

High Temperature Operation Analysis of Thermoplastic Polypropylene Insulated Power Cables

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Abstract—As the next generation eco-friendly cables, polypropylene (PP) insulated cables currently lack clearly specified test standards and operating criteria. This study comprehensively evaluates the thermal, electrical, and mechanical properties of grafted PP cable materials over a wide temperature range using quantitative approaches. Variations in material performance during thermal cycles are attributed to the evolution of crystal structure. Based on performance parameters, a simulation model of multi-field coupling was established to assess both normal and short circuit operations of cables. The feasibility of grafted PP cables working above the prevailing maximum normal operation temperature is discussed according to temperature and electric field distribution analysis. And thermal process, electric field behavior, and conductor eccentricity of cable under short circuit conditions described in IEC standards are also analyzed in detail. The results show that the PP cable still works normally after a prescribed short circuit fault with a maximum conductor temperature of 250 °C for 5 seconds. According to the operation characteristics of cables, the relationship between the short circuit current, duration and the maximum conductor temperature is calculated for the operating guideline. This paper provides an important simulated reference case for evaluating the safe operating limitation of the thermoplastic PP insulated cable operation.

Index Terms—Power cables, polypropylene insulation, material performances, multi-physical simulation, thermal analysis, high temperature operation, short circuit fault

I. INTRODUCTION

POWER cables are the lifeline of electrical energy transmission system [1]. As the guarantee of safe use of high voltage cables, prevailing cable insulating material is cross-linked polyethylene (XLPE), with its excellent high temperature electrical performance and thermal stability to replace low density polyethylene (LDPE) and high density polyethylene (HDPE) extruded insulation in the last century [2-3]. However, the degassing process during production and thermosetting characteristics make XLPE

insulation inconsistent with environment protection goals. Recently, polypropylene (PP) based thermoplastic insulating material is regarded as a candidate for the next generation of green high-voltage cable insulation with its excellent electrical performances at higher temperature operating condition [4-8].

Thermoplastic insulation material, different from the thermosetting material that is able to maintain the mechanical strength under heat shock because of its crosslinking structure [9], will change into the viscous state above the melting point so that the material nature will occur a sudden transition, which should be considered in power transmission line protection criterion. According to the requirements of HVDC and HVAC cable system test regulated by IEC 62895 [10] and IEC 62607 [11], the maximum affordable conductor temperature is decided as 130 °C, 160 °C and 250 °C under 5 seconds short-circuit duration for LDPE, HDPE and XLPE insulation respectively, based on their own maximum normal operation temperature of 70 °C, 80 °C and 90 °C [12]. Among them, the highest short-circuit conductor temperature of thermoplastic cables is always higher than the melting point of corresponding insulation. On the other side, because most current standards and specifications are based on the studies related to XLPE cables [13-14], it is not clear that whether they are suitable for PP cables or not. Due to the lack of experimental and simulation studies about the operating conditions of PP cables [15-16], the industrial circle has a cautious attitude towards the application of polypropylene cables. Thus, it is necessary to carefully evaluate the process of normal or short-circuit operation and determine a credible operating limitation of PP cables.

Due to its features of linear polymer and semi crystallization, PP will soften at the Vicat point [17] and eventually melt above the melting point with a temperature increasing from normal operating condition. During this process, the variation of semi-crystalline structure will influence its electrical, mechanical and thermal properties resulting in the distortion of the cable configuration and the electrical field. Moreover, the thermal process caused by the short circuit, which is different from that of cable manufacture procedure, will eventually lead to changes in material properties [18]. When these complex physical processes occur inside the cable, it is difficult to monitor and observe through real-time experimental methods. All of these problems reflect the urgent requirement of researching the detailed characteristics of cable material and constructing a refined simulation model to assess the safe operating range of thermoplastic cable systems.

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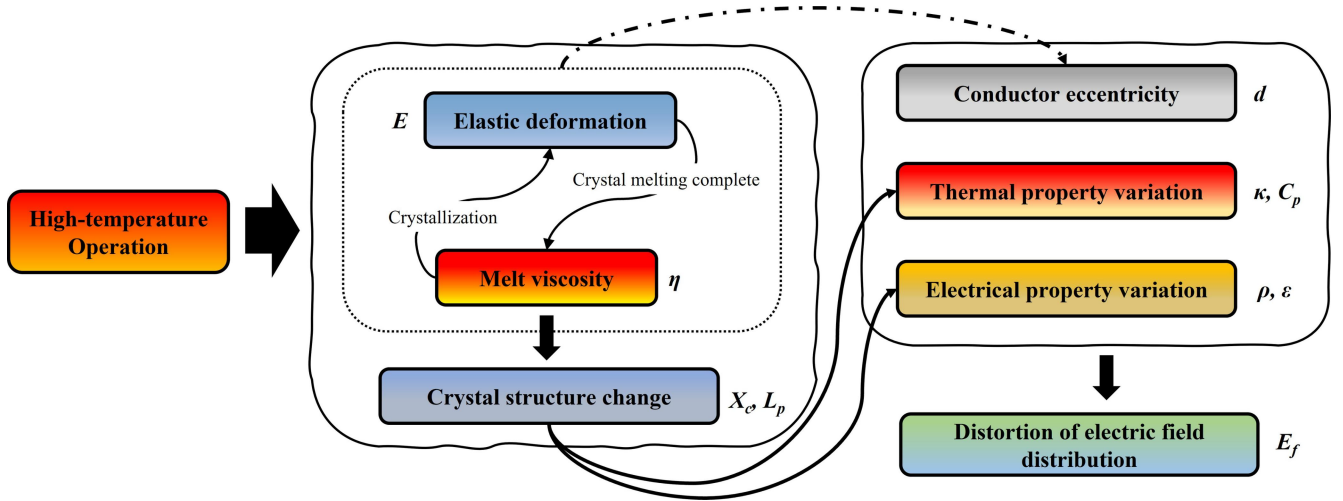


Fig. 1. The mind map of physical process occurring in grafted PP HVDC cables under high temperature operation.

As a competitive solution to be widely used in power cable systems, the grafted PP insulated HVDC cable is considered to have the potential to operate over 90 °C in former studies [5] and eventually manufactured. To ensure the capability of manufactured cables operating under normal and short circuit condition, this work developed a research paradigm to discuss the influence of high temperature operation (Fig. 1). The crucial electrical, mechanical and thermal parameters of the insulating layer and the shielding layer were characterized over a wide temperature range from the room temperature (RT) to short-circuit temperature. And the in-situ X-ray scattering experiments were conducted to relate material properties to its intrinsic semi-crystalline structure. Based on experiments, a multi-physics coupling simulation model was launched to discuss the thermal process during normal and short circuit operation, and finally gave a limitation of operation security. The purpose of this work is to provide the reference basis for standard and operation criteria design of PP HVDC power cables.

II. EXPERIMENTAL METHODS AND SIMULATION CONDITIONS

A. Materials and Samples

The grafted PP insulating material was developed by Tsinghua University and Beijing SINOPEC Research Institute of Chemical Industry [19-20]. The PP based cable shielding material was developed by Tsinghua University and Haijiang Polymer China Co., Ltd [21]. Manufactured cable samples were circumferentially cut into thin slices (Fig. 2 (a)) with the width of 10 cm and the thicknesses of 0.2 mm, 0.5 mm and 1 mm, including the insulating layer, the conductor shielding layer and the insulation shielding layer.

B. Temperature Modulated DSC (TMDSC)

To investigate the heat capacity of materials, TMDSC measurements were carried out on TA-DSC-Q2000 (TA Instruments, USA, Fig. 2 (b)). Compared with traditional DSC, TMDSC method performs more accurate and sensitive in heat capacity measurement and requires no reference sample (such as sapphire). It is attributed to the introduction of modulated

temperature, based on which the thermal process is set as [22]:

$$T(t) = T_0 + \beta t + A_T \sin(\omega t) \quad (1)$$

where, T is the real-time temperature (in °C), t is the time (in s), T_0 is the initial temperature (in °C), β is the basic heating rate (in °C/min), A_T is the modulated temperature amplitude (in °C) and ω is the modulation frequency (in rad/s).

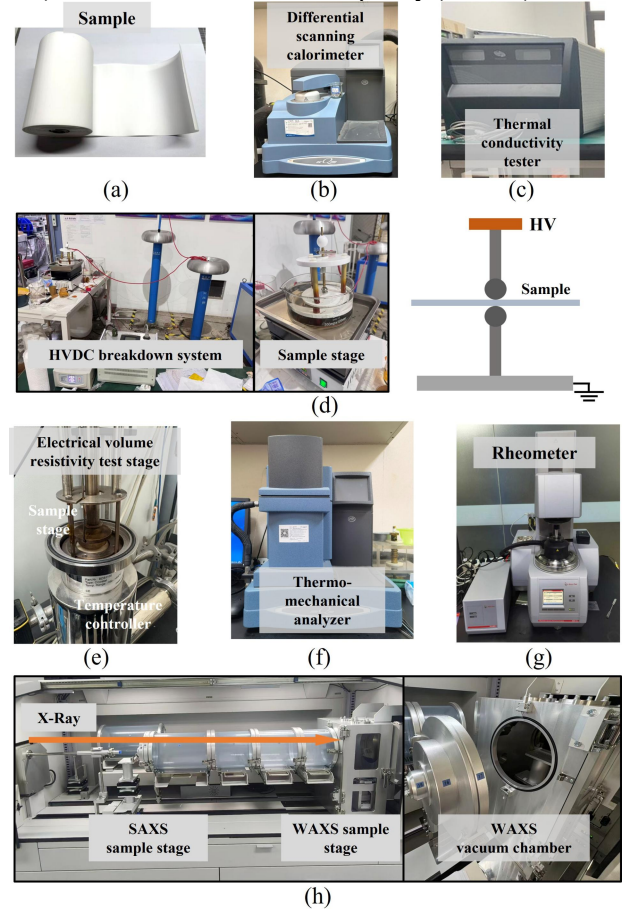


Fig. 2. Details of the sample and the test equipment. (a) The Sample fetched from the PP power cable; (b) Differential scanning calorimeter; (c) Thermal conductivity tester; (d) DC breakdown system and sample stage; (e) Experimental detail of the electrical volume resistivity test; (f) Thermomechanical analyzer; (g) Rheometer; (h) Device arrangement for SAXS/WAXS experiments.

The experiment was conducted in heat-cool mode after standard Tzero calibration. According to TMDSC guidance made by TA instruments, β , A_T and modulation period $2\pi/\omega$ are set as 2 °C/min, ± 0.32 °C and 60s respectively. During experiment, the sample was heated from 20 °C to 250 °C and then cooled to 20 °C with given parameters.

C. Thermal Conductivity Test

The hot disc method was applied to measure the thermal conductivity of materials by Thermal Constant Analyzer (TCA1500, Hot Disk, Sweden, Fig. 2 (c)). The sample was shaped into a block 30 mm in diameter and 1 mm in thickness to adapt the thermal field and probing depth. The experiment was conducted under room temperature (RT, 20 ± 2 °C in the lab).

D. DC Electrical Breakdown Strength Test

The DC electrical breakdown strength was tested by DC breakdown system (Haiwo Science & Technology, China) showed in Fig. 2 (d). Samples with the thickness of 200 μm were sandwiched by $\Phi 25$ mm sphere-sphere electrodes in the silicone oil. The test was conducted at 30 °C, 90 °C and 115 °C. The system applies a DC high voltage at a rising rate of 1 kV/s until the sample was broken down. For each sample, at least 16 DC breakdown tests are conducted. The data are statistically analyzed using the Weibull distribution as follows:

$$P(E_b; \alpha_w, \beta_w) = 1 - e^{-(E_b / \alpha_w)^{\beta_w}} \quad (2)$$

where, P is the breakdown probability. E_b is the breakdown strength variable (in kV/mm). α_w is the scale parameter (the breakdown strength when the breakdown probability is 63.2%, in kV/mm). β_w is the shape parameter.

E. Volume Resistivity Test

Since the sample with a thickness of 200 μm and a diameter of 2 cm was prepared in the mold made by polyimide to limit the deformation, it was sandwiched by two copper circular electrodes using a spring mechanism and put into a temperature-controlled device. The experiment was completed at the electrical impedance spectrometer (Concept82, NOVCONTROL, Germany, Fig. 2 (e)). The temperature rose to 200 °C with a heating rate of 2 °C/min and then dropped to 30 °C with the same rate. After standing at 30 °C for 1 hour, the sample was heated again to 150 °C for checking its volume resistivity after short circuit operation. The test temperature points were set according to the operation temperature and melting temperature of PP insulating material. The sample was tested for 10 min at each temperature point under an applied electric field of 11.5 kV/mm (the average electric stress in ± 200 kV HVDC cables).

F. Dynamic and Thermal Mechanical Analysis

The dynamic mechanical analysis (DMA) and the thermal mechanical analysis (TMA) was carried out to investigate the thermomechanical properties analyzer (TA-DMA-Q800, TA instrument, U.S., Fig. 2(f)). Specimens with a size of 20 mm $\times$ 5 mm $\times$ 0.5 mm were prepared. The temperature procedure of both experiments was set to heat from -50 °C to 170 °C at the rate of 3 °C /min. For DMA test, the amplitude and

frequency were set as 1% and 1 Hz respectively. For TMA test, the equipment applied a slight force to hold the sample upright.

G. Rheology Test

The investigation of rheological properties was conducted by a rotational rheometer (MCR302, Anton Paar, Austria, Fig. 2 (g)). During the experiment, the sample disc (25 mm in diameter and 1 mm in thickness) was put into a parallel-plate system and heated to the test temperature points from 180 °C to 210 °C with an interval of 10 °C. After completely melted, the sample was tested under a 5% shear strain with the shear rate from 0.05 s^{-1} to 100 s^{-1} .

H. In-situ X-ray Scattering

The small angle X-ray scattering (SAXS) experiment and wide angle X-ray scattering (WAXS) was conducted on the NANOPIX (Rigaku, Japan, Fig. 2 (h)) and time-resolved USAXS Beamline BL10U1 (Shanghai Synchrotron Radiation Facility, SSRF), Beamline 1w1a (Beijing Synchrotron Radiation Facility, BSRF) to resolve crystal structures. During in-situ WAXS experiment, the sample was firstly heated from 20 °C (RT) to 200 °C then cooled to 20 °C with the same heating/cooling rate of 2 °C/min. The obtained patterns were subsequently radically integrated into SAXS/WAXS curves by xpolar software. The diffraction angle 2θ is calibrated by the standard sample Si. WAXS/SAXS scattering curves were radically integrated from sample patterns. As for SAXS scattering curves, $q_s = 4\pi \sin\theta/\lambda$ (in nm^{-1}) was the scattering vector (λ is the wavelength of X-ray). The long period structure was analyzed by correlation function $K(z)$:

$$K(z) = \frac{\int_0^\infty I q_s^2 \cos(q_s z) dq_s}{\int_0^\infty I q_s dq_s} \quad (3)$$

where, I is the scattering intensity (in counts) and z is the distance (in nm).

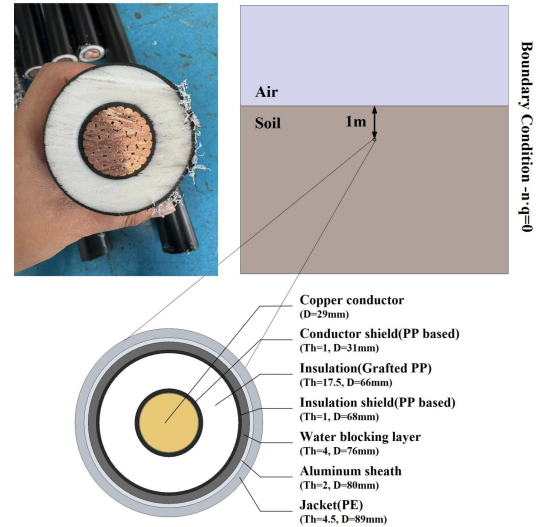


Fig. 3. The sketch map of simulation model topology and the structure of ± 200 kV PP HVDC cable.

I. Simulation Model and Conditions

The model structure of the cable as shown in Fig. 3 refers to the construction of DC-YJL03-200kV 1 $\times$ 630 mm^2 cable. Its

shielding layer and insulating layer are replaced by developed PP-based materials.

In the simulation model, the cable is direct-buried in the soil in depth 1 meter away from the ground. The ground temperature is assumed as 20 °C and the thermal resistivity of the soil is set as 1.2 K·m/W according to national standard GB 50217 [23]. At the sides and bottom boundaries, boundary condition $-\mathbf{n} \cdot \mathbf{q} = 0$ is acquired for thermal calculation, where $\mathbf{n}$ is a vector perpendicular to the edge and $\mathbf{q}$ is the heat flux.

All physical property parameters of the developed PP-based insulating and shielding materials used in this model are measured or deduced values that are highly consistent with operating conditions to improve model accuracy. However, because of the complex physical properties of polymers, several assumptions are necessary to be proposed to simplify the analysis:

- (1) The cable is long enough so that the thermal process and electrical field distribution are able to be described in a 2D section model.
- (2) The change of polymer gel point caused by cooling rate can be ignored [24].
- (3) Assuming that the cable is laid horizontally and straight, the internal stress caused by bending or other conditions during cable laying is not considered.
- (4) The mixing of shield and insulation in the melting process and the change of heat conduction due to deformation are not considered.

In the simulation, current is loaded to make the normal or transient operation temperature of the conductor reach the set value. The transient simulation considers a standard short circuit process in which the temperature of conductor rises from normal operation temperature to short-circuit temperature for 5 seconds. Then the cable cools down

naturally for recovery. In this operation, the heat transfer, electric field distortion and material physical parameters change should be taken into consideration.

During normal or short circuit operation, the generation and conduction of the heat should be controlled by Joule's law (4) and Fourier's law(5):

$$Q_e = \mathbf{J}_a \cdot \mathbf{E}_a \quad (4)$$

$$\begin{cases} \rho C_p \frac{\partial T}{\partial t} + \rho C_p \mathbf{u} \cdot \nabla T + \nabla \cdot \mathbf{q} = Q_e \\ \mathbf{q} = -\kappa \nabla T \end{cases} \quad (5)$$

where Q_e is the electric heating power (in W/m³) produced by related axial current density $\mathbf{J}_a$ (in A/m²) and axial electric field $\mathbf{E}_a$ (in V/m). ρ is the mass density (in kg/m³), C_p is the heat capacity [in J/(g·°C)] and κ is the thermal conductivity [in W/(m·K)]. In temperature field T (in °C), the heat power from Q_e is absorbed by the substance or conducted as the heat flow $\mathbf{q}$ (in W/m²).

Thermal effect will affect the material properties including electrical conductivity and mechanical strength when high temperature leads to crystallization change and even melt of thermoplastic materials (Fig. 1). Thus, the electric field (6), and force field (7) needs to be considered.

$$\begin{cases} \mathbf{E}_r = -\nabla \varphi_r \\ \mathbf{J}_r = \frac{1}{\rho_v(T)} \mathbf{E}_r \end{cases} \quad (6)$$

$$\sigma = \mathbf{D} \varepsilon \quad (7)$$

where $\mathbf{E}_r$ is the radical electric field in the power cable (in V/m). φ_r is the radical electric potential (in V). $\mathbf{J}_r$ is the radical current density (in A/m²). ρ_v is the volume electrical resistivity (in Ω·m). The stress σ (in Pa) and strain ε are associated by stiffness matrix $\mathbf{D}$ (in Pa).

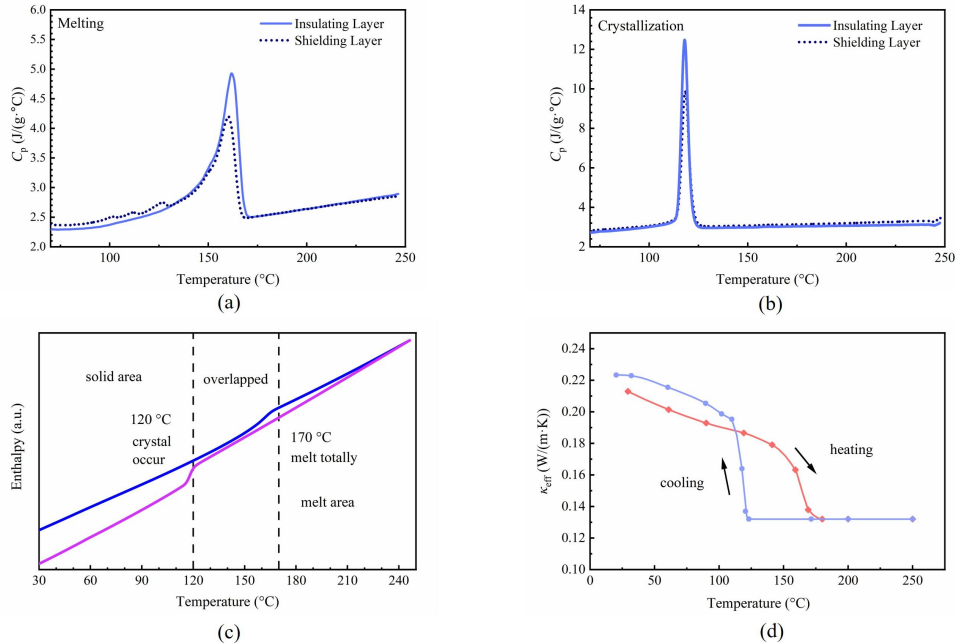


Fig. 4. Temperature dependent thermal properties up to short-circuit temperature. (a)(b) Heat capacity in melting and crystallization process; (c) Enthalpy curve; (d) Heat conductivity.

Based on the temperature distribution, temperature dependent function of electrical conductivity and the applied voltage, the distribution of radical current density J_r can be calculated. To evaluate the leakage current in the insulating layer, following equation is applied.

$$I_g = \int_S J_r \cdot dS \quad (8)$$

where I_g is the leakage current per unit length (in A/m). S is the curved surface encircling the conductor within a unit length of the insulating layer (in m^2).

III. MATERIAL PROPERTIES VARIATION AND TRANSITION DURING CABLE OPERATION

A. Thermal Properties

Thermal properties, including heat capacity and thermal conductivity, determine the thermostability of the cable. As shown in Fig. 4 (a) and (b), the heat capacity has been evaluated by using TMDSC method mentioned in section II, B. Except the sensible heat capacity that increases at a fixed slope as the temperature rises, the latent heat appears around the melt and crystallization temperature is represented by latent heat capacity. Over the entire temperature range, the sensible heat capacity is around 2.5 J/(g·°C). While there is some difference in the trend of enthalpy variation between heating and cooling process, which can be proved by misaligned enthalpy curve shown in Fig. 4 (c). It is attributed to the lag effect and the heat history difference during the melting and crystallization process of PP [16]. According to the WAXS curves (Fig. 5 (a)) radically integrated from the

WAXS patterns in Fig. 5 (c), the fitted crystallinity is 25.76% and 28.36% for the insulating layer before and after the thermal cycle respectively. This verifies the different heat histories during the cable production and the short-circuit process. Slower cooling process after the short circuit results in more enthalpy reduction and higher crystallinity.

To investigate the heat transport process, the thermal conductivity should be determined under wide temperature range to evaluate the heat stability of cables. The thermal conductivity κ_{in} [in W/(m·K)] of the insulating layer is estimated by the Maxwell model [25]:

$$\kappa_{in} = \kappa_1 \frac{2\kappa_1 + \kappa_2 + 2\varphi(\kappa_2 - \kappa_1)}{2\kappa_1 + \kappa_2 - \varphi(\kappa_2 - \kappa_1)} \quad (9)$$

where κ_1 and κ_2 are the thermal conductivity [in W/(m·K)] of the matrix and the island phase respectively. In semi-crystalline polymer such as polypropylene, where the lamellar structure is surrounded by amorphous phase, κ_1 and κ_2 could be amorphous and crystalline region, respectively. φ is the volume fraction of crystalline area, which can be translated from XRD crystallinity X_c through the following formula:

$$\varphi = \frac{X_c}{X_c + \frac{\rho_c}{\rho_a}(1 - X_c)} \quad (10)$$

where, ρ_c and ρ_a are the mass density (in kg/m³) of crystalline and amorphous phases, respectively.

For shielding layer made by PP/carbon black (CB) composites, in which both PP and CB are continuous phase, a modified Maxwell model for interpenetrating system is considered [26]:

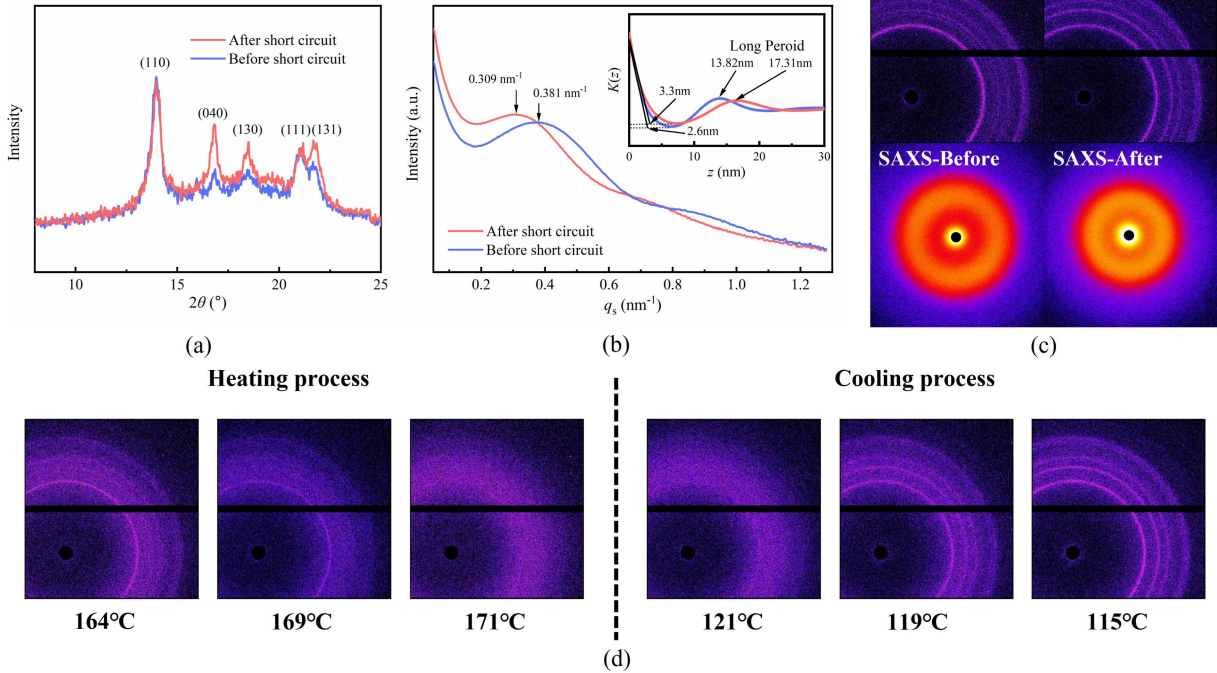


Fig. 5. In-situ WAXS and SAXS experiments of insulating layer under operation conditions. (a) WAXS curves and (b) SAXS curves before and after short circuit fault. (c) WAXS and SAXS patterns before and after short circuit fault. (d) In-situ WAXS patterns near the melt point or crystallization point.

$$\kappa_{\text{semi}} = \frac{1}{4} [3\varphi(\kappa_2 - \kappa_1) + (2\kappa_1 - \kappa_2) + \sqrt{[3\varphi(\kappa_2 - \kappa_1) + (2\kappa_1 - \kappa_2)]^2 + 8\kappa_1\kappa_2}] \quad (11)$$

where, κ_1 and κ_2 are the thermal conductivity [in W/(m·K)] of PP matrix and CB particle respectively. φ is the volume fraction of CB. κ_{semi} is the evaluated heat conductivity [in W/(m·K)] of the percolation system.

According to in-situ WAXS experiment of the PP insulating layer shown in Fig. 5 (c), the crystal structure in PP matrix disappears at 170 °C in heating process and constructs again at approximately 120 °C. Based on the experimental heat conductivity 0.213 W/(m·K) at RT characterized by the hot disk method mentioned in section II, C, the trend of the calculated corresponding heat conductivity of the insulating layer shown in Fig. 4 (d) is in agreement with the experimental results in the literature [27]. It is convinced that the heat conductivity is positively correlated with the crystal phase which provides longer mean free path of phonons. This is reflected by an abrupt change occurred in heat conductivity curve during melting and crystallizing. Moreover, the thermal conductivity of the material increases slightly after undergoing a thermal cycle due to the increase in crystallinity.

Thus, a thermal nature of thermoplastic crystalline polymer insulation and shielding material for high voltage power cable could be concluded that the high heat capacity, low heat conductivity and latent heat of phase transformation would restrain polymer matrix from entering the viscous state due to difficulties in temperature increasing and heat transferring. It can be regarded as a natural protection mechanism for PP cable system under heat shock, especially in poor heat dissipation environment.

B. Electrical Properties

The electrical breakdown strength of the insulating layer is the crucial parameter for ensuring operating safety. As presented in Fig. 6 (a), the DC breakdown strength are 314.40 kV/mm, 257.62 kV/mm and 211.03 kV/mm at 30 °C, 90 °C and 115 °C, respectively. As operating temperature rises, the breakdown strength decreases and its variance slightly increases. Compared with XLPE insulation, PP insulation exhibits better DC electrical strength at higher temperature (e.g. 257.62 kV/mm for PP at 90 °C versus 197.1 kV/mm for XLPE at 70 °C [28]). This is the key factor that enables the PP cable to operate reliably with higher capacity.

For HVDC cables, the electric field is often non-uniformly distributed in the insulation layer, on account of the temperature dependence of electrical volume resistivity $\rho_v(T)$. Fig. 6 (b) presents the electrical volume resistivity spectrum of the insulating layer during a heat shock cycle, characterized by using the method in section II, E. In heating process, ρ_v obeys the Arrhenius law showing an exponential downtrend firstly. When the sample is heated up to more than 170 °C, the viscous transition point predicted by in-situ WAXS test, ρ_v has an obvious sudden drop from $10^{13} \Omega \cdot \text{m}$ to $10^{10} \Omega \cdot \text{m}$. It is evident that the volume resistivity mechanism of thermoplastic crystalline materials is also strongly dependent on the

crystalline structure. Then the insulating layer is cooled for recovery at the same cooling rate as that in the case of simulated short circuit model (Fig. 10 (b)). Due to the hysteresis of phase transformation temperature, polymer matrix will not crystallize immediately below the melt point. So it remains low ρ_v , which is two orders of magnitude lower than before the short circuit. Until the temperature drops below the crystallization point, ρ_v gradually approaches the level before the short circuit. While even after recovering at RT for hours, insulation cannot perform the same properties as before. By reheating the sample, ρ_v - T relationship is recharacterized and the volume resistivity is $6.92 \times 10^{13} \Omega \cdot \text{m}$ at 90 °C, presenting an order of magnitude down from before ($4.58 \times 10^{14} \Omega \cdot \text{m}$ at 90 °C).

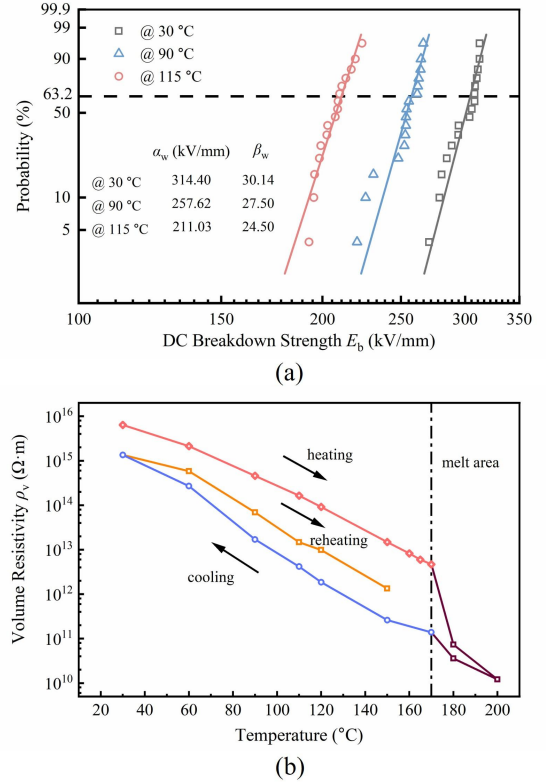


Fig. 6. Electrical properties. (a) DC breakdown strength of the insulating layer at different operating temperature; (b) Electrical volume resistivity under thermal cycle.

To further investigate the relationship between charge transport and the evolution of crystalline structure, WAXS/SAXS patterns of the insulating layer were characterized before and after short circuit process, as shown in Fig. 5 (a) and (b). The WAXS/SAXS curves in Fig. 5 (a) are obtained by performing radical integration on patterns in Fig. 5 (b). As illustrated in Fig. 5 (b) given by SAXS experiment, the long period of lamella structure z , calculated by related correlation function, changes from 13.82 nm to 17.31 nm during a short circuit operation, indicating looser spherulite structures. It means that the widening of amorphous regions between lamellas will make it easier for charge injection and transport [29]. Therefore, even if the insulating layer is more crystalline (X_c changes from 25.76% to 28.36% fitted from WAXS curves, Fig. 5 (a)) after melting and

eventually recovering in short-circuit thermal shock cycle, its volume resistivity properties still cannot revive as before. This phenomenon indicates that the difference of thermal process between short circuit and cable manufacturing leads to different formation of crystalline structures in the insulating layer, resulting in different electrical properties.

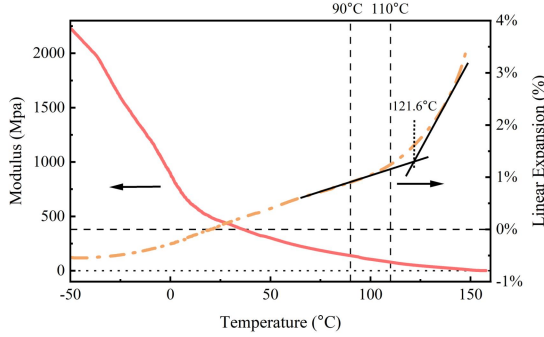


Fig. 7. Temperature dependent mechanical modulus and linear thermal expansion of the insulating layer.

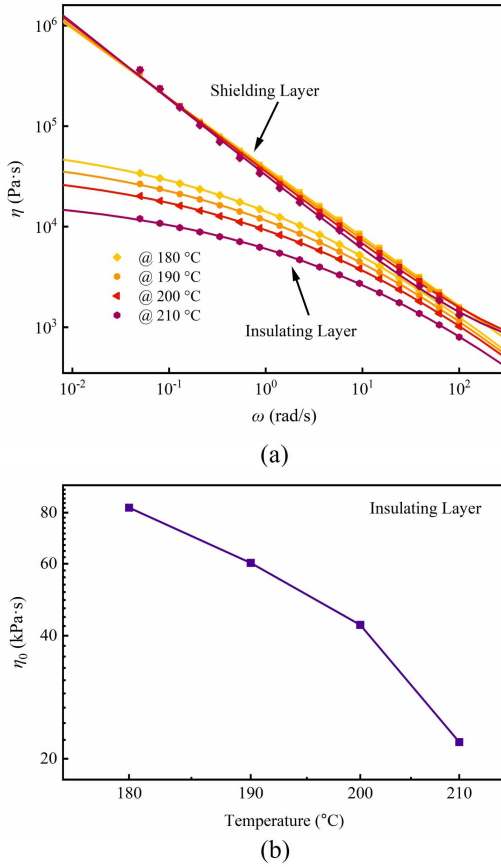


Fig. 8. (a) The rheological curve of insulating and shielding layer (dots for experiment and solid for fitness). (b) The temperature dependence of zero-shear viscosity for insulating layer.

C. Mechanical Properties

As shown in Fig. 7, modulus and linear expansion were obtained by applying DMA and TMA method illustrated in section II, F. During the overload operation, the mechanical strength of cable materials will occur a gradual deduction due to increased flexibility of molecular chains. At 115 °C, the linear expansion rate reaches 1.36% and the storage modulus

still remains 65 MPa. Compared with XLPE [30], the crystal structure of PP insulation makes it perform a considerable mechanical strength and higher thermal reliability over a wide temperature range. When the temperature reaches more than 121.6 °C, the linear expansion rate gets a dramatic increase, so the long-term operation temperature had better to be lower than 121.6 °C.

Once it comes to a short circuit fault, the conductor would suddenly raise to an extreme high temperature so that the shielding layer and insulating layer would be soften and even melted. In case that polymer near the conductor enters into a viscous state, the rheological property will dominate the mechanical behavior of the cable structure. The viscoelastic model (Equation (12)) is applied to evaluate cable structural deformation.

$$\varepsilon = \frac{\sigma}{E} + \frac{\sigma}{E} \left(1 - e^{-\frac{Et}{\eta}}\right) + \frac{\sigma}{\eta} t \quad (12)$$

where, ε is the strain and σ is the stress (in Pa). E is the modulus (in Pa) and η is the viscosity (in Pa·s). t is the force acted time (in s). The viscoelastic model divides the deformation into instantaneous elastic, delayed elastic, and viscous deformation, which correspond to the terms of the formula (12) respectively. In this case, η is fitted by Carreau-Yasuda model [31] (Fig. 8 (a)). According to the rheology test (section II, G) over 180 °C, the zero viscosity η_0 of the insulating layer is larger than 10^4 Pa·s and decreases with increasing temperature (Fig. 8 (b)). While for shielding layer, η_0 maintains beyond 10^6 Pa·s and hardly changes with temperature. The temperature dependent viscosity of thermoplastic insulation satisfies the Arrhenius relationship [32]:

$$\eta = A e^{\frac{\Delta E_{\eta}}{RT}} \quad (13)$$

where, A is a constant, T is the Kelvin temperature (in K) and R is the gas constant [8.314 J/(mol·K)]. ΔE_{η} is the activation energy (in J/mol), which is 78.2 kJ/mol for the insulating layer.

When polymers are faced with crossing the melt point or crystallization point, predecessors' researches have proved that modulus of polymers changes drastically at very low crystallinity (approx. 6%) called gelation point [33]. Due to the mechanical characteristic of semi-crystalline is determined by crystal structure [34] and in-situ WAXS test shows a rapid change near phase transition points, the appearance and disappearance of crystals are used as a boundary of the transformation of mechanical properties to decide whether the material is dominated by elasticity or viscosity. And the modulus is set to meet the exponential rule when it changes sharply to accord with the actual behavior [35].

IV. SIMULATION AND DISCUSSION OF POWER CABLE HIGH TEMPERATURE OPERATION

A. Normal Operation Analysis

In long-term stable operation state, the cable system could be underloaded, rated loaded and overloaded. Considering 90 °C, the maximum conductor temperature under normal operation for XLPE-based cable defined by IEC 62895, as the

rating temperature of the conductor, the normal operating characteristics of the cable, including temperature and electric field distribution, were investigated from 50 °C up to 115 °C as shown in Fig. 9 and TABLE I by the multi-physics field coupling model established in section II, I. As the conductor temperature increases, the maximum temperature difference $\Delta T_{\max}$ over the cable insulation varies from 11 °C to 37 °C. At 90 °C, the rated load current is 1327 A, and that of 115 °C operation is 1537 A. Due to the effect of thermal distribution

and the temperature dependence of volume resistivity, the maximum electric field strength moves from the interface of insulation and conductor shield to the interface of insulation and insulation shield between 50 °C and 70 °C operation. Under the rated DC voltage $U_0 = 200$ kV, the calculated maximum electric stress is 14.21 kV/mm at 90 °C and 16.07 kV/mm at 115 °C, lower than the typical designed electric field 20 kV/mm for XLPE insulation [36].

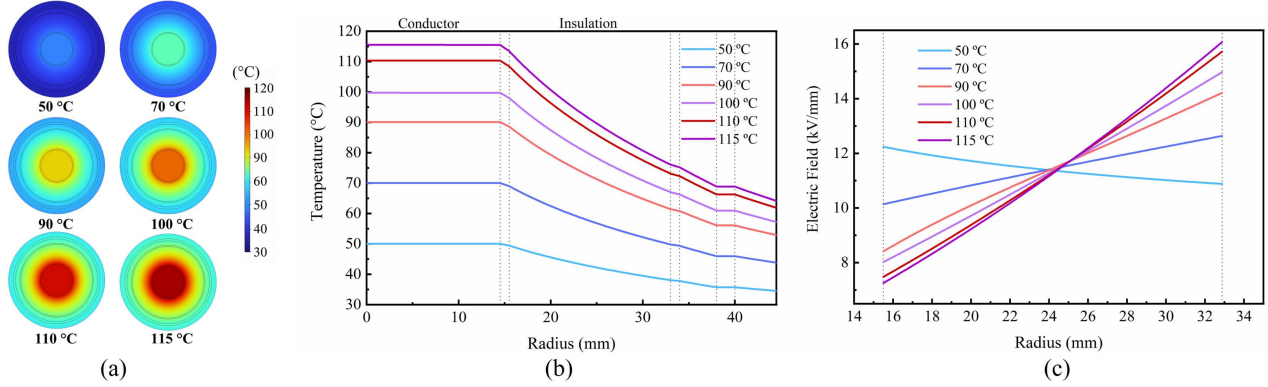


Fig. 9. Distribution of cable temperature and electric field under different load condition. (a)(b) Radial temperature distribution and (c) electrical field distribution.

TABLE I
THE COMPARISON OF PP AND XLPE INSULATED CABLE UNDER NORMAL OPERATION

Temp.	PP Insulation		XLPE Insulation	
	Load Current	Leakage Current	Load Current	Leakage Current
50 °C	881 A	0.3688 nA/m	903 A	0.5045 nA/m
70 °C	1129 A	0.8256 nA/m	1162 A	1.1615 nA/m
90 °C	1327 A	1.8156 nA/m	1372 A	2.5816 nA/m
100 °C	1411 A	2.5782 nA/m	—	—
110 °C	1497 A	3.9649 nA/m	—	—
115 °C	1537 A	4.8202 nA/m	—	—

The leakage current was evaluated by equation (8) based on the multi-field coupled computation. Compared with XLPE insulation, PP cable always has lower leakage current at the same operating temperature (e.g. 1.8156 nA versus 2.5816 nA per meter of cable for PP and XLPE at the rating temperature), almost reducing 30% leakage current loss. Although the load current of PP cable is slightly less than XLPE at the same operating temperature by the reason of PP's weakness of heat dissipation ability, it can be compensated by increasing the operating temperature. While operating at 115 °C, the modulus of 65 MPa (approx. 10 MPa for XLPE at the same temperature [30]) enables the grafted PP insulation to support the cable conductor. And high electrical strength and resistivity presented in section III, B ensure the safe operation. It is possible for PP cables to operate at 115 °C with 1.16 times rated current. Moreover, the manufactured PP cable cables have passed the type test, including bending test, voltage test and cable materials aging test, further confirming the reliability of PP cables during the normal operation.

B. Short- Circuit Operation Process Analysis

When it comes to a short circuit fault which makes the conductor reach an ultra-high temperature, the distribution of

temperature, electrical field and mechanical stress will have a sudden transition. Considering a standard short circuit procedure for XLPE cables illustrated in IEC-62895 [10], a dramatic conductor temperature rising up to 250 °C from normal operation temperature 90 °C with a duration of 5 s is applied by a transient current 55.347 kA (Fig. 10 (a) and (b)).

Regarding the end of heat shock as $t=0$ s, the radial temperature distribution is presented in Fig. 10 (c). After the fault is fixed, the cable enters into the no-load state for recovery with a cooling process for more than 30 min. At 0 s, the temperature gradient and the heat flux are mainly concentrated in conductor shielding layer with a temperature difference of 140 °C (Fig. 10 (c) and (d)) and 30% conductor shielding layer is fleetly melted (Fig. 10 (g) and (h)). Meanwhile, due to the high thermal capacity of PP and the latent heat effect of phase transition, the temperature distribution of the insulating layer remains almost the same as that in normal operation. Subsequently, when the conductor shielding layer is completely melted at $t=20$ s, the heat propagates to the insulating layer and leads to the gradual melting of the insulating layer, which finally reaches the maximum melted ratio of 3.56% at 160 s as shown in Fig. 10 (h). Because of the hysteretic transition point, melted shielding

layer and insulating layer keep viscous state in following 30 min with an average cooling rate of 2 °C/min (Fig. 10 (b)). Not until 1960 s did melted insulation begins to crystallize and the shielding layer starts to solidify at 2040 s. The overlapped crystallization process between 2040 s and 2120 s is attributed to a slight difference of the crystallization point, in which

shielding material is 1.1 °C higher than insulation, resulting in “double melted layer” phenomenon shown by “2080 s” section in Fig. 10 (g). After $t=2160$ s, the melting damage caused by short circuit fault finally recovered completely. While the change of the electric stress distribution and conductor eccentricity caused by short circuit need detailed discussion.

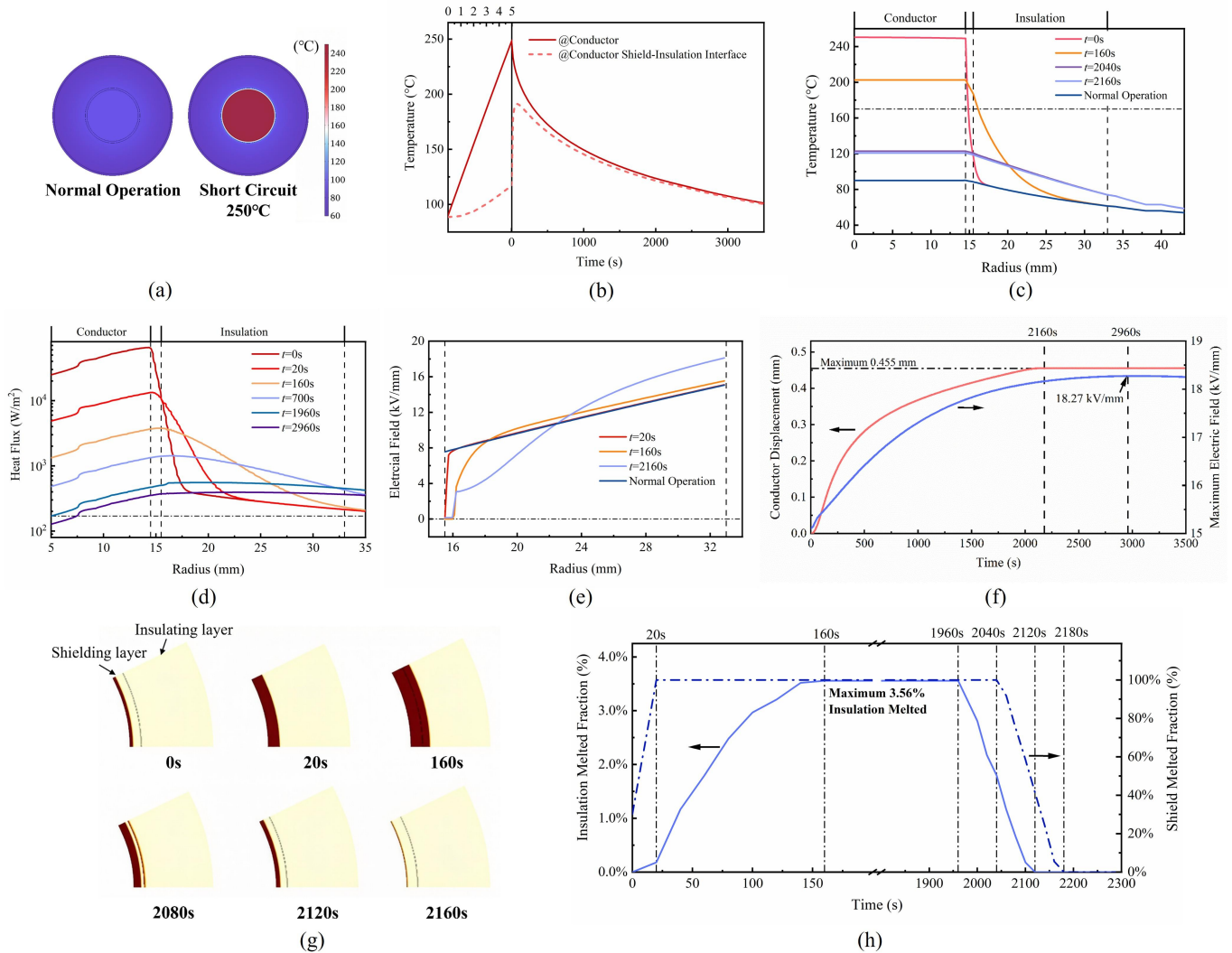


Fig. 10. The summary of short circuit operation under 250 °C. (a) Short circuit fault induced temperature distribution of cable section. (b) Temperature variation at conductor and conductor shield-insulation interface. The evolution of (c) radial temperature distribution, (d) heat flux distribution and (e) electrical field distribution. (f) Variation of conductor displacement and maximum electric field inside the cable. (g) Phase transition (red for melted area) conditions at different moment. (h) Melted fraction record for both insulating and shielding layer.

The mechanical deformation was estimated based on equation (12). When a short circuit fault occurs, the conductor displaces 0.2 mm along the direction of gravity within the first 300 s (Fig. 10 (f)). Then the displacement gradually increases with a slower rate on account of increasing modulus and viscosity during nature cooling process. Finally, it reaches 0.455 mm at 2160 s. Along the direction of conductor displacement, the insulating and conductor shielding layer are thinned by 0.34 mm and 0.11 mm respectively. Based on this result, the radial mean electric field in this direction will increase by only 0.23 kV/mm after recovery.

When the connected fault system is removed, considering the situation if the line is not cut or remains no-load state after

reconnecting, the simulation with rated voltage was conducted to evaluate the safety of possible misoperation and reconnecting operation. As shown in Fig. 10 (e), it turns out that the electric field distribution in the insulation layer does not change dramatically at the beginning of recovery process, except that the electric field is greatly reduced in melted insulation because of a sudden decrease of its volume resistivity. After 160 s, Fig. 10 (d) presents that the heat is gradually transferred from the conductor boundary to the insulating layer, resulting in uneven temperature rising throughout the insulating layer, and finally the electric stress distribution changes. This process lasts for more than 1000 s. Even if the melting damage has been recovered, the outward

propagation of heat is still slowly distorting the electric field. Unlike the rapid occurrence of phase transformation and eccentricity processes, the electric stress near the insulation shield finally reaches its maximum value 18.27 kV/mm at 2960 s (Fig. 10 (f)). Compared with that of normal operation, it presents almost 25% increase but is still lower than the safety threshold of 20 kV/mm. It means that all no-load operations after the short circuit are secure for the cable. After the cable enters the steady state operation again, the maximum electric stress increases by 0.39 kV/mm to 14.60 kV/mm compared with that before the short circuit due to the variation of the electrical conductivity and thermal characteristics during the fault characterized in section III.

In the practical qualification test, after a specified short circuit test (250 °C, 5 s), the tested cable successfully passed the high-voltage test. Both of experimental and simulation results show that the PP cable can still operate normally after a short circuit fault.

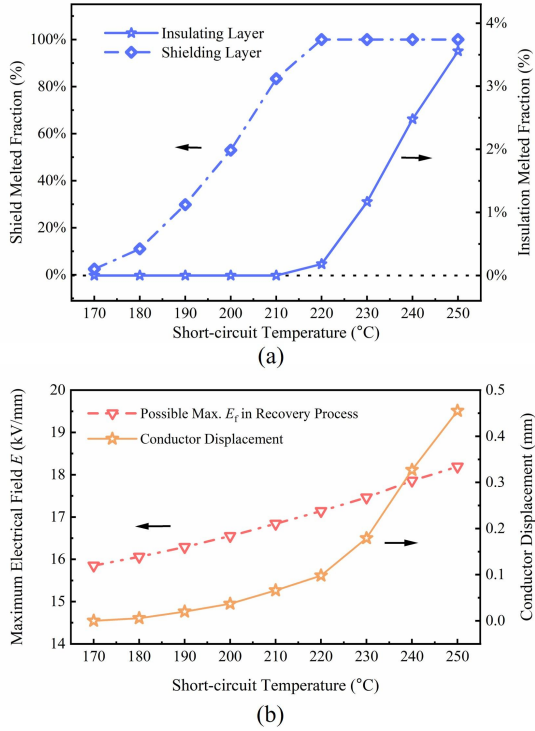


Fig. 11. (a) Melted fraction for insulating and conductor shielding layer at different T_{scmax} and corresponding short-circuit current. (b) Possible maximum electric field and conductor displacement at different T_{scmax} .

C. Short Circuit Safety Limitation Analysis

Although previous section has illustrated that PP cable is reliable to be back into service after a severe short circuit fault (250 °C, 5 s), it also demonstrates that melting process permanently changes the properties of the insulation near the conductor shielding layer and leads to irretrievable electric field distortion and conductor eccentricity. Hence, it is considerable to determine a proper limitation in short circuit operation for PP-based thermoplastic cable.

It is considered that the conductor is heated to different temperatures exceeding the melting point of cable materials by short circuit currents with the same duration of 5 s. As shown

in Fig. 11 (a), the fraction of insulation melting is reduced with the decrease of the short circuit maximum conductor temperature T_{scmax} and finally reaches zero at 210 °C. The shielding layer is completely melted over 220 °C and keeps affected by thermal shock until T_{scmax} is 170 °C. Because less joule heat generation and propagation will result in a smaller change in temperature distribution, the possible maximum electric field is reduced from 18.27 kV/mm at 250 °C to 15.85 kV/mm at 170 °C (Fig. 11 (b)). Meanwhile, the decrease of short circuit temperature will greatly reduce the conductor eccentricity. When T_{scmax} is 210 °C with its short circuit current 47.9 kA, the conductor displacement has been as low as 0.06 mm. Consequently, since the insulation will not be damaged and the conductor eccentricity is small enough when T_{scmax} is below 210 °C, a temperature between 170 °C and 210 °C could be considered as the permissible maximum short-circuit temperature with a short circuit duration no more than 5 seconds for this type of grafted PP based power cables.

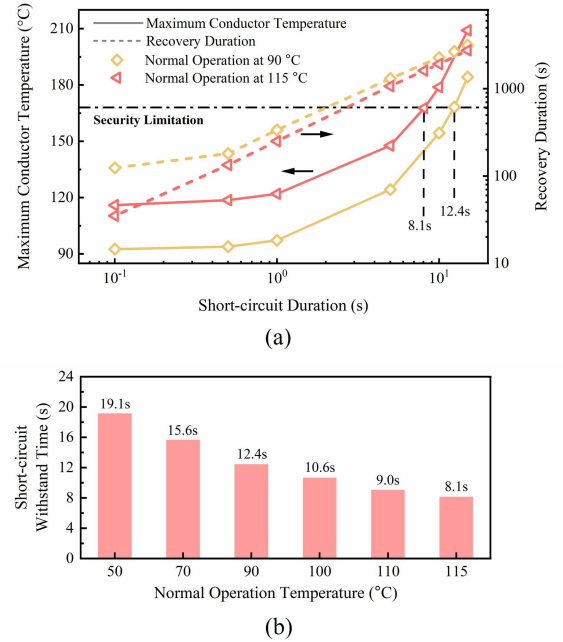


Fig. 12. Short-circuit endurance analysis under different normal operation temperature. (a) Maximum conductor temperature after different short-circuit duration and time required for conductor temperature recovery under normal operation temperature of 90 °C and 115 °C. (b) Short-circuit withstand time under different normal operation temperature.

In practice, the short-circuit current is generally 10-15 times of the normal operation load. The short circuit current of 15 times the maximum load current is referred to maximum breaking current of circuit breakers of Zhoushan ±200 kV HVDC transmission project in China [37]. Referring to the recommended maximum current 1537 A, the most severe short-circuit current could be fixed as 25 kA. As shown in Fig. 12 (a), when the short circuit duration is less than 1s, the conductor temperature rise is less than 10 °C and the time required for conductor recovering back to normal operating temperature is less than 5 minutes. Under 90 °C normal operation, PP cable is able to withstand 12.4 s under 25 kA short circuit current without melting damage and that time of

115 °C normal operation is 8.1 s. Fig. 12 (b) demonstrates that the short circuit withstand time ranges from 19.1 s to 8.1 s under normal operating temperatures from 50 to 115 °C. Fig. 13 provides the relationship between short circuit current, duration and maximum conductor temperature under different normal operation temperature for operation guideline.

For actual operation, as a short circuit fault occurs, it takes only a few milliseconds to turn off the DC circuit breaker or no more than tens of milliseconds to turn off the AC circuit breaker [38]. If the circuit breaker does not work, it can be re-operated within 3 s (the rated duration of short circuit of circuit breaker specified by IEEE Std C37.100.1 [39]). It is convinced that the endurance of the cable is sufficient for the system to handle the short-circuit current and then return to normal operation.

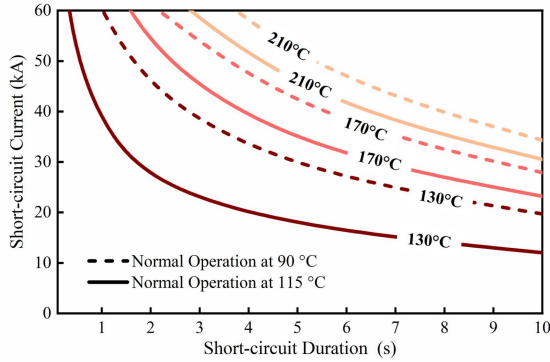


Fig. 13. The relationship between short circuit current, duration and T_{scmax} under different normal operation temperature.

V. CONCLUSION AND PROSPECTION

In this paper, a systematic characterization was conducted to understand the variation of performances and structures of the produced PP based cable material, and a detailed simulation model based on physical parameters was developed to quantitatively evaluate thermal process, structure deformation and electric stress for the grafted PP-based HVDC cable. The analysis and results are concluded as follows:

- (1) The thermal, electrical and mechanical performances of the cable materials have been comprehensively and quantitatively characterized over a wide temperature range. Importantly, the DC breakdown strength and the volume electric resistivity of the cable insulation at 90 °C are 257.62 kV/mm and $6.92 \times 10^{13} \Omega \cdot m$ respectively. And the heat distortion temperature is determined to be 121.6 °C. In addition, the crystalline structure evolution with increasing crystallinity and looser spherulitic structure is regarded as the cause of the performance change during the short-term thermal cycling.
- (2) Based on the physical performance parameters characterized, the temperature and electric field distributions under different operating temperatures are quantitatively presented by multifield modeling. Due to the better thermal stability of performances and the lower leakage currents at high temperature operation, grafted PP insulated power cables would be possible to withstand

larger current carrying capacity at 115 °C.

- (3) Under 250 °C short circuit fault with a duration of 5 s simulated, 3.56% of the cable insulation was melted, the conductor displaced by 0.455 mm and a maximum electric field of 18.27 kV/mm might be generated upon reconnection. Finally, the insulating and shielding layer of the cable recovered from the viscous state at 2180 s after the short circuit and the maximum electric field of the normal operation increased by 2.7%.
- (4) For the sake of the system safety and the principle of protecting cable insulation, a temperature between 170 °C and 210 °C could be considered as the permissible maximum short-circuit temperature with a short circuit duration no more than 5 seconds for simulated PP cable.
- (5) Considering the short circuit current of 15 times the maximum load current in actual operating conditions, the short circuit withstand time reaches 8.1 s even at the maximum normal operating temperature of 115 °C suggested in this work, which provides enough safety margin for the power system.

This work is inspired by the type test and the short-circuit test for manufactured grafted PP high voltage cable. After the test, though the tested cable successfully passed the high-voltage test, it is hard to detect potential thermal deformation and damage in the PP cable. In order to determine whether short-circuit fault will cause damage to the cable, simulation based on detailed parameters becomes a reliable method to help the design and operation of the cable. It is of great significance to formulate new standard and operation criteria for PP cables.

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