Temperature detection circuit on the low-temperature superconducting coils (postprint)

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Abstract

Experimental Advanced Superconducting Tokamak (EAST) is the fully superconducting Tokamak. The EAST magnet system comprises 16 D-shaped toroidal field coils and 14 poloidal field coils which are cooled by supercritical helium at 4.2 K and 3.8 K. The temperature of superconducting coils is measured by Cernox as a new type low-temperature sensor, and monitored during the cooling and operation. The helium temperature can offer reference for quench signal. In this paper, a technique for the weak temperature signal measurement of superconducting coils is introduced, and its weak voltage is extracted from the intrinsic noise of the amplifier by the low-noise instrumentation amplifier, filter circuit, and high-linearity analog optocoupler. The temperature detection circuit works accurately and safely whether in cooling or operating process. This technique is an effective for the temperature detection on the low-temperature superconducting coils.

Full Text

Preamble

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Temperature Detection Circuit for Low-Temperature Superconducting Coils

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Abstract

The Experimental Advanced Superconducting Tokamak (EAST) is a fully superconducting tokamak device. Its magnet system comprises 16 D-shaped toroidal field (TF) coils and 14 poloidal field (PF) coils, which are cooled by supercritical helium at 4.2 K and 3.8 K, respectively. The temperature of the superconducting coils is measured using Cernox sensors, a new type of low-temperature sensor, and continuously monitored during both cooling and operation. The helium temperature provides a critical reference for quench detection. This paper introduces a technique for measuring weak temperature signals from superconducting coils, wherein the weak voltage is extracted from amplifier intrinsic noise using a low-noise instrumentation amplifier, filter circuit, and high-linearity analog optocoupler. The temperature detection circuit operates accurately and safely during both cooling and operating processes, demonstrating its effectiveness for low-temperature superconducting coil temperature detection.

Key words: Supercritical helium temperature, Temperature sensors, Weak signal measurement

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Introduction

The Experimental Advanced Superconducting Tokamak (EAST) is a steady-state-capable advanced experimental device for high-temperature plasma research[1]. The device comprises a superconducting poloidal field (PF) system, a toroidal field (TF) magnet system, a vacuum vessel, a cryostat, and a thermal radiation shield [Figure 1: see original paper]. The PF system contains 14 coils located symmetrically about the equatorial plane, with six inner PF coils forming the central solenoid (CS) assembly. The TF magnet system features a toroidal array of 16 D-shaped coils producing a 3.5 T toroidal field at the 1.7-m plasma major radius[2].

The TF magnet systems are cooled with supercritical helium during both cooling and operation. Temperature at each point of the magnet coil is obtained using multiplexed temperature sensors installed at different locations. The cooling rate and temperature difference between various device components are strictly controlled to ensure uniform cooling and prevent damage to device insulation or components caused by excessive thermal stress. During operation, the coil temperature must be maintained below its critical value to prevent quenching.

During experiments, the TF coils run in steady-state mode with a normal operating current of 14.3 kA at 4.2 K and 16.35 kA at 3.8 K. The PF coils operate in pulse mode with a maximum current of 14.3 kA and a time variation rate of 20 kA/s[3].

CX-1050AA, a new type of low-temperature resistance sensor prepared by ceramic nitride oxide (CERNOX), is adopted for the coil systems. The standard temperature sensor, X11181, is calibrated by American Lake Shore Co., while the others are calibrated using a self-developed low-temperature calibration device[4]. The Cernox is a negative temperature coefficient sensor with a calibrated temperature range of 3.5-300 K and scaled precision better than 10 mK at 4.2 K[5]. Typical resistance and temperature values are shown in Table 1 .

Cernox thermometers are installed on the outer walls of cooling pipe inlets and outlets in magnet coils and coil boxes. The quantity and installation positions of PF and TF coils are shown in [Figure 2: see original paper] and [Figure 3: see original paper]. Measurement errors are reduced through several steps[5]. First, Al_2O_3 powder and vacuum grease are added into thermometer sockets to ensure good thermal contact with the measured objects. Second, heat leakage along measurement lines is reduced to prevent thermal radiation effects. Third, since PF coils operate in pulse mode with a maximum current ramping rate of 20 kA/s, which can produce strong interfering signals, shielded twisted-pair cables are adopted to avoid electromagnetic interference. Fourth, thermometers are powered by a high-stability constant current source and measured using a four-wire system.

When using two-wire measurement, the constant current source generates voltage on lead resistors (R1, R4), affecting thermometer measurement accuracy. As shown in [Figure 4: see original paper], the current source and voltage measurement circuits are separated using four-wire measurement. Resistors R1 and R4 do not affect the current, and the measured voltage is the true voltage across the thermometer because the circuit current through R2 and R3 is very small, and the large input resistance of the operational amplifier makes the lead resistors (R2 and R3) negligible.

To eliminate analog signal circuit noise caused by common ground interference such as hidden ground loops and improper grounding in measurement and control systems, signal pretreatment, amplification, filtering, and isolation must be considered. Pretreatment requires selecting a low-noise amplifier with high common-mode rejection ratio (CMRR) and suitable filter circuits.

Analog signal isolation demands high standards for signal transmission linearity and gain temperature stability, making linear analog signal isolation difficult to achieve. Basic approaches include isolation synchronous voltage-to-frequency conversion, linear transformer demodulation, and optocoupler linear amplification. The first method works reliably but is limited in frequency bandwidth and signal transmission rate. The second offers good linearity and high isolation voltage but its large volume confines it primarily to audio power signal transmission. The third provides high frequency bandwidth and linearity, but isolation voltage is less than 3,500 V. Ordinary optical couplers are seldom used due to their narrow linear region and poor temperature stability.

To construct the low-temperature superconducting coil detection circuit, we adopt a low-noise, high CMRR amplifier, a Butterworth second-order filter with good flatness characteristics in the pass-band, and the HCNR201 optocoupler with high linearity, isolation voltage up to 50,000 V, and temperature stability with temperature compensation. During experiments, a 10- A constant-current source is applied to the sensor, producing an output voltage of 0.45–0.6 mV at room temperature and 40–50 mV at supercritical helium temperature. After 100-times amplification, low-pass filtering, and isolation by a high-linearity analog optocoupler, the conditioned signal is sent to a 16-bit high-resolution data acquisition card for real-time processing and display by computer.

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2. Basic Detection Circuit Composition

To match the optimal measurement ranges of the data acquisition card, millivolt signals from temperature sensors should be amplified by two-stage amplifiers, each with a fixed gain of 10. The INA217, a low-noise, high CMRR instrumentation amplifier, and the OP07, with ultra-low input offset voltage, are employed. The magnet system cools from 300 K to 4.2 K at an average rate of 1 K/h. A designed low-pass filter circuit should avoid noise caused by large currents and varying high electromagnetic fields. Considering both the cooldown rate and temperature signal response rate when the magnet system quenches, the filter cutoff frequency is set at 7.5 Hz. The PF coils operate in pulse mode, with PF7 and PF8 having a maximum instantaneous terminal voltage exceeding 3500 V. To ensure safety, an isolation device isolates the field from the data acquisition system, separating the signal to a clean and safe signal subsystem ground[6]. To satisfy the isolation voltage requirement, the HCNR201 high-linearity analog optocoupler with 5,000 V isolation voltage is selected.

The block diagram of the temperature detection system is shown in [Figure 5: see original paper].

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3. Amplifier Unit

The INA217 serves as the preamplifier—a low-noise instrumentation amplifier providing superior performance in professional weak signal detection applications[7]. Current-feedback circuitry allows wide bandwidth, excellent dynamic response over a wide gain range, and unique distortion cancellation circuitry.

As shown in [Figure 6: see original paper], the gain for the INA217 is set with an external resistor (RG) and expressed as:

$G = 1 + 10000/RG$

The input impedance of the INA217 is approximately 60 MΩ. Without a bias current return path, its inputs will float to a potential exceeding the common-mode range, saturating the input amplifiers. Two 1 MΩ resistors provide a balanced input with advantages of lower input offset voltage due to bias current and better common-mode rejection.

Very low source impedance can cause the INA217 to oscillate, and the sensor resistance is about 50 Ω at room temperature. An input network consisting of a small inductor and resistor can greatly reduce any oscillating tendency.

4. Filter Circuit

A Butterworth filter provides maximally flat response in the pass-band without ripple distortion accompanying other implementations such as Chebyshev or Elliptic filters. Above the -3 dB point, attenuation is relatively steep with a slope of -20 dB/decade/pole.

Two cascaded second-order Butterworth low-pass filters control the transition sharpness from pass-band to stop-band ([Figure 7: see original paper]). When the signal is amplified 100 times, the gain is 1, and the filter cutoff frequency is 7.5 Hz. The parameters are selected as ai = 20.5, bi = 1, Q = 0.707, c1 = 1 µF, and c2 = 2 µF. The values of R1 and R2 can be expressed as follows.

The R1 and R2 values of approximately 15 kΩ are calculated by substituting the known parameters.

5. High-Linearity Analog Optocoupler Isolation Circuit

The HCNR201 analog optocoupler consists of a high-performance AlGaAs LED that illuminates two closely matched photodiodes[8], ensuring high linearity and stable gain characteristics for analog signal isolation.

5.1 Operation Theory of HCNR201

The HCNR201 unipolar circuit topology is shown in [Figure 8: see original paper]. An external amplifier (A1) and photodiode PD1 comprise a feedback loop. PD1 monitors the light output of the LED and automatically adjusts the LED current to compensate for any nonlinearities. The output PD2 converts the stable light output of the LED into a linear current, which can be converted back into a voltage by A1.

In the unipolar working mode, PD1 works as a current follower, and linearity improvement is implemented by maintaining zero potential at the A1 inverting input. Briefly, amplifier A1 adjusts the LED current (IF), and therefore the current in PD1 (IPD1), to maintain its "-"input terminal at 0 V. The relationship between input current and output voltage is as follows.

IPD1 is exactly proportional to Vin, giving a very linear relationship between input voltage and photodiode current. The ratio of Vin to Vout is constant and independent of the light output characteristics of the LED.

The bipolar circuit topology is shown in [Figure 9: see original paper]. AR1 serves as an inverting amplifier with gain 1, applied to a 3-V DC bias voltage input. The relationship between Vin and Vo1 is expressed as:

Vo1 = -(R7/R6)Vin + (1 + R7/R6)VA (7)

Under the condition R6 = R7 and VA = 3 V, Eq. (7) simplifies to Vo1 = 6 -Vin. The appropriate quiescent point of HCNR201 is established at 6 V, simplifying circuit design and achieving better bipolar signal isolation.

In actual design, when each isolation circuit front-end has its own power supply, the 3-V bias voltages VA and VB should be provided by precision voltage reference sources to reduce deviation of each channel’ s 6-V quiescent point, thus enhancing interchangeability of each isolation circuit.

5.2 High-Linearity Analog Optocoupler Isolation Circuit Parameter Selection

Here we discuss the values of R1, R2, and R3 in [Figure 9: see original paper]. IF and IPD1 are expressed as.

Since IPD1 = 0.005IF (typical value in parameter table), Eq. (10) is obtained:

Vo1/R1 = (12 -VLED -Vo2)/200R2 (10)

With R1 = 200R2, R3 + RS = R, Vo1 = 12 -VLED -Vo2, and R2 = Vo1/IF.

R2 is selected to achieve an LED current of approximately 10 mA at nominal input. With the linear region of Vo1 at 6 V, R2 = 600 Ω, and R1 = R = 200R2 = 120 kΩ.

HCNR201 is a current-driven device, and the LED quiescent current is about 10 mA, requiring the driving current of amplifier (A1) to exceed 10 mA.

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6. Signal Isolation Line Test and Discussion

A 10 µA constant-current source and precision resistance box are used to simulate superconducting coil output signals. Monitoring supercritical helium temperature is important as it provides reference for quench signals; therefore, the resistance box is set to 4.2 kΩ when debugging the circuit. After complete circuit testing, the resistance box is adjusted to 4, 3, 2, 1, and 0.5 kΩ in sequence to determine circuit linearity and accuracy across the superconducting temperature range. Test results show circuit accuracy within 0.5‰ for resistances above 3 kΩ, within 1‰ for 1-3 kΩ, and within 5‰ for resistances below 1 kΩ.

The EAST device design requires liquid helium temperature measurement error to be less than 10 mK[3]. From Table 1, thermometer sensitivity is about 10 Ω/10 mK at liquid helium temperature, and measurement accuracy is better than 0.5‰, meaning resistance measurement error is less than 2.1 Ω (4200 ×

0.5‰ = 2.1). Therefore, the circuit can accurately measure temperature data and quench signals during both cooling and operation.

The first cooldown procedure of the TF magnet system is shown in [Figure 10: see original paper]. A 4.5 K cryogenic refrigerator system cooled the superconducting magnets to the superconducting phase after 14 days (March 4).

The superconducting coil charging was performed on PF12 as one of four large PF coils. The current was set to 1 kA at a rate of ~50 A/s. Following 260 charges on other PF coils and the central solenoid, the current reached 2 kA at a charge rate of 2 kA/s. The longest pulse for the TF is 5000 s. The TF magnet system was charged to 8.2 kA, achieving a toroidal field of 2 T at the major radius of 1.7 m[9-12].

The temperature detection circuits operate accurately and safely during both cooling and operating processes, enabling the cryogenic and refrigerator system to strictly control cooling rate and temperature difference between various device components while maintaining stable critical temperature to prevent quenching of low-temperature superconducting coils.

7. Conclusions

In this paper, the composition, working principle, and test results of the low-temperature superconducting coil temperature detection circuit are introduced. The weak voltage from superconducting temperature sensors can be extracted and amplified by pretreatment circuits and high-linearity analog optocouplers. The temperature detection circuit operates accurately and safely during both cooling and operating processes, proving effective for coil temperature detection.

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