Design, Manufacture, and Test of a 30 m 10 kV/2.5 kA Concentric HTS Cable Prototype for Urban Grid

BANGZHU WANG1, XIAOCHEN WU2, HONG XIE2, ZHINING LV2, ZHENZI WANG2, MENG SONG3, YONG HUANG4, YAJUN XIA3, ZHE WANG2, TENGBIAO CHEN2, BO TIAN4, AND SHAOTAO DAI1

1School of Electrical Engineering, Beijing Jiaotong University, Beijing 100044, China
2Shenzhen Power Supply Bureau Company Ltd., Shenzhen 518048, China
3Joint Laboratory on Power Superconducting Technology, China Southern Power Grid Company Ltd., Dongguan 523290, China
4ZTT Superconducting Technology Company Ltd., Shanghai 201108, China

Corresponding author: Shaotao Dai (stdai@bjtu.edu.cn)

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ABSTRACT High temperature superconducting (HTS) cable, with significant low dissipation and massive current carrying capability, is a promising solution for the shortage of transmission capacity in mega-cities. China Southern Grid launched a HTS cable project in 2017 to develop a medium voltage concentric HTS cable system for installation in the distribution grid at urban area in Shenzhen City. It is the first time that concentric HTS cable system is developed and will be the first HTS cable installed in urban grid in China. The cable core mainly consists of three concentric phases winded by YBCO tapes and cold dielectric insulations in between phase-to-phase, phase-to-former, and phase-to-screen. The cable has a rated voltage of 10 kV and a rated current of 2.5 kA. The critical current ($I_c$) is at least 6 kA per phase. The outer diameter of the cable core is 76 mm and the cryogenic pipe is 175 mm. As a middle step, we designed and manufactured a 30 m long prototype cable system and it was tested generally according to IEC 63075. For improvement of the manufacture processes, several short cable core samples were made, tested, and dismantled. The ultimate goal of the 30 m prototype is to verify the design and accumulate experience for the installation of the 400 m fully functional cable system in the grid. The test results of the 30 m cable prototype are presented and discussed. The 400 m class HTS concentric cable demonstration project has already started and it is expected to energize in grid in late September, 2021.

INDEX TERMS Concentric cable structure, urban distribution grid, HTS cable design, type test.

I. INTRODUCTION High temperature superconducting (HTS) cable technology is at the cutting edge of power transmission sector. HTS cables’ current density is 3-5 times higher than the conventional ones that they would replace and they could provide a package solution for the power grids by their merits of massive power capacity, energy efficiency, compact corridor, and environment friendliness. The advantages are more prominent in urban area application, where duct banks are nearly fully utilized and civil constructions are difficult to conduct. Several HTS cable transmission projects have demonstrated their feasibility and necessity in the last two decades [1]–[3].

China was once and is still one of the key players in HTS cable research and development. Four HTS cable programs had been carried out in Kunming, Baiyin, Gongyi, and Shanghai [4]–[7]. From 2017 on, a key R&D program on HTS power transmission in urban distribution grid supported by China Southern Grid was conducted. The program focuses on the feasibility and practical operation of HTS cables in urban area to mitigate the challenges of more power capacity within a smaller corridor. It also explores the upgradation feasibility of urban distribution network by HTS cables. The demonstration site was selected at Shenzhen, a modern and innovative mega-city at coastal of Guangdong Province in South China. The HTS cable will be installed in Futian Distinct, connecting the 10 kV bus in 220 kV Binhe substation and 110 kV Xinghe substation. The cable total length is about 400 m and the
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FIGURE 1. Schematic structure of concentric HTS cable core.

rated current is 2500 Arms. Considering the compactness requirements and layout conditions, concentric type structure was adopted. Shenzhen Grid, the owner, expects that the HTS cable can be both a demonstration one and an industrial one. Operation-like-a-conventional-one became one of the R&D goals.

It is worth noting that this is the first concentric HTS cable project in China. The main materials of the cable are produced in China mainland. The HTS tape winding line, insulation paper wrapping line, cryogenic pipe welding and forming line, and other key production equipment are developed by the project team.

This paper is organized as follows: Firstly, the detailed design scheme of the concentric HTS cable core, termination, and other important components is presented. Secondly, the manufacture process and key points of the HTS cable prototype is introduced. Thirdly, the type test methods and results of the 30 m HTS cable prototype system is discussed. The subsequent work of the project is prospected.

II. CABLE DESIGN

The structure of the concentric HTS cable core is shown in Fig.1 in an axisymmetric way. It is a typical multilayer combined structure.

The concentric cable core mainly consists of hollow former, cushion layer, HTS phase conductor layers, electrical insulation layers, screen layers, and protecting layer. The former uses corrugated stainless steel pipe, which also serves as a flow path for the cryogen [8]. Table 1. describes the specifications in details.

A. HTS PHASE CONDUCTOR LAYERS

The three concentric HTS phase conductor layers are winded by YBCO superconducting tapes. Each phase has two HTS tape layers with opposite winding direction (‘s’ vs. ‘z’) to achieve the critical current required. The winding pitches of each phase are optimized based on inductance balance, mechanical bending characteristics, and cost-effectiveness [9], [10]. The two layers’ winding pitches in the same phase are nearly identical. This configuration not only essentially eliminates the hoop direction component of the magnetic field of each phase as a whole, but also improves the mechanical fixation performance of the two adjacent layers.

The YBCO tapes are produced by Shanghai Superconductor Co., Ltd. The tape’s main specifications are listed in Table 2. In order to obtain a improved fault current tolerance capability, we choose the thick HTS tape, which has two 180 µm reinforcing copper layers, one on each side of the superconducting layer.

We tested the $I_c$ characteristics of this type HTS tape at different magnetic field amplitudes and angles under 77.3 K and self field condition, which serves as the basis for the design and calibration of current carrying capability of the superconducting layers.

The rated current of the HTS cable is 2.5 kA rms. So the direct current (DC) $I_c$ should be at least $\sqrt{2} \times 2.5 \approx 3.6$ kA to ensure that at any time under normal operation the HTS cable is in superconducting state. However, the power grid may encounter various transient conditions. We consider a current fluctuations factor $k_1 \approx 1.2$ mainly for possible system overload operation. A certain engineering margin factor $k_2 \approx 1.4$ for system safety is also considered. So we design the DC $I_c$ of each superconducting phase to be at least $k_1 \times k_2 \times 2.5 \approx 6$ kA (77 K at self field). Thus, the number of tapes for phase A, B, and C are determined, which is 60, 64, and 68, respectively.

B. INSULATION

The concentric HTS cable core has three high voltage (HV) phase and two grounding layers, which makes its electric field complex. There are insulation layers between two adjacent conducting phases, phase A to former, and phase C to screen layer. Insulation layers consist of polypropylene laminated...
paper (PPLP), which has good mechanical and electrical performance at liquid nitrogen (LN2) environment. PPLP is the most used insulation material in HTS cable fabrication.

According to the structure of concentric cable core, we can consider each insulation layer as a ring from the cross-section view. If we ignore the end effects, then we know that the maximum electric field appears on the inner surface of each insulation layer

$$E_{\text{max}} = \frac{U_0}{r_o \cdot \ln(r_o/r_i)}.$$  \hspace{1cm} (1)

where $U_0$ is the applied voltage, which may be the operation voltage or testing voltage. $r_o$ and $r_i$ are the inner and outer radii of the insulation ring, respectively.

The maximum electric field in the insulation, $E_{\text{max}}$, should not exceed the permissible value of the insulation structure. As for HTS cable insulation, the insulation is PPLP-LN2 composite structure in nature. HV experimental tests [11] show that the PPLP’s lightning breakdown strength is 67.6 kV/mm (Weibull 0.1% possibility) and AC breakdown strength is 28.6 kV/mm (Weibull 0.1% possibility) in 77.3 K LN2 under 0.1 MPa. According to some studies, the voltage withstanding capability of PPLP-LN2 structure will increase in lower temperature LN2 and/or higher operation pressure. To ensure the insulation operation safety, we use the 77.3 K and 0.1 MPa values.

In our design, $U_0$ used are standard voltages for type test. For 10 kV concentric HTS cable, AC withstand test voltages are not same for the three phases as the insulation A-B and insulation B-C withstand line voltage, which is $\sqrt{3}$ times phase voltage. It is 15 kV@30 min for phase A and C and $\sqrt{3} \times 15$ kV@30 min for phase B. The lightning withstanding test standard for the three phases are same, which requires 10 times positive polarity 75 kV standard lightning test and 10 times negative polarity 75 kV standard lightning test.

Based on the test voltages of each insulation we can determine the minimal thickness needed of each insulation layers by

$$\Delta = r_o - r_i = r_i \cdot \left(\frac{U_0}{E_{\text{max}}} - 1\right).$$  \hspace{1cm} (2)

where $\Delta$ is the minimal thickness requirement of the insulation layer.

We have noticed that some designs have no insulation between phase A and former [12]–[14]. In that case, the former will have same electric potential with phase A. The former in the concentric configuration is a cryogen flow channel as well and if it is not insulated, the terminal would be in high voltage or the inflow pipe inside the terminal would require insulated interconnection. We insulated phase A from the former so that the former could be connected directly to the cryogenic system piping and the termination shell could earthing directly for protective purpose.

We also use five layers of PPLP outside the screen layer to isolate the screen layer and inner cryogenic pipe. As when system faults, especially asymmetric faults, occur in the HTS cable, the screen layer will have a large induced voltage and the voltage may result in discharge from the screen layer to the cryostat, which may cause safety hazards.

Safety margins for insulation must be taken into account as well according to the power cable industry’s practice. And standardization of the manufacturing process also needs to be considered. Finally, we determined the insulation layers’ thickness are 2 mm for phase voltage and 2.5 mm for line voltage, respectively.

C. OTHER CONSIDERATIONS

1) SEMICONDUCTING LAYERS

In conjunction with every insulation layers, semiconducting carbon paper layers are employed. The geometry of conducting layers are not smooth as HTS tapes have a large width-to-thickness ratio and certain rigidity, which leads to non-uniform electric field distribution in insulation. They are subjected to tip discharges, air gap discharges, and other forms of partial discharges (PD) and/or penetrating discharges. Semiconducting carbon layers will provide the conducting layers a relatively smooth surface and the electric fields are homogenized.

In Fig.1, the black layers adjacent to insulation layers are semiconducting layers.

2) CUSHION LAYER

The function of cushion layer is to smooth out the surface of the former as the former is corrugated pipe. Thus, the electric field of phase A to former could be more symmetrical. Cushion layer consists of copper tapes, which is 4.8 mm $\times$ 0.4 mm. The tapes winding method is same with the HTS tapes. In addition, the cushion layer also helps to reduce the folds formation possibility in A-f insulation, that is why we call it cushion layer.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{Normalized $I_c$ as a function of the magnitude and angle of the applied magnetic field.}
\end{figure}
3) PROTECTING LAYER
The outermost layer is the protecting layer, which is made of glass fiber cloth. The protecting layer serves to fasten and protect the cable core. During transportation and laying, etc., the cable core may have relative displacement inside the cryostat and the protecting layer could prevent the cable core from being scratched or other damages.

The diameter of the cable core, namely the outer diameter of the protecting layer, is about 76 mm.

D. SCREEN LAYER GROUNDING
The concentric HTS cable has zero external magnetic field outside the cable core, under ideal conditions of complete symmetry of the three phases. However, in practice, differences in electrical parameters of the three phases, unbalance of the three phase load, asymmetric short faults, and other likely conditions can cause the external magnetic field to be non-zero. Therefore, induced voltage at the screen layer is generated.

Double-ended grounding method can play a certain role in magnetic shielding. But the shielding current will produce Joule heat loss as the screen is composed of copper tapes. The heat will increase the load of the refrigeration system and reduce the energy efficiency of the HTS cable system. More seriously, because the HTS cable is installed between two substations, the fault current of other equipment or circuits in the substation is also possible to pass through the screen layer as this path in LN2 has lower resistance. In this condition, the large fault current may cause fatal damage to HTS cable system and so the situation must be avoided although unlikely to occur.

Considering the above factors, the single-ended grounding method was chosen.

E. FAULT CURRENT ENDURANCE
The resistance response of YBCO tape under AC fault current is shown in Fig. 3. The HTS tape appears resistance for a very short time and grows rapidly. After around 0.01 s, the HTS tape is quenched totally and the resistance depends on the conventional conductor in the tape.

According to the fault duration <1 s and refrigeration capacity of ~5 kW, the heat transfer from HTS tapes to other layers can be modeled as approximately adiabatic process. In other words, we assume that the heat generated only make the temperature rise of HTS tapes in the fault cases. The heat introduced by fault will eventually lead to temperature rise of the cable core and LN2. If heat is generated enough, it would vaporize the LN2 and then increase the pressure inside the cryostat. Once the relief valves act, the system must stop service for safety reasons. We take this as a criterion for the allowable heat generation of the cable.

In our design, the cryogenic pipe is filled with 70-72 K subcooled LN2 and the relief pressure is set to be 0.8 MPa, where the boiling temperature of LN2 is about 100 K. Based on the assumptions, the permissible cumulative heat generation \(Q_{\text{max}}\) by the HTS cable under three phases fault current is 4.9 kJ/m/phase.

According to the prediction of the power system that the cable will be installed, the maximum three phases fault current consisted of a periodic component 23.424 kArms and a non-periodic component 33.127 kA with a delay time constant of 0.161 s. The expected maximum fault waveform is shown in Fig. 4. Fault currents may be smaller due to the specific situation, but the waveform is similar.

The relationship between heat per length and fault duration for the HTS cable at different fault currents is shown in Fig. 5. Only the conditions below the maximum permissible heat line are allowed.

Using \(Q_{\text{max}}\) as the boundary condition, the permissible duration of the HTS cable under different fault currents can be obtained as shown in Fig. 6. The duration and amplitude pairs under the curve are safe for the system. The protection system has to cut the specific fault current within the time required by the curve.

III. TERMINATION AND CYOGENIC PIPE DESIGN
The HTS cable termination is the connection of the HTS cable to the grid or to the terminal of other equipment such as superconducting fault current limiter (SFCL). Basically, the cable termination consists of three main components, which are the
terminal cryostat, the current lead, and the high voltage (HV) bushing. The termination is also the lead interfaces of various types of measurement, such as temperature, pressure, and flow rate. In addition, HTS cable strain relief expansion joints are also assembled at the terminations.

Generally, the termination should provide electric connection, cryogen connection, dielectric integrity and thermal management.

A. TERMINAL CRYOSTAT

The terminal cryostat first should meet the general technical requirements of cryostat, such as mechanical strength, high pressure, vacuum degree, and temperature induced expansion/shrinkage.

In HTS cable terminal cryostat, the dielectric integrity is challenging as three phase conductors and screen conductor are all connected inside and the electric field is much more complex than in the cable body. The electrical clearance between the live parts of the cable terminal and cryostat inner wall should withstand the toughest working conditions of the system.

Careful thermal management is also critical for the cryostat because the termination cryostat is one of the largest heat sources, which may easily cause local hot spot and affect the cryogen flow stability and dielectric integrity of the system. Generally, multilayer insulation (MLI, also known as superinsulation) is used in the cryostat. MLI prevents gas heat flow by evacuating the insulated space to a residual gas pressure of less than 1 Pa, avoid solid heat bridges as much as possible by discrete supports, and counteract radiation losses by installing highly reflective metal foils [15].

As almost all the measurement signals are led at the terminal, the cryostat must provide a suitable interface (vacuum crossing, sealing, shielding, etc) for the signals and take the signal integrity into account.

B. CURRENT LEAD

The HTS tapes in every phase are welded together at the end and connected to copper conductor, which is also known as current lead.

The current lead has two main heat loss, one is electric loss in compliance with Joule’s law and the other is heat conduction loss following Fourier’s law. Optimal approach is employed to determine the ratio of cross-section area and length of the current lead to minimize the total heat loss of Joule loss and Fourier loss. The optimal ratio formula given in [16] is as follow

$$\frac{L}{A}_{\text{op}} = \frac{1}{I} \frac{k_a}{L_a} \cos^{-1} \left( \frac{T_L}{T_H} \right).$$  \hspace{1cm} (3)

where $T_H$ and $T_L$ are the temperature at the ambient and LN2, respectively. $k_a$ and $L_a$ are average thermal conductivity and average Lorentz constant.

For oxygen free copper (purity of 99.99%) in the temperature range of LN2 and ambient, $k_a = 436 \text{ W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$ and $L_a = 2.17 \times 10^{-8} \text{ W} \cdot \Omega \cdot \text{K}^{-2}$.

With the optimal ratio of cross-section area and length of the current lead, the minimal total heat loss is given by

$$Q_{\text{min}} = I \cdot \sqrt{L_a (T_H^2 - T_L^2)}.$$

If we simply take $T_H = 300 \text{ K}$ and $T_L = 77 \text{ K}$, we can get the total loss per unit current

$$Q_{\text{min, per}} = 42.7 \text{ W/kA}.\hspace{1cm} (5)$$

where the optimal ratio $L/A_{\text{op}} = 1552 \text{ mm}^2$.

As the rated current of the HTS cable is 2500 Arms, a cross-sectional area of 600 mm$^2$ at least is needed. So the optimal lead length is 0.93 m.

Skin effect under AC condition should be considered. For $f = 50 \text{ Hz}$, the skin depth $\delta = \sqrt{\rho/(\pi f \mu)} \simeq 8 \text{ mm}$. That is, if copper rods are used as current leads, the skin effect will be remarkable when the rod radius is greater than 8 mm (the corresponding cross section is around 200 mm$^2$). For this reason, we choose multifilament copper flexible wires
bundle as current leads to avoid skin effect and to reduce the appearance cross-section of the lead. At the same time, the flexible leads could facilitate the connection assembly with HTS cable as well.

It is worth pointing out that the engineering design should take the coordination between components into account. For current leads, the length needs to match with the bushing and terminal cryostat. In general, the final design is a set of values close to, but not exactly equal to, the optimized values. Table 3 describes the specifications in details.

### C. HV BUSHING

HV bushing serves to insulate lead that are carrying HV current through the grounded terminal cryostat. The HV bushing in the termination should not only control electric stress, but also endure the cryogenic temperature and the high range temperature gradient condition. Thus, a special condenser type bushing was selected. It uses resin impregnated fiberglass (RIFG) as the main insulation, which has good thermal and mechanical performance in both ambient and LN2 temperature.

We noticed that the support metal tube (made of copper or aluminum) that traditional bushings used between the bushing and the current lead rod generally has different thermal expansion coefficient from RIFG, which would cause thermal stress in between the two parts when temperature changes in a large range and may eventually lead to degradation or destruction of insulation performance. For the reasons above, we adopted a no-tube-supporting scheme in which the support tube was pulled out during the curing of the RIFG. To eliminate the undesired discharge behavior of the current lead inside, we shorted the innermost capacitive screen with the lead at the ambient end so that the innermost capacitive screen could act as an electrical shield for the current lead. The designed HV bushing is shown as Fig. 7.

To verify the HV bushing design, we conducted a series of tests. The performance under LN2-to-ambient thermal cyclic shock was focused. We submerged the HV bushing into LN2 to cool it down rapidly and let it stay for 15 min at least until it was completely cold, then pulled it out and warmed it up to room temperature (see Fig. 8). We did that for 5 cycles and after each cycle, the capacitance and partial discharge were measured. No significant changes in the measured values were found, which means that our design is suitable for HTS cable operating conditions.

### D. TERMINATION DESIGN AND REMARKS

The termination final design is shown as Fig. 9. From left to right, the four leads are for screen layer, phase C, phase B, and phase A, respectively.

As the cable system use the counterflow cooling scheme, in which the inflow passes through the former and the outflow through the space between the cable core and the inner cryostat pipe, two types of terminations are needed. The figure gives the type near the cooling system end (Type A). The far end type termination basically is same with the near end one, but it does not have LN2 inlet and outlet and auxiliary measuring devices (Type B). In the Type B termination cryostat, the cryogen flows out of the inner pipe and then bends back into the outer flow channel.

1) SCREEN LEAD AND BUSHING

Although the screen layer lead does not have as same high voltage as the phase lead, we still design it to be the same specification as the HTS conducting phases. This design, which reduce different types of system components, could bring great convenience for manufacturing and assembling, both technically and economically. Noteworthy, the screen layer lead’s cross-section area is not 600 mm$^2$ but 80 mm$^2$, same as the screen copper layers total cross-section area.

2) HEAT LOSS ESTIMATION

In the termination, the heat loss is mainly consisted of 1) cryostat’s heat loss, 2) current leads’ conduction heat loss, and 3) current leads’ Joule heat loss. The first two makes the static heat loss, which is about 210 W under LN2 temperature and independent of applied current. When rated current of 2.5 kA is applied, the Joule heat loss is about 170 W. This analytical estimation should add a safe margin to determine the cryogenic system’s capacity, so a margin factor 1.2 is adopted based on our working experience. Thus, we take 450 W$(=210 + 170) \times 1.2$ as the design heat loss of one termination at rated condition (rated current applied and LN2 temperature).
FIGURE 9. Termination for the concentric HTS cable.

FIGURE 10. Structure of the cryogenic pipes.

E. CRYOGENIC PIPE DESIGN

The structure of the cryogenic pipes is shown in Fig. 10. Based on the dimension of HTS cable core, we design the inner pipe to be DN110 and the outer one DN170, which are corrugated and made of stainless steel 304L. MLI technique is used to achieve a good thermal performance. The outermost sheath is extruded Polyvinyl Chloride (PVC). The specifications of the design (such as corrugated height and pitch) are listed in Table 4.

1) HEAT LOSS MEASUREMENT

The measured heat loss of a 30 m cryostat pipe sample by calorimetric method was less than 2 W/m when the inner pipe was fulfilled with LN2 and the interpipe vacuum level is at $1 \times 10^{-3}$ Pa.

2) CRYOGEN LOSS ESTIMATION

We use Darcy-Weisbach formula to compute the pressure drop per unit length of the cryogen in the pipe

$$\frac{\Delta p}{L} = f \cdot \frac{1}{D_h} \cdot \frac{\rho}{2} \cdot v^2. \tag{6}$$

where $\Delta p$ is the pressure drop, $L$ is the pipe length, $D_h$ is the hydraulic diameter of the pipe, $\rho$ is the density of the cryogen, $f$ is the friction factor, and $v$ is cryogen’s velocity.

Practically, the hydraulic diameter is defined as

$$D_h = \frac{4A}{P}. \tag{7}$$

where $A$ is the wetting area and $P$ is the wetting perimeter of the channel.

The friction factor is related to Reynolds number, which is defined as

$$Re = \frac{\rho v D_h}{\mu}. \tag{8}$$

where $\mu$ is dynamic viscosity of the cryogen. For different Re, the calculation method differs. Manadilli equation [17] is valid for $Re = 4000 - 5 \times 10^8$ and $\epsilon/D_h = 0 - 0.05$, where $\epsilon$ is the roughness of the channel wall.

$$\frac{1}{\sqrt{f}} = -2 \log\left(\frac{\epsilon}{D_h} \cdot 3.7 + \frac{95}{Re^{0.393}} - 96.82 \cdot \frac{96.82}{Re}\right). \tag{9}$$

Because we adopt the counterflow cooling method, the total circulation loss of the cryogen is the sum of inflow and outflow. We use the cryogen’s physical property at 77.3 K and 0.1 MPa and disregard their variation with temperature. However, the analytical method do not take some practical conditions such as channel bending and cable core’s nonstraightness, which will lead to underestimate the pressure drop. We multiply the calculated value by a factor for correction. The pressure drop is shown in Fig. 11.

Take flow rate 0.35 kg/s (rated value for the 400 m HTS cable) and correction factor 1.2 for example. The cryogen circulation pressure drop of a 400 m cable is 0.31 MPa in total, which means for the 400 m HTS cable, using counterflow cooling method, the inflow pressure should be at least 0.5 MPa.

IV. PROTOTYPE FABRICATION AND TESTING

A. FABRICATION, TEST, AND DISMANTLE OF SHORT CABLE CORE SAMPLES

In order to verify the validity of cable design and to explore the optimized manufacturing process, short cable core samples were made. Among them, 2 samples were fabricated to evaluate the current-carrying capability. And several dumb cable cores were fabricated for insulation performance verification and optimization of the HTS cable winding process. In the so called dumb cable cores, the HTS tapes were replaced by copper tapes with same cross-section and nearly identical rigidity to simulate the same geometry characteristics (thus same electric field profile) and comparable mechanical properties.

The HTS cable product line for the manufacture of the cable core samples is shown in Fig. 12, which is located at
ZTT Superconducting Technology Co., Ltd., Shanghai. The product line can be automated to complete the tapes winding and paper wrapping. The tension and pitch of every tape and paper can be controlled individually and/or coordinately.

Our fabrication, test, and dismantle practice shows that one of the most important key processes for the manufacturing and fabrication of HTS cable cores is the quality control of the semiconducting and insulation layers.

The semiconducting layer of our design consists of two layers of carbon paper tapes. Each layer is wrapped with gaps and the gaps between the upper and lower layers should be exactly staggered, as shown in Fig. 13.

However, during the bending process, the gaps do not move synchronously and after bending, the gaps in the two layers may overlap. Moreover, the HTS/copper tape joints may pierce the semiconducting layer as the semiconducting layer is adjacent to conducting/screen layers. Fig. 14 shows the main defects found in carbon semiconducting paper layers. Both of these defects will cause the semiconducting layer to lose its electric field shielding function and cause local electric field concentration, which will result in partial discharge, air gap discharge, and other forms of discharges.

So the critical practices are to avoid overlap of the two layers under bending and other mechanical conditions. The width of the semiconducting paper should match the winding radius where it is located and the bending radius of the cable core as well. The smoothness of the HTS or copper tapes and tapes’ joints must be checked carefully prior to use. And we also made a requirement that no disintegrate should occur under twisting and bending for tapes joints.

As the insulation is much thicker than semiconducting layers, the bending induced folds (as in Fig. 15) becomes particularly important because it can seriously impact on insulation performance. The requirements of gap between adjacent layers of insulation and paper tape width are identical to the rules of semiconducting layers. Besides, the wrapping tension of the insulating paper and tension matching relationship of each layer are key factors in whether or not folds are produced during bending procedure.

As bending performance is the most important mechanical features of the HTS cable core, we designed a device for cable
bending tests as shown in Fig. 16. The allowable bending radius is adjustable by changing the mounting position of the support rollers. It can be used for evaluating the minimum bending radius of the cable core or cable. According to the code, the cable should be bent at ambient temperature for three cycles of wound and unwound operation. After one bending operation, the HTS cable core should be straightened to relieve the internal stress. Through several trials, for the designed cable, the bending radius is set to be 2 m.

Based on the accumulated experimental results and process experience from manufacture, test, and dismantle of short cable samples, we fabricated a 5 m HTS cable core. From April 13 to 17, 2020, it was tested successively with $I_c$ measurement, electrical parameters measurement (capacitance, inductance, tanδ, etc.), AC withstanding voltage test, lightning withstanding voltage test, and rated three phase current carrying test according to our design requirements. The testing results met the theoretical expectations. The quality of the 5 m prototype was confirmed and the design and manufacture process were verified.

**B. 30 M CABLE SYSTEM FABRICATION**

The parameters and manufacture process of the cable core of the 30 m prototype system have nothing different with the final 5 m cable core tested.

The cable core was pulled into the cryostat pipe and then the terminals of the cable core were made. The terminal treatment mainly includes stripping the insulation layers to expose the conductors, soldering the conductors with the hoops, and making stress cones, etc. One stress cone and terminal hoop is shown in Fig. 17. The terminal hoop and the current lead are connected via a Ω-shaped connector. To reduce contact resistance, the surface of the hoop is silver-plated.

The cable and the terminations were transferred to the testing site—Joint Laboratory on Power Superconducting Technology of China Southern Grid, located in Dongguan, Guangdong Province. The system integration is operated in the field. And the layout of the cable system is shown as in Fig. 18.

The subcooled cryogenic environment for the 30 m prototype cable system was provided by the Laboratory.

**C. TYPE TEST OF THE 30 M CABLE SYSTEM PROTOTYPE**

Electric type test is to demonstrate satisfactory performance characteristics to meet the intended application. The test standards are the most toughest and if and only if the HTS cable system prototype passes the type test, the long system with the same parameters can be supplied and applied to the demonstration project.

The type test requirements are generally based on the guideline of IEC 63075 [18] and Chinese national standards (only when there exists conflicting regulations). The test items and requirements are summarized as Table. 5. In the table, $T_{am}$ indicates the temperature of ambient, which is around 300 K.

1) **VACUUM LEAK TEST**

The vacuum leak of the cable system is tested by Helium mass spectrometer. The vacuum leak rate at the two terminations and cryostat pipe is $3.39 \times 10^{-10}$ Pa·m$^3$·m$^{-1}$, $3.35 \times 10^{-10}$ Pa·m$^3$·m$^{-1}$, and $3.46 \times 10^{-10}$ Pa·m$^3$·m$^{-1}$, respectively. They all meet and better than the requirement, which is $\leq 2 \times 10^{-7}$ Pa·m$^3$·m$^{-1}$.

2) **PRESSURE TEST**

In the pressure test, we use a pressurized gaseous nitrogen tank as the pressure source. The test pressure increased from 1 atmospheric pressure in steps of 0.05 MPa to 0.55 MPa by controlling the valve. Compared to the required holding time of 10 min, we held this pressure for 16 h and no significant pressure drop and/or other abnormalities were observed. We extended the pressure holding time mainly because the pressure performance is closely related to the system safety.
TABLE 5. Type test items and their requirements.

| No. | Items                   | Requirements                                                                 |
|-----|-------------------------|------------------------------------------------------------------------------|
| 1   | Vacuum leak test        | No greater than $2 \times 10^{-2}$ Pa·m⁻¹·m⁻¹ at terminations and cryostat pipe. |
| 2   | Pressure test           | Test pressure is 0.55 MPa at $T_{	ext{sim}}$, using gap. The pressure increased in 0.05 MPa steps and held every step for 2 min until 0.55 MPa is reached. When 0.55 MPa is reached the pressure source shall be disconnected. After 10 min the pressure shall not be less than 0.55 MPa. |
| 3   | $I_c$ measurement      | $I_c$ per phase should be at least 6 kA after the value converted to 77.3 K and 0.1 MPa if it is not measured at this condition. The criteria is 1 μV/cm and the voltage of the conventional part should be subtracted. 5 cycles are required. Each cycle consists of cooling down from $T_{	ext{sim}}$ to 74 K and followed warming up the system to $T_{	ext{sim}}$. Temperature and pressure should not experience large fluctuations and no abnormal conditions such as (rupture, abnormal deformation) should be observed. |
| 4   | Thermal cycle test      | Sensitivity being 5 pc or better. The test voltage is 10 kV for phase A and C while $10\sqrt{3}$ kV for phase B. Detected partial discharge should not be greater than the sensitivity. |
| 5   | Partial discharge test  | Before voltage withstanding tests, the background PD was about 30 pC. And after the lightning impulse voltage test and power frequency voltage test, the background PD became about 15 pC. The measured PD were no higher than the corresponding phase’s background PD. From the PD ellipsogram, no obvious discharge signals were recognized. Based on the special characteristics of the composite insulation structure of LN2-PPLP, we believe that the measured partial discharges of the three phases indicate that there are no significant changes or defects in the insulation structures that could cause degradation of damage of the cable system’s high voltage performance. |
| 6   | tanδ measurement        | No greater than 0.5% at 10 kV for every insulation layer. |
| 7   | Load cycle voltage test | 20 cycles are required. Each cycle consists of 8 h with 2.5 kArms current followed by 16 h without current in the phase conductor. The phase currents shall exhibit a phase difference of about 120 degree. During the whole duration of the test period, three phase 12 kV shall be applied to the cable system. |
| 8   | Lightning impulse voltage test | 10 positive and 10 negative standard lightning impulse voltage of 75 kV for every phase. No failure or flashover should be observed. 15 kV@30 min for phase A and C while $15\sqrt{3}$ kV@30 min for phase B. No failure or flashover should be observed. |
| 9   | Power frequency voltage test | 10 positive and 10 negative standard lightning impulse voltage of 75 kV for every phase. No failure or flashover should be observed. 15 kV@30 min for phase A and C while $15\sqrt{3}$ kV@30 min for phase B. No failure or flashover should be observed. |
| 10  | Partial discharge test  | Same with No. 5. |

3) CRITICAL CURRENT MEASUREMENT

Critical currents of the cable prototype were measured at about 74 K. The measured results of the three phases are shown in Fig. 19.

As 74 K is close to 77.3 K enough, we converted $I_c$ to 77.3 K using a simple linear approximation [19]

$$I_c(T) = I_{c0} \cdot \left(1 - \frac{T}{T_c}\right).$$  (10)

where $I_{c0}$ is the $I_c$ at 0 K, $T_c$ is the critical temperature, which is 92 K for YBCO superconductor produced by Shanghai Superconductor Co., Ltd.

After value conversion, the critical currents of phase A, B, and C are 6800 A, 6685 A, and 6684 A. It should be noted that the maximum output of the power supply used to measure the critical currents is 7 kA and all three phases at the maximum current did not appear the ‘turning tendencies’ as shown in the figure indicated by the power law of type II superconductor.

FIGURE 19. $I_c$ measurement results of the three phases.

In other words, the actual critical currents should be greater than the measured results.

4) PARTIAL DISCHARGE TEST

In the field, we did not manage to achieve a very good electrically shielded environment. Furthermore, cryogenic pipes and some other lines had to cross the shielded environment and introduced interference inevitably.

Before voltage withstanding tests, the background PD was about 30 pC. And after the lightning impulse voltage test and power frequency voltage test, the background PD became about 15 pC. The measured PD were no higher than the corresponding phase’s background PD. From the PD ellipsogram, no obvious discharge signals were recognized. Based on the special characteristics of the composite insulation structure of LN2-PPLP, we believe that the measured partial discharges of the three phases indicate that there are no significant changes or defects in the insulation structures that could cause degradation of damage of the cable system’s high voltage performance.

5) OTHER TESTS

Thermal cycle test, load cycle voltage test, lightning impulse voltage test, and power frequency voltage test were conducted as the requirements and no abnormalities were observed. The tanδ is less than 0.1% for every phase.

6) SUMMARY AND REMARKS

Essentially, the prototype cable passed the type test. The test results prove that the quality of the HTS cable system prototype meets the design standards and the requirements of field deployment.

In addition to the test items required by the type test standard, some other tests and measurements such as fault current test, dynamic thermal load test, asymmetric current carrying test, and etc. are also important for the economic operation and safe operation of the system. Subsequently,
we will use the prototype system to conduct a series of research experiments including but not limited to the above mentioned items.

V. CONCLUSION

A new HTS cable project was launched in Shenzhen, China in 2007 by China Southern Grid. The project focused to demonstrate and operate a 10 kV/2.5 kA/400 m concentric HTS cable system in urban area. It would be the first concentric HTS cable project in China.

The designed HTS cable consisted of three concentric phases winded by YBCO tapes and cold dielectric insulation in between. The critical current was set to be at least 6 kA per phase when current transient condition and safety operation were taken into consideration. The insulation between phase A and former was adopted to improve the terminal design. As for the termination, we chose a 600 mm A pipe and former was adopted to improve the terminal design. The insulation between phase A and former was adopted to improve the terminal design. The insulation between phase A and former was adopted to improve the terminal design.

The designed HTS cable was fabricated and tested according to the engineering design—Analytical solution. Based on the design and oriented on the engineering grade cable system manufacturing process, several cable core samples were made, tested, and dismantled to verify the cable design and process parameters. Special attention was given to bending characteristics of HTS cable. Finally, a 30 m class prototype HTS cable system were fabricated and tested according to IEC 63075 and Chinese national standards. The prototype system passed the type test and the results showed that the HTS cable system prototype met the design standards and requirements of field installation.

The 400 m class concentric HTS cable demonstration project was launched after the 30 m system test was confirmed. The demonstration project is expected to energize in grid on late September, 2021.

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BANGZHU WANG was born in Hebei, China, in 1988. He received the B.S. degree in electrical engineering and its automation from China University of Mining and Technology, in 2011, and the M.E. degree in electrical theory and new technology from the University of Chinese Academy of Sciences, in 2014. He was a Research Intern from July 2014 to May 2016. He has been an Assistant Researcher with Beijing Jiaotong University, since May 2016. His research interests include HTS cable transmission technology, HTS magnet analysis, and high-voltage in cryogenic environment.
XIAOCHE WU received the B.E. and M.E. degrees from Huazhong University of Science and Technology, Wuhan, China, in 1993 and 1996, respectively. He is currently the Chairman of Shenzhen Power Supply Bureau, Shenzhen, China. His research interests include the operation control technology of superconducting cable and power system stability analysis and control.

HONG XIE received the M.E. degree in power system and its automation from China Academy of Electricity. He is currently the Deputy General Manager of Shenzhen Power Supply Bureau Company Ltd. His research interests include power system dispatching operation, high voltage equipment operation and maintenance, and digital transformation.

ZHINING LV received the M.E. degree in power system and its automation from Zhejiang University. He is currently the Director of ICT Joint Innovation Laboratory, Shenzhen Power Supply Bureau. He is also the Department Director of Shenzhen Power Supply Bureau and in charge of the construction of the 400 m HTS cable systems. He has been engaged in the technical research and application of power informatization and automation protection related monitoring system for decades.

ZHENG WANG received the B.E. degree from the South China University of Technology, Guangzhou, China, in 2000. She is currently the Deputy Department Director of Shenzhen Power Supply Bureau, China. Her research interest includes the design technology of superconducting cable.

MENG SONG was born in Wuhan, China, in 1982. He received the B.S., M.E., and Ph.D. degrees in electrical engineering from Huazhong University of Science and Technology, Wuhan, China, in 2002, 2005, and 2011, respectively. He is currently the Director of the Joint Laboratory on Power Superconducting Technology of China Southern Grid. He is a member of the National Superconductivity Standardization Technical Committee and has been engaged in the research and development of superconducting power equipment for decades.

YONG HUANG was born in Shanghai, China, in 1966. He received the B.S. degree in mechanical design engineering from Shanghai University of Applied Science and Technology, in 1987. He has been the General Manager of ZTT Superconducting Technology Company Ltd., since 2019. His main research interest includes design and manufacturing of superconducting power systems.

YAJUN XIA was born in Shanghai, China, in 1986. She received the master’s degree in electrical engineering from Huazhong University of Science and Technology, in 2012. Since 2012, she has been an Engineer of Guangdong Power Grid Company Ltd. Her main research interest includes application of superconducting technology in electric power.

ZHENG WANG received the B.S. degree in electrical engineering from Chongqing University. He is currently an Executive Coordinator of the HTS Cable Demonstration Project. His research interests include power system protection and control, electric new technology and application, and HTS power equipment research and development.

TENGBIAO CHEN was born in Shanzhou, Guangdong, in 1966. He received the B.S. degree in electrical insulation and power cable from Harbin Institute of Electrical Technology. He is currently a Power Cable Technical Expert with Shenzhen Power Supply Bureau, China. His research interest includes operation and maintenance techniques of transmission cables.

BO TIAN was born in Beijing, China, in 1982. He received the B.S. degree in computer science and technology from Beijing University of Technology, Beijing, in 2003, and the M.E. degree in mechanical engineering from Beihang University, Beijing, in 2018. Since 2019, he has been the Deputy General Manager of ZTT Superconducting Technology Company Ltd., and in charge of research and development of superconducting power devices.

SHAOTAO DAI was born in Jiangxi, China, in 1972. He received the B.S. and M.E. degrees from Central South University, Changsha, China, in 1994 and 1997, respectively, and the Ph.D. degree from the Graduate School of the Chinese Academy of Sciences, in 2010. He was a Professor with Beijing Jiaotong University, Beijing, China. He is leading the research team in the area applied the application of HTS, including cables, fault current limiters, energy storage, machines, transformer, and power transmission lines. He was a member of the Superconducting Applied Technology Professional Committee of China Electrotechnical Society.