Design of temperature monitoring system of 35 kV km-Level Domestic Second Generation High Temperature Superconducting Power Cable in Shanghai, China

Ting Jiao1*, Bengang Wei2, Honglei Li1, Kai Gao1, Chenzhao Fu1, and Liming Wang2

1 State Grid Shanghai Electric Power Research Institute, Shanghai, 200437, China
2 State Grid Shanghai Municipal Electric Power Company, Shanghai, 200122, China
*Corresponding author’s e-mail: 137794930@qq.com

Abstract. The city of Shanghai, China plans to deploy the first domestic 35 kV km-level High-Temperature Superconducting Power Cable (HTS-PC) project for connecting two substations in the downtown region in 2021, of which the HTS-PC can transport the current with a maximum value of 2200 A. The HTS-PC needs to operate at a temperature level of the liquid nitrogen temperature zone to maintain the electrically superconducting state. The real-time temperature information of the HTS-PC is crucial for its safe operation. Therefore, this paper proposes a temperature monitoring system suitable for the 35 kV km-level domestic HTS-PC. The system is based on the optical fiber temperature measurement technology and mainly consists of the optical generation, photoelectric detection, fiber sensor, signal acquisition, signal processing, and other components. The conclusion of this paper can be consulted in the operation of the high-temperature superconducting power cable project in the future.

1. Introduction
Metropolis is facing the problem of the increasing power demand within the downtown area, where the land resource is limited and expensive. To eliminate the inefficiency in the power supplements and save the land resource within the downtown area, the high-temperature superconducting technology is developed and adopted[1-4]. Meanwhile, using the high-temperature superconducting cables can have lower power loss (at least an order of magnitude smaller) for carrying the equivalent energy compared to the conventional cables[2]. Therefore, Shanghai, China launched the first domestic 35 kV high-temperature superconducting power cable (HTS-PC) project, of which the HTS-PC is designed to have one kilometer long laid underground and connecting the two substations within the downtown region[1,4].

High-temperature superconductors are known to behave electrically superconducting at temperatures above the boiling point of liquid nitrogen (~77 K)[5]. When the operating temperature of the HTS-PC exceeds the critical point, the superconductivity condition can not be maintained. The resistance of the HTS-PC will increase instantaneously and more Joule heating will generate, which will cause catastrophic accidents in electrical transportation. Clearly, monitoring the temperature of the HTS-PC during operation is of great importance to the safe operation and draws the close attention of the researchers. Chiuchiolo et al. introduced the advances in fiber optic sensors technology development for temperature measurements in superconducting devices[6,7]. Boyd et al. proposed a fiber optic
distributed temperature measurement system and Scurti et al. presented the application of the Rayleigh-back scattering interrogated optical fibers (RIOF) to monitor the temperature[8,9].

Therefore, this paper investigates the temperature monitoring system that is suitable for the domestic 35 kV km-level HTS-PC. A temperature monitoring system, based on the optical fiber temperature measurement technology, is proposed to monitor the temperature of the HTS-PC. The system consists of the optical generation, photoelectric detection, fiber sensor, signal acquisition, signal processing, and other components. The proposed system has a practical engineering application to the HTS cable operation.

2. Temperature monitoring system

2.1. Three-phase HTS-PC

The HTS-PC, adopted in the 35 kV km-level High-Temperature Superconducting Power Cable project, has a three-phase package structure and is manufactured by Shanghai Superconducting Technology Co., Ltd.. Every phase of the HTS-PC consists of two layers of superconducting transmission belts and the associated shielding tapes. The tape of the HTS-PC in every phase is fabricated by the material of Yttrium Barium Copper Oxide (YBCO) with a width of 4.8 mm, of which the critical current of one single tape is 140 A (the total maximum current of the HTS-PC is 2200 A). Between the superconductor layers, it is electrically insulated by the material of polypropylene laminated paper (PPLP). The cross-section of the HTS-PC is shown in Fig. 1.

![Cross-section of the HTS-PC](image)

As shown in Fig.1, the HTS-PC mainly consists of the superconducting tapes (A/B/C phases) and the associated insulation layers, the outer protection layer. The diameter of the three-phase package HTS-PC is 92.7 mm[10,11]. Between the A/B/C phase and the insulation layer, the liquid nitrogen is fully filled to maintain the low temperature for the superconducting tapes, where monitoring the temperature is very important for the operation of the HTS-PC.

2.2. Temperature measurement formula based on optical fiber

The optical fiber uses light as a carrier and the changes in light intensity as an indicator to measure the temperature. The optical fiber works as the core element and can directly evaluate the changes in the thermal signal. Besides, the optical fiber sensor signal is not susceptible to electromagnetic interference, making the optical fiber workable in strong electromagnetic fields. And the optical fiber has the outstanding tensile resistance and pressure resistance, which is suitable to be used in narrow regions, e.g. the narrow space between the A/B/C phase and the insulation layer of the HTS-PC. Therefore, the optical fiber temperature measurement technology is adopted to design the temperature monitoring system of the HTS-PC.

In theory, when light is transmitted in an optical fiber, the Raman scattering phenomenon will occur at any point in the light transmission process. This kind of scattering occurs in all directions, and
meanwhile, part of the scattered light will be reflected. The calculation method of the scattered echo light signal at the position $L$ in the optical fiber is shown in Equation (1).

$$L = \frac{Vt}{2} \quad (1)$$

Where $t$ is the time difference between the time of the light pulse entering the optical fiber and the time of the echo signal being received. $v$ is the propagation speed of light in the optical fiber. $L$ is the position where the light scattering occurs.

By analyzing the refractive index of the optical fiber, the propagation speed of light in the optical fiber can be calculated. The reflected signal intensity is obtained at time $t$ to represent the scattering intensity at $L$, of which the sampling frequency directly determines the accuracy and spatial resolution. For the spontaneous Raman scattering, the intensity ratio between the anti-Stokes line and the Stokes intensity satisfies a rated mathematical relationship. The Stokes Raman backscattered luminous flux can be calculated by Equation (2).

$$N_s = N_e \cdot S \cdot v_s \cdot N_e \cdot R_s(T) \cdot e^{-\frac{\Delta v_s}{2}} \quad (2)$$

Where $N_e$ is the number of incident laser photons. $K_s$ is the backscattering coefficient of the Stokes light per unit length. $v_s$ is Stokes Raman photon frequency. $S$ represents the fiber backscattering factor. $R_s(T)$ is related to the energy level of the molecule related to the Raman scattering of the fiber molecule, which can be calculated in Equation (3).

$$R_s(T) = \frac{a_0 + a_s}{1 - e^{\frac{E_s}{kT}}} \quad (3)$$

Where $K$ is Boltzmann's constant. $a_0$ is the average transmission loss of the incident photons in the optical fiber. $a_s$ is the loss of Stokes scattered photons per unit length. $L$ is the length of the optical fiber. $h$ is the Planck’s constant.

The number of photons scattered by anti-Stokes Raman can be calculated by Equation (4).

$$N_{as} = K_{as} \cdot S \cdot v_{as} \cdot N_e \cdot R_{as}(T) \cdot e^{-\frac{\Delta v_{as}}{2}} \quad (4)$$

Where $S$ represents the fiber backscattering factor. $v_{as}$ is the anti-Stokes Raman photon frequency. $R_{as}(T)$ is related to the energy layout of the molecules related to the Raman scattering of the optical fiber molecules, which can be calculated in Equation (5).

$$R_{as}(T) = \frac{1}{e^{\frac{E_{as}}{kT}} - 1} \quad (5)$$

From the Equation (2)-(5), it is deduced that,

$$\frac{N_s(T)}{N_s(T_0)} = \frac{K_s \cdot \left(\frac{v_s}{v_s}\right)^{\Delta v_s} \cdot e^{\frac{E_s}{kT}} \cdot e^{-\frac{\Delta v_s}{2}}}{K_s \cdot \left(\frac{v_s}{v_s}\right)^{\Delta v_s} \cdot e^{\frac{E_s}{kT_0}} \cdot e^{-\frac{\Delta v_s}{2}}}$$

(6)

For the condition of the baseline temperature $T_0$, it is deduced that,

$$\frac{N_s(T)}{N_s(T_0)} = \frac{K_s \cdot \left(\frac{v_s}{v_s}\right)^{\Delta v_s} \cdot e^{\frac{E_s}{kT}} \cdot e^{-\frac{\Delta v_s}{2}}}{K_s \cdot \left(\frac{v_s}{v_s}\right)^{\Delta v_s} \cdot e^{\frac{E_s}{kT_0}} \cdot e^{-\frac{\Delta v_s}{2}}}$$

(7)

So, when the fiber changes from the baseline temperature $T_0$ to the random temperature $T$, the relationship can be described as Equation (8) and (9). In this way, the temperature measurement formula based on the optical fiber can be obtained. We can get the temperature information of each position of the optical fiber.
Based on the temperature measurement formula of optical fiber, the optical fiber temperature measurement monitoring system is designed. The system mainly consists of the optical part (including the pulse drive power, laser emission, and wavelength division multiplexer), photoelectric detection, fiber sensor, signal acquisition, and processing part (including the signal amplification, analog-to-digital conversion, data acquisition, and processing).

As shown in Fig. 2, the fiber sensor is arranged along the superconducting cable. Firstly, a computer-controlled circuit sends out signals to start the pulse driving current source (laser diode, LD) and the semiconductor laser. The output pulses of LD pass through the wavelength division multiplexer. Then the laser is launched into the optical fiber. Depending on the situation of the measurement site, the Raman scattered light will be reflected along with the optical fiber carrying the real-time temperature information. The scattered light is collected by the avalanche photodiode (APD) and then converted to the electrical signals. To adapt to the condition of relatively weak Raman scattered light, an amplifier is designed to amplifying the signal. At last, the analog-to-digital converter converts the measurement result into a digital result by using the temperature demodulation process. The data acquisition and processing board includes the signal amplification, A/D conversion, digital signal processor, and other parts. The host provides a standard Ethernet interface, which can be easily networked with the monitoring system through the TCP/IP protocol for networked monitoring and management.

3. Conclusion
The 35 kV km-level domestic High-Temperature Superconducting Power Cable Project in Shanghai is the first superconducting cable project connecting two substations in the downtown region in China. This paper presents the temperature measurement formula and proposes a temperature monitoring system suitable for the 35 kV km-level domestic HTS-PC, which is based on optical fiber temperature measurement. The system mainly consists of the optical generation, photoelectric detection, fiber sensor,
signal acquisition, signal processing, and other components. The conclusion can be consulted in the operation of the high-temperature superconducting power cable project in the future.

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