circuit is shown in Fig. 12 [Figure 12: see original paper]. When the crowbar switch closes, capacitor Cb discharges through Rrb. The voltage across capacitor Cb is:

$$u(t) = U_b \cdot \exp\left(-\frac{t}{C_b R_{rb}}\right)$$

The cathode voltage drops to about 10% of its original value in:

$$t \approx 2.3 R_{rb} C_b \approx 0.7 \mu \mathrm{s}$$

The actual cathode voltage waveform is shown in Fig. 13 [Figure 13: see original paper], and it can be seen that the voltage falling edge is indeed about 0.7 s. However, because the voltage source turns off too quickly, voltage oscillations are generated. The oscillation occurs due to signal transmission and reflection between the left end of Cb and ground.

The current flowing through Rrb is:

$$i(t) = -\frac{U_b}{R_{rb}} \exp\left(-\frac{t}{C_b R_{rb}}\right)$$

When $U_b = 41$ kV, the current is about 2.05 kA at time zero, and the current direction through Rrb is opposite to the initial direction. It then decreases to about 205 A after 0.7 s and to about 20.5 A after 1.4 s. The beam current signal in Fig. 13 shows a large surge, but since the oscilloscope' s preset signal amplitude range is small, the specific maximum value is not visible. The current signal drops to near 0 A in about 1 s, which matches theoretical expectations. However, due to the excessively fast current edge, the current signal transmits back and forth on the signal line, causing current oscillations.

The transient response of the anode current and anode voltage when the power supply shuts down is similar to that of the cathode. The equivalent resistor Ra shown in Fig. 8 is related to the voltage across Ca (the sum of the absolute values of cathode voltage and anode voltage). The resistance of Ra decreases as the anode voltage increases. Ra is probably several megohms; Ca is probably several picofarads, and Ca may increase under overcurrent conditions. Therefore, the time for the anode voltage to drop to about 10% of its original value may be longer than in the normal case. If only the cathode voltage is applied to the gyrotron and the anode is not connected to the anode power supply or ground, the potential on the anode will equal the potential on the cathode. If the anode potential is not equal to the cathode potential, there may be an equivalent resistor between the anode and ground. More detailed analysis and testing will be conducted in the future.

V. Conclusion

The gyrotron is the key component of the ECRH system. As a sophisticated vacuum device, it requires many ancillary systems to operate. The cathode power supply and anode power supply are the most important ancillary devices. Gyrotrons must be operated with the correct timing sequence; otherwise, they may be damaged. During gyrotron experiments, we found that the waveforms of cathode voltage and cathode current vary under different conditions. The cathode voltage drops to about 10% of its original value in approximately 90 s during overcurrent conditions, which is much longer than the 25 s observed in normal operation. An equivalent circuit of the gyrotron gun is proposed to analyze the transient phenomena of cathode voltage and cathode current. The equivalent circuit, composed of parallel resistors and capacitors, can explain the test results well. We also briefly predicted the response of anode voltage and current based on the equivalent circuit model. More detailed tests will be conducted in the future.

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