Design of an online monitoring system for three-phase belted HTS cables

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Abstract. Three-phase belted High Temperature Superconductor (HTS) cables have compact dimensions and small inter-phase magnetic interference, and have been applied in the Demonstration Project of Domestic km-Level HTS Cable System of State Grid Corporation of China. The three cores of three-phase belted HTS cables are bundled together in the same low-temperature bellows, so a single-phase fault may cause the quench of other two phases, and even lead to an overall failure of the three-phase belted cable. Based on the cable body characteristics, cable termination characteristics, and cooling system characteristics of the three-phase belted HTS cables, the related online monitoring parameters and monitoring methods are proposed. The design of an online monitoring system for the three-phase belted HTS cables is introduced.

1. Introduction
In large cities of China, the power consumption has increased dramatically. However, conventional power cables and overhead lines are difficult to meet the increasing load demand. Therefore, superconductor cable technology has been widely studied. HTS cable has the advantages of large transmission capacity, low loss and little occupied space, which makes it a good choice for solving the problem of large power transmission. Compared to the single-phase independent HTS cable, the three-phase belted HTS cable binds the three cores together to share a low temperature environment, which saves space and materials. To this end, State Grid Corporation of China is implementing the demonstration project of its first km-level three-phase belted HTS cable in Shanghai.

Due to the high cost of HTS cable and its harsh operation conditions, it is necessary to monitor the entire system. The monitoring parts should include the cable body, the cooling system and the terminations of HTS cable. Monitoring technologies of superconducting cables have been widely studied in the United States, Europe, Japan and other countries [1-9]. Monitoring methods of the temperature, pressure, current and some other parameters of HTS cable have been addressed. However, most of the monitored HTS cables are operating in a relatively stable testing environment with limited length. In view of the actual operating environment of the first kilometre-level three-phase belted HTS cable in Shanghai, this paper selects relevant monitoring parameters and proposes the monitoring method of each parameter. Finally, the integrated monitoring scheme of each parameter constitutes an online monitoring system for three-phase belted HTS cable.
2. Selection of online monitoring parameters and motoring methods

The normal and stable operation of HTS cable needs to meet three conditions, which are critical current, critical temperature and critical magnetic field strength. The three conditions are related to each other and mutually constrained. When any one of the conditions is not met, it will cause the quench of HTS cable. It may further destroy the internal structure of the superconductor and burn the tapes [6]. Since the most applications of HTS cable are in demonstration projects, the online monitoring scheme of HTS cable is limited. In this paper, the parameters of online monitoring system are selected from the body characteristics, termination characteristics and cooling system characteristics of three-phase belted HTS cable, as shown in Figure 1.

![Figure 1: The selection of online monitoring parameters.](image)

2.1 Online monitoring parameters selected from the body of three-phase belted HTS cable

The structure of three-phase belted HTS cable is mainly composed of copper former, superconductor, electric insulation, electric shield, cryostat and outer sheath, as shown in Figure 3. For the body of three-phase belted HTS cable, this paper selects temperature, vacuum, vibration and partial discharge as the monitoring parameters.

2.1.1 Temperature

The superconducting state of the superconductor must be below the critical temperature. If the temperature of liquid nitrogen (LN2) is higher than the critical temperature, the HTS cable will be quenched. At the same time, the large current flowing through the superconductor generates a large amount of Joule heat and further increases the temperature of the operating environment of the HTS cable, which is bad for the operation of the HTS cable. In Figure 2, it can be seen that the flowing liquid nitrogen provides a low temperature environment for three-phase belted HTS cable, so we need to monitor the temperature of the liquid nitrogen.

Traditional temperature sensing technology mainly uses sensors such as thermocouples and thermal resistors which is based on electrical signals. These technologies are relatively mature and have the advantages of simple structure, high measurement accuracy and low cost. However, these technologies are susceptible to strong electromagnetic interference. And they are generally used for temperature measurements at a limited number of points. By contrast, distributed optical fibre temperature measurement technology enables continuous temperature field measurement along the fibre. This
technology breaks through the limitations of traditional single-point measurement mode and can monitor temperature of the entire cable lines \cite{7}. Therefore, this paper uses distributed optical fibre temperature measurement technology to monitor the temperature of three-phase belted HTS cable.

![Diagram of HTS Cable Body](image)

**Figure 2.** The body of three-phase belted HTS cable.

Based on distributed optical fibre temperature measurement technology, this paper proposes an online monitoring system, as shown in Figure 3. In the distributed optical fibre temperature measurement system, the fibre is used as both transmission medium and sensor. The system consists of optical components, signal acquisition and processing part. The sensing fibre is arranged along superconducting cable. The pulse driven by the computer control circuit can start the pulse driving current source and the laser diode (LD). Then the outputs of LD pass through the wavelength division multiplexer (WDM), emitted into the optical fibre. Next, the Raman scattered light which carries the real-time temperature information of the optical fibre will be reflected back along the optical fibre, and the scattered light is collected by a photodiode (APD) to realize photoelectric conversion. Because Raman scattered light is weak, its signals need to be amplified. Then the analog-to-digital converter (A/D converter) converts the measurement results into digital signals and then demodulates these digital signals into temperature. The host provides a standard Ethernet interface. It can be easily connected to the monitoring system through TCP/IP protocol for network monitoring and management. Figure 4 shows the location of optical fibre installation. The internal fibre measures the temperature of liquid nitrogen, and the external fibre measures the ambient temperature to monitor the leakage of liquid nitrogen.

### 2.1.2 Vacuum

From the structure of three-phase belted HTS cable, it can be seen that the cryostat composed of double-layer bellows plays the role of thermal insulation. It separates the superconductor from the external environment, making it difficult for external heat to enter. The degree of vacuum directly determines the effect of thermal insulation, so it must be monitored. The body of three-phase belted HTS cables is basically a complete closed environment, so it is mainly considered to install vacuum sensors at the terminations and joints of the cable to monitor the vacuum degree of cryostat.
2.1.3 Vibration

In large cities, the impact of the external environment on the HTS cable must be considered. Based on the installation path of Shanghai's first km-Level three-phase belted HTS cable, it is necessary to consider the vibration online monitoring of HTS cable. The source of vibration mainly includes subway vibration and external force damage. At present, research on the influence of vibration on HTS cable is limited, but vibration will affect the structure of HTS cable. Long-term vibration can make the HTS cable unbalanced, expanding the gap between the insulating papers to generate partial discharge. Abnormal situation such as external force damage is more harmful to HTS cable, and may even lead to the collapse of the entire system. Considering above situation, this paper proposes a vibration online monitoring system for three-phase belted HTS cable.

At present, the optical fibre vibration measurement technology has been developed relatively mature. The distributed optical fibre vibration system based on Sagnac interferometer has high sensitivity, but its sensing distance is short and its signal demodulation method is too complicated\[8\]. The system based on MZI has a simple structure, but it is susceptible to the external environment and the accuracy of location is not good enough\[9\]. The optical fibre vibration measurement technology based on Φ-OTDR has extremely high detection sensitivity and fast response speed. Additionally, it can monitor weak disturbance events and dynamic disturbance events\[10\]. Therefore, it is a good choice to monitor the vibration of HTS cable.

The vibration measurement scheme of HTS cable proposed in this paper is shown in Figure 5. The narrow linewidth laser emits continuous light. After passing through the polarization controller, the acousto-optic modulator driven by FPGA modulates light into pulsed light. Then the pulsed fibre amplifier amplifies the pulsed light. After passing through the filter, the probe light pulse is injected into the fibre through a circulator.

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Figure 3. The temperature online monitoring system of three-phase belted HTS cable.

Figure 4. Location of fibre installation.
The backward Rayleigh scattered light generated by the pulsed light in the fibre enters the photodetector after passing through the circulator. When the FPGA synchronously controls the acousto-optic modulator, the backscattered signal is synchronously acquired, and the collected data is transmitted to the upper computer. Finally, the data is demodulated by the upper computer to locate the vibration events.

2.1.4 Partial discharge
The electric insulation of the three-phase belted HTS cable may cause partial discharge due to its manufacturing process and aging. Long-term partial discharges can significantly degrade the performance of the insulating layer. The partial discharge monitoring is necessary.

The ultra-high frequency detection method converts the ultra-high frequency electromagnetic wave signal generated by the partial discharge into an electrical signal that can be processed and measured, and it is suitable for the detection of HTS cable’s body. The results of partial discharge online monitoring can be considered as an auxiliary judgment, as shown in Figure 6.

2.2 Online monitoring parameters selected from the terminations of three-phase belted HTS cable
The terminations of three-phase belted HTS cable are mainly composed of current lead, terminal thermostat, electric insulation and liquid nitrogen channel. The parameters monitored at the terminations are temperature, voltage, current and partial discharge.

2.2.1 Temperature
In terminations, one end of the current lead is connected to the power grid, and the other end is connected to the superconductor. The temperature difference between the ends is about 200 °C, so it can cause heat leakage. If the heat leakage cannot be taken away by the liquid nitrogen in time, it can further lead to the failure of the HTS cable. Therefore, temperature sensors should be considered to monitor the temperature of the current lead. If the temperature is too high, an alarm should be issued.
2.2.2 Voltage and current
HTS cable has a rated voltage and current, and they should be monitored. The voltage can be taken from the substation bus and the current can be monitored with current sensors.

2.2.3 Partial discharge
At the termination, the current lead is connected to the superconductor and there is corresponding electric insulation at the connected locations. The insulation of terminations may age during the long-term operation, which may cause partial discharge of three-phase belted HTS cable. The long-term partial discharge may have a serious impact on the whole cooling system, so it should be monitored. The joints of three-phase belted HTS cable also have the same problem.

The ultrasonic detection method is almost free from external electromagnetic interference, and can perform charging detection. It is suitable for the joints and the joints’ adjacent position of three-phase belted HTS cable, as shown in Figure 7.

Figure 7. The ultrasonic detection system for terminations and joints of three-phase belted HTS cable.

2.3 Online monitoring parameters selected from the cooling system of three-phase belted HTS cable
The cooling system of the three-phase belted HTS cable is mainly composed of a liquid nitrogen tank, a refrigerator, a liquid nitrogen pump, etc. It provides a low temperature environment for the operation of the three-phase belted HTS cable. For the cooling system, the main monitored parameters are pressure, flow, and level.

2.3.1 Liquid nitrogen pressure
The liquid nitrogen pump provides power for the circulation of liquid nitrogen, forming a certain pressure difference at the two terminations. Therefore, the pressure of liquid nitrogen should be monitored at both terminations. If the pressure difference is too small, it should be checked whether or not the working state of the liquid nitrogen pump is normal.

2.3.2 Liquid nitrogen flow
The liquid nitrogen circulates the AC loss and the leaking heat generated by the three-phase belted HTS cable, and then the heat is absorbed by the refrigerator and released to the outside. The longer the length of the HTS cable and the higher the rated current, the greater the flow of liquid nitrogen required per unit time. Insufficient flow will cause the heat generated by the three-phase belted HTS cable not to be released in time, resulting in a cooling failure. Therefore, flow meters should be installed at the inlet and outlet of liquid nitrogen channels to monitor the flow rate of liquid nitrogen.

2.3.3 Liquid nitrogen level
Liquid nitrogen tank is an essential part of the cooling system which stores liquid nitrogen. Sufficient liquid nitrogen reserve can guarantee the low temperature environment of the three-phase belted HTS cable, allowing the HTS cable to operate for a short period of time even in the event of a small leak. In the liquid nitrogen tank, a level sensor should be provided to monitor the liquid level. If the liquid level is too low, it may reflect problems such as damage to the liquid nitrogen pipeline and the cooling system should be checked at this time.
3. Construction of the overall online monitoring system

Considering the monitoring parameters discussed above, an online monitoring system for three-phase belted HTS cables is designed, as shown in Figure 8. Infrared camera method can monitor key parts of three-phase belted HTS cable. The distributed optical fibre temperature measurement method monitors the temperature of the entire liquid nitrogen and the external environment of three-phase belted HTS cable, and the optical fibre vibration measurement method monitors the external vibration of the three-phase belted HTS cable. In this system, these different data are collected and processed and then aggregated to the host. Based on these data, the operating state of the three-phase belted HTS cable can be judged.

![Diagram of the overall online monitoring system of three-phase belted HTS cable.](image)

Figure 8. The overall online monitoring system of three-phase belted HTS cable.

4. Conclusion

The relevant online monitoring parameters are chosen from the characteristics of three-phase belted HTS cables. An online monitoring system is proposed.

The operation of three-phase belted HTS cable must meet the critical temperature conditions. A temperature online monitoring system of three-phase belted HTS cable based on distributed fibre temperature measurement is proposed.

The external vibration or external damage can seriously affect the operation of HTS cable. A vibration online monitoring system of three-phase belted HTS cable based on distributed optical fibre vibration measurement is proposed.

Partial discharge is a great hazard to HTS cable. A partial discharge online monitoring system for the three-phase belted HTS cable is proposed.

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