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Feasibility Study of High Temperature Superconducting Cables for Distribution Power Grids in Metropolises

Tianhui Yang[1], Hui Jin[1], Wenxin Li[1], Wei Hong[1], Bo Tian[1], Quan Li[2] and Ying Xin[13]

[1] School of Electrical & Information Engineering, Tianjin University, Tianjin 300072, China
[2] School of Engineering, University of Edinburgh, Edinburgh EH9 3JL, U.K.

E-mail: yingxin@tju.edu.cn

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Abstract

High Temperature Superconducting (HTS) cables have numerous advantages in comparison with conventional power cables, such as high power density and low power losses, so they have great potential in enhancing the transmission capacity and improving the quality of power grids. In this work, we studied various cases to evaluate the feasibility of replacing conventional cables with HTS cables in metropolitan distribution networks. These cases represent three principal strategies. The first, HTS cables are applied at the same or lower voltage levels with the same transmission capacity, named as “equal capacity replacement”. The second, considering the increasing power demands we demonstrate how HTS cables can benefit the power grids with expanded capacity (expanded capacity replacement). The third, we consider the case of unequal routes from the perspective of saving land resources (unequal routing replacement). In this paper, we introduce the methods and results of this study and give some preliminary conclusive remarks.

Keywords: Superconductivity, Superconducting cable, Power transmission, Distribution network

1. Introduction

With the fast development of economy and the increasing prosperity of metropolises, demands for electricity have been growing rapidly in China for the last three decades. In China, the power supply area can be plotted into six categories, A+, A, B, C, D and E, the division rules are shown in table 1. The metropolises generally belong to category A+, A and B, and the load density is always greater than 6 MW/km^2 [1]. However, many existing transmission lines have limitations in meeting the growing need of power transmission [2-5]. Increasing the voltage level of the transmission line is a conventional method to achieve the urban power expansion. However, this method requires new costly electrical equipment, such as high voltage transformers, circuit breakers and reactors. The rising of voltage of a power network may also lead to a surge of short-circuit fault current, which may subside the safety of the grids. Besides, to fit the higher voltage level, the insulation level of the cable should be raised and the attachments and laying methods of the cable should be changed accordingly, which may cause additional investment cost increasing [6-8]. Furthermore, the scarcity of underground resources and the intricate underground laying system make the construction of underground passages more difficult [9, 10]. All of these weaknesses indicate that the

[3] Author to whom any correspondence should be addressed

Table 1. Division rules of power supply area [1]

Categories	Load density (σ)	Power supply area
A+	σ≥30 MW/km^2	Municipalities or the central area of metropolises
A	15 MW/km^2≤σ<30 MW/km^2	
B	6 MW/km^2≤σ<15 MW/km^2	Urban areas or towns
C	1 MW/km^2≤σ<6 MW/km^2	
D	0.1 MW/km^2≤σ<1 MW/km^2	Rural or pastoral areas
E	σ<0.1 MW/km^2	

problem of expanding capacity of urban power grid needs a better solution urgently.

As compared with conventional cables, High Temperature Superconducting (HTS) cables have many distinct advantages such as large capacity, low loss, small size, light weight, resource saving, and environment-friendly, which are of a great prospect in enhancing the transmission capacity of power grids. An HTS cable system can utilize the existing cable trenches, and improve the transmission capacity of the power grid according to the actual needs. Therefore, replacing the conventional cable with the HTS cable is expected to be an effective solution for expanding capacity of metropolitan power grid [11-14].

Many countries in the world have carried out R&D programs in HTS cable applications. There are some well-known projects in the past five years. A 1 km-long, 10kV, 3 phase concentric, 15 cm diameter HTS cable was installed in the city of Essen to replace a ten-time thicker 110 kV copper cable in 2014 [15]. In the same year, a 500 m, 80 kV, 3.15 kA DC HTS transmission line was installed and commissioned in Korea [16]. In 2016, a 1 km, 154 kV, 2.25 kA AC HTS transmission line was completed and started grid operation in Hanlim-Ceumak power system of Jeju Island [17, 18]. HTS cable is basically mature in technology at present [19, 20].

However, the large-scale commercial application of HTS cable is not yet available. There are still some challenges in large scale commercial applications of HTS cables. HTS cable as a new type of power cable, people sometimes have doubts about the economics and safety of its applications [21]. Moreover, in recent years, ultra-high voltage transmission technology in china has developed rapidly, and the strong technical competition from ultra-high voltage transmission has weakened passion for superconducting transmission technology to some extent [22, 23]. In addition, Braess' paradox in power grids also should be considered when HTS cables are used for large-scale power expansion, which means people need to pay more attention to the problem of desynchronization of the electric network [24, 25]. One of the topmost challenges is that the initial investment of an HTS cable system is much larger than that of conventional cable system because of the high price of HTS materials and high complexity of HTS cable system [26, 27]. Nevertheless, the superiorities of HTS cable, such as large capacity and low loss, can not only make the power dissipation of transmission line during operation smaller, but also enable HTS cable line to meet the demand of power supply even if the voltage level is lowered [28]. All of these superiorities lead to energy save during HTS cable system operation, which can compensate for its shortcoming of high initial cost to some extent.

The research of HTS cable has gradually deepened with the development of the technology. Some studies carried out power flow analysis of power system with HTS cables [29], verified the superiority of superconducting cable transmission over traditional transmission methods [9], and guided the selection of the best types of HTS cables [30]. However, there is still a lack of systematic research and analysis on the feasibility of its practical application in the metropolitan power system. Therefore, it is of great theoretical and practical significance to compare the HTS cable with the conventional cable and analyse the efficiency of performance of HTS cables in practical power system.

In this work, we propose three strategies, equal capacity replacement, unequal capacity replacement, and unequal routing replacement, and design different implementing schemes for each strategy. By comparing the operation power loss of the HTS cable distribution network and the conventional cable distribution network in each scheme, the applicable situation of the HTS cable used to optimize the conventional distribution network is analysed, thereby the feasibility of application of the HTS cable in the metropolitan power system is discussed.

2. Bases of Calculation for Efficiency of Performance

2.1 Calculation Model

For conventional cables, the power loss during operation is mainly the conduction loss caused by the resistance of the conductor, which is greatly affected by the current flowing through it (proportional to the square of the current). Whereas the main power loss of HTS cable includes the AC loss of conductor during AC transmission and the thermal power dissipation caused by the heat leakage of cryostat, which the current has little effect on it. In order to compare the power loss of HTS cable and conventional cable during operation, a set of mathematical formulas for calculating power loss is proposed in [31]. On this basis, this study supplements the influence of joints in superconducting cable system, and the improved mathematical formulas are presented as follows

$$P_s = \left[(\omega + \theta) l_s + 2\tau_1 + (2l_s - 1)\tau_2 \right] \rho + \omega l_s \tag{1}$$

$$P_c = I_c^{\,2} r l_c \tag{2}$$

Where P_i is the total power loss of the cable during operation, kW, subscript i is standing for s or c which represents the parameters of HTS or conventional cable respectively in this paper. l_i is the length of the cable, km, ω is the conduction loss per unit length of the cable, W/m, θ is the thermal loss per unit length of the HTS cable, W/m, τ_1 is the thermal loss per termination of HTS cable, kW/unit, τ_2 is the thermal loss per joint of HTS cable, kW/unit, by considering manufacturing and transportation constraints, the length of a single HTS cable is generally between 300 m and 500 m. It is assumed that a cable intermediate joint is installed every 500 m [32], ρ is the power consumption coefficient of the cryocooler, which is input power of the cryocooler to remove 1 W of thermal load at the HTS cable operating temperature. The range of ρ based on practical applications in liquid nitrogen temperature is 9.8 to 29 at present [33]. I_i is the current of the cable, A, r is the resistance per unit length of the conventional cable, Ω/m.

Based on this calculation model, the relationship between the power loss of HTS cable and conventional cable during operation can be obtained, and then the efficiency of performance of these two kinds of cables in metropolitan distribution network can be compared.

2.2 Region Selection

A 110/35 kV substation with its distribution network in Tianjin City is selected and its structure is shown in figure 1. The network consists of two 35 kV underground distribution lines, of which line 1 carries electricity to a factory town, and line 2 connects to a 35/10 kV substation for a residential area. Their parameters are shown in table 2. This region belongs to the Class A power supply section and its load density is about 20 MW/km^2 in 2017.

3. Strategies, Schemes, calculations and Analyses

Three strategies to renovate the 35 kV conventional distribution network into an HTS cable distribution network are proposed, equal capacity replacement, expanded capacity replacement, and unequal routing replacement. Based on these three strategies, five implementing schemes that replace conventional cable by 35 kV or 10 kV HTS cable in the selected region are designed, and the details are showed in table 3.

The parameters of the HTS cables used in this study are shown in table 4 [34, 35]. Through calculation, we find that both two kinds of HTS cables with different voltage levels can meet the power capacity requirements of distribution network in the selected region.

3.1 Strategy 1

When conventional cable is replaced by HTS cable with equal capacity and equal length, the total power loss of the two kinds of cable, P_s and P_c, can be calculated with (1) and (2) respectively. When $P_s<P_c$, the HTS cable has more advantages

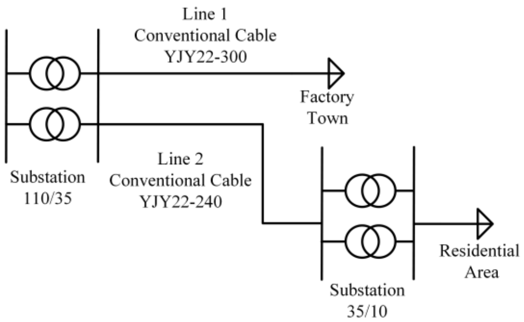

Figure 1. Structure of distribution system in the selected region.

Table 2. Parameters of distribution lines in the selected region

Parameters	Line 1	Line 2
Cable type	YJY22-300	YJY22-240
Cable length (km)	3.8	6.7
Voltage level (kV)	35	35
Cable capacity (MVA)	34	31
Three-phase resistance (Ω/m)	2.36×10^{-4}	2.93×10^{-4}
Annual peak load in 2016 (MVA)	28	18
Rated current (A)	462	297
Annual load growth rate in 2017 (%)	5.2	4.8

Table 3. Strategies and schemes proposed in this study

Strategies	Schemes	
Strategy 1 Equal capacity replacement	Scheme 1	35kV conventional cables in the selected region are replaced by 35kV HTS cables.
	Scheme 2	35kV conventional cables in the selected region are replaced by 10kV HTS cables.
Strategy 2 Expanded capacity replacement	Scheme 3	35kV HTS cables are used to expand the power capacity of the selected region.
	Scheme 4	10kV HTS cables are used to expand the power capacity of the selected region.
Strategy 3 Unequal routing replacement	Scheme 5	10kV HTS cables with T-joints are used to renovate the distribution network in the selected region.

in energy-saving. The criterion should be fulfilled as follows in this case

$$\left(2\tau_1-\tau_2\right)\rho<\left\{I^2r-\left[\left(\omega+\theta\right)\rho+2\tau_2\rho+\omega\right]\right\}l \tag{3}$$

A and B can be defined according to

$$A=\left(2\tau_1-\tau_2\right)\rho \tag{4}$$

$$B=I^2r-\left[\left(\omega+\theta\right)\rho+2\tau_2\rho+\omega\right] \tag{5}$$

where A denotes the part of the HTS cable power loss during operation and unrelate to the cable length, which is due to

Table 4. Parameters of HTS cables used in this study

Parameters	35 kV Transmission Line	10 kV Transmission Line
Cable type	Three-phase independent HTS cable with warm dielectric	Three-phase coaxial HTS cable with cold dielectric
Cable capacity (MVA)	121	52
Conduction loss of cable (W/m)	1.44	1.2
Thermal loss of cable (W/m)	1.68	1.5
Thermal loss of termination (kW/unit)	0.36	0.12
Thermal loss of joint (kW/unit)	0.06	0.02

thermal loss of terminations and joints. B denotes the difference in power loss during operation between the body of conventional cable and HTS cable per unit length, which is the power difference and related to the cable length.

Normally, τ_1 is much greater than τ_2, so that the value of A is greater than 0. When $B\leq 0$, the relationship between each parameter can be obtained as

$$I \leq \sqrt{\frac{\left[\left(\omega+\theta\right)\rho+2\tau_2\rho+\omega\right]}{r}} \tag{6}$$

At this time, regardless of the length of the HTS cable, P_s cannot be less than P_c, which means that HTS cable cannot able to realize energy saving. When $B>0$, we can get

$$I > \sqrt{\frac{\left[\left(\omega+\theta\right)\rho+2\tau_2\rho+\omega\right]}{r}} \tag{7}$$

In this case, a minimum of l can be deduced

$$l_{\min} = \frac{A}{B} = \frac{\left(2\tau_1-\tau_2\right)\rho}{I^2 r-\left[\left(\omega+\theta\right)\rho+2\tau_2\rho+\omega\right]} \tag{8}$$

l_{min} represents the minimum energy-saving length of HTS cable and when $l>l_{min}$, $P_s< P_c$, which means that the HTS cable can realize the advantage of energy-saving.

3.1.1 Scheme 1. In scheme 1, 35 kV conventional cables in the selected region are replaced by 35 kV HTS cables, and the transmission capacity and routing of each line remain unchanged. The renovated power distribution system structure is shown in figure 2 (a). By substituting the parameters in table 3 and table 4 into (4) and (5), it can be found that for line 1, when $B=B_1>0$,

$$I_1 > \sqrt{\frac{3.24\rho_1+1.44}{2.36\times10^{-4}}} \tag{9}$$

There is a minimum of l in this case, i.e.

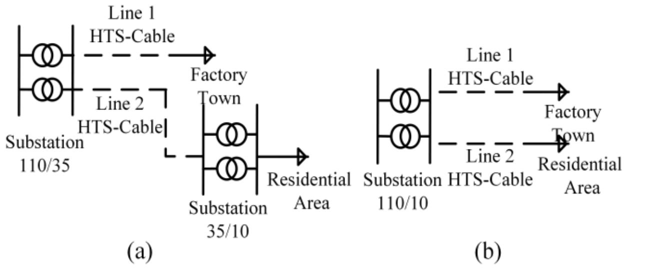

Figure 2. Structures of selected distribution system renovated by strategy 1. (a) Structure of selected distribution system renovated by scheme 1. (b) Structure of selected distribution system renovated by scheme 2.

$$l_{1\min} = \frac{A_1}{B_1} = \frac{0.66\rho_1}{2.36\times10^{-4}\times I_1^{\,2}-3.24\rho_1-1.44} \tag{10}$$

When $l_1>l_{1min}$, $P_{1s}<P_{1c}$, which means that for line 1, using HTS cable has energy-saving advantages than using conventional cable. The subscript '1' represents the parameters of line 1.

By substituting the rated current of line 1 into (9), it is obtained that when the cryocoolers with $\rho_1<15.1$ are adopted here, the l_{1min} exists. By considering the current cryocooler manufacturing technology in the world, the inverse Brayton cryocoolers with $\rho=14$ are selected in this study [36, 37]. Then l_{1min} obtained by (10) is 2.59 kilometers. Since $l_1=3.8$ km and $l_1>l_{1min}$, using 35 kv HTS cable to distribute power for line 1 can realize its energy-saving advantages in scheme 1.

For line 2, when $B=B_2>0$, we get

$$I_2 > \sqrt{\frac{3.24\rho_1+1.44}{2.93\times10^{-4}}} \tag{11}$$

The minimum of l in this case is given by

$$l_{2\min} = \frac{A_2}{B_2} = \frac{0.66\rho_2}{2.93\times10^{-4}\times I_2^{\,2}-3.24\rho_2-1.44} \tag{12}$$

When $l_2>l_{2min}$, $P_{2s}<P_{2c}$. Similarly, the subscript '2' represents the parameters of line 2.

It is obtained according to (11) that when the cryocoolers with $\rho_2<7.5$ are adopted here, the l_{2min} exists. The power consumption coefficient of cryocoolers adopted in this study is 14, which does not satisfy the above condition, consequently, regardless of the length of the line 2, using 35 kV HTS cable to distribute power for line 2 cannot realize its energy-saving advantages in scheme 1.

By substituting the parameters of 35 kV conventional cable and 35 kV HTS cable in table 2 and table 4 into (1) and (2), it can be figured out that P_{1s}=187.07 kW, P_{1c}=191.42 kW, P_{2s}=322.8 kW, P_{2c}=173.16 kW, namely the operation power loss of HTS cable is lower than that of conventional cable for line 1, whereas is higher for line 2. The total power dissipated by 35 kV conventional cables in the selected region is 364.58 kW. However, if 35 kV HTS cables with equal capacity and length are used, the total power loss is 509.87 kW, which is 139.9% of that of using conventional cables. Therefore, HTS cable distribution network is not energy-saving when scheme

1 is used to renovate the distribution network in the selected region.

3.1.2 Scheme 2. In scheme 2, 10 kV HTS cables are used to replace 35 kV conventional cables in the selected region, and the transmission capacity and routing of each line remain unchanged as same as scheme 1. The renovated power distribution system structure is shown in figure 2 (b). For line 1, when $B=B_{l2}>0$, with (4) and (5), we get

$$I_1 > \sqrt{\frac{2.74\rho_1 + 1.2}{2.36\times10^{-4}}} \tag{13}$$

$$l_{1\min} = \frac{A_1}{B_1} = \frac{0.22\rho_1}{2.36\times10^{-4}\times I_1^2 - 2.74\rho_1 - 1.2} \tag{14}$$

In this case, when $l_1>l_{1min}$, $P_{1s}<P_{1c}$.

According to (13), when $\rho_1<17.9$, the l_{1min} exists. By substituting $\rho_1=14$ into (14), $l_{1min}=0.28$ km can be figured out. Since $l_1>l_{1min}$, using 10 kV HTS cable to distribute power for line 1 can realize its energy-saving advantages in scheme 2.

For line 2, when $B=B_{l2}>0$,

$$I_2 > \sqrt{\frac{2.74\rho_1 + 1.2}{2.93\times10^{-4}}} \tag{15}$$

$$l_{2\min} = \frac{A_2}{B_2} = \frac{0.22\rho_2}{2.93\times10^{-4}\times I_2^2 - 2.74\rho_2 - 1.2} \tag{16}$$

When $l_2>l_{2min}$, $P_{2s}<P_{2c}$.

According to (15), when $\rho_2<9.0$, the l_{2min} exists. Therefore, using 10 kV HTS cable to distribute power for line 2 cannot realize its energy-saving advantages in scheme 2.

By substituting the parameters of 10 kV HTS cable in table 4 into (1), it can be figured out that P_{1s}=153.41 kW, P_{1s}=268.13 kW. The total power loss of 10 kV HTS cables with equal capacity and length to the original 35 kV conventional cables used in the selected region is 421.54 kW, and is 115.6% of that of original conventional cables. Hence HTS cable distribution network cannot realize energy-saving advantages when scheme 2 is used to renovate the distribution network in the selected region, and this result is similar to the result of scheme 1.

3.1.3 Summary. According to (9), (11), (13), and (15), the relation curves between the current flowing through the conventional cable and the power consumption coefficient of the cryocooler can be obtained and shown in figure 3. The area above the curve is the area where the energy-saving length of the HTS cable exists, namely when the length of HTS cable is greater than a certain critical length of energy saving, HTS cable can show energy-saving advantages in this area. It can be seen from the graph that when the current flowing through the conventional cable is greater than a certain minimum current, energy-saving length of the HTS cable exists, which makes the HTS cable possible to show the advantages in energy saving. The smaller the power consumption coefficient of the cryocooler is, the smaller the minimum current can

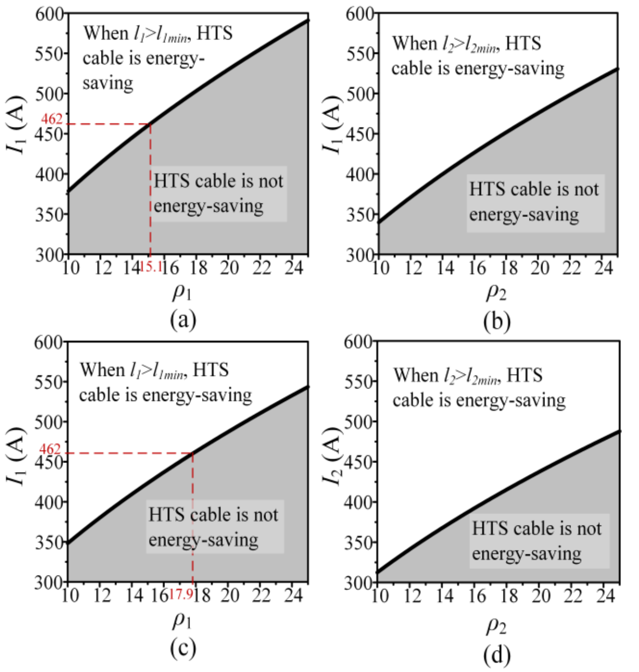

Figure 3. The relation curve between the power consumption coefficient of the cryocooler and the current of conventional cable. (a) The relation curve between the power consumption coefficient of the cryocooler and the current of conventional cable for line 1 in scheme 1. (b) The relation curve between the power consumption coefficient of the cryocooler and the current of conventional cable for line 2 in scheme 1. (c) The relation curve between the power consumption coefficient of the cryocooler and the current of conventional cable for line 1 in scheme 2. (d) The relation curve between the power consumption coefficient of the cryocooler and the current of conventional cable for line 2 in scheme 2.

satisfy the condition.

Figure 4 shows the relation curves between the current of conventional cable and the minimum energy-saving length of cable when cryocoolers with the power consumption coefficient of 10-25 are adopted. Moreover the relation curves in the case of using cryocoolers with a power consumption factor of 14 are enlarged in this figure. Figure 4 (a)-(d) correspond to (10), (12), (14), and (16) respectively. For line 1, the minimum energy-saving length of cable l_{1min} exists only when a 35 kV HTS cable replacing the conventional cable whose transmission current is above 445.3 A, or a 10 kV HTS cable replacing the conventional cable whose current is above 409.4 A. When $l_1>l_{1min}$, HTS cable is more energy-saving. For line 2, l_{2min} exists only when 35 kV HTS cable replacing the conventional cable whose transmission current is above 399.7 A, or 10 kV HTS cable replacing the conventional cable whose current is above 367.4 A. When $l_2>l_{2min}$, HTS cable is more energy-saving. All those curves indicate that the smaller the power consumption coefficient of the cryocooler and the larger the demand for transmission capacity, the more likely the HTS cable show advantages over the conventional cable in energy saving.

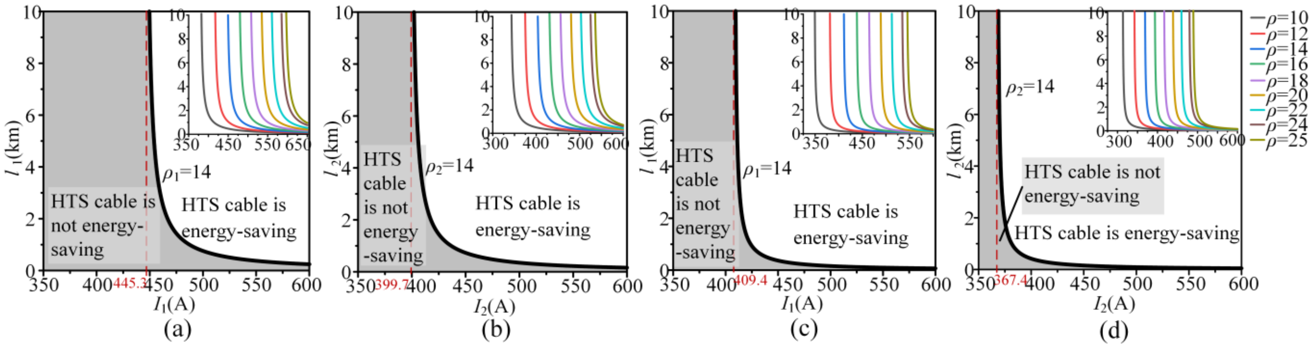

Figure 4. The relation curves between current and cable length when using cryocoolers with different power consumption coefficients. (a) The relation curves between current and cable length for line 1 in scheme 1. (b) The relation curves between current and cable length for line 2 in scheme 1. (c) The relation curves between current and cable length for line 1 in scheme 2. (d) The relation curves between current and cable length for line 2 in scheme 2.

The results of scheme 1 and scheme 2 suggest that the power loss of 10 kV HTS cable distribution network is slightly less than that of using 35 kV HTS cable distribution network due to smaller loss parameters (ω_s, θ_s, τ_1, and τ_2). However, HTS cable distribution system cannot realize its energy-saving advantages whether using 35 kV or 10 kV HTS cables to replace the original 35 kV conventional cables with equal capacity and length in the selected region.

3.2 Strategy 2

From above analysis, the HTS cable cannot realize its energy-saving advantages and the request of underground resources cannot be alleviated by strategy 1 as well in the selected region. Since the HTS cable has much enhanced current carrying capability, power capacity expansion in metropolises using HTS cables is considered. In order to compare the power loss of conventional cables and HTS cables under different transmission capacities, a capacity factor [31] is defined according to

$$R = \frac{\text{Capacity of HTS cable}}{\text{Capacity of conventional cable}} \tag{17}$$

The transmission capacity of the line can be expanded to R times of the conventional cable by using HTS cable. When $P_s < RP_c$ after capacity expansion, HTS cables have more energy-saving advantages.

3.2.1 Scheme 3. In scheme 3, the total power loss of using 35 kV conventional cables or 35 kV HTS cables to realize power expansion in the selected region has been calculated. The structure of HTS cable distribution system is shown in figure 5 (a). By substituting the capacity of 35 kV conventional cable and 35 kV HTS cable (refer tables 2 and 4) into (17), it is obtained that R_1=3.6 and R_2=3.9. Based on the results of scheme 1, it can be figured out that R_1P_{1c}=689.11 kW, R_2P_{2c}=675.32 kW, and the total power loss of 35 kV conventional cables used in the selected region is 1364.43 kW. Moreover, the total power loss of 35 kV HTS cables used in this case is as same as that of scheme 1, which is 509.88 kW,

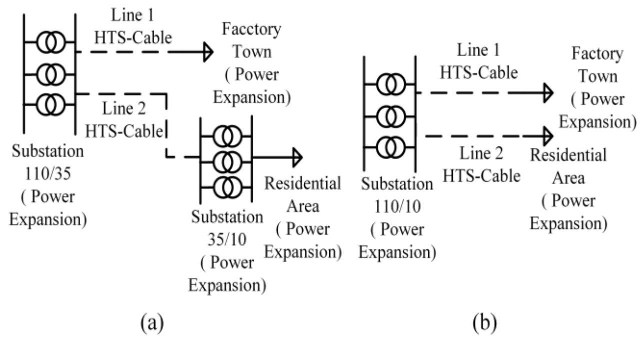

Figure 5. Structures of selected distribution system renovated by strategy 2. (a) Structure of selected distribution system renovated by scheme 3. (b) Structure of the selected distribution system renovated by scheme 4.

and is 37.4% of that of using conventional cables in this case. This result means when the capacity of the transmission line in the selected region is expanded, the total power dissipated by using 35 kV HTS cables is much less than that dissipated by using 35 kV conventional cables.

3.2.2 Scheme 4. In scheme 4, 10 kV HTS cables are used to realize power expansion of selected region, the structure of that is shown in figure 5 (b). R_1=1.5 and R_2=1.7 are calculated based on (17). According to the result of scheme 2, the power loss of 35 kV conventional cable in each line can be figured out as R_1P_{1c}=287.13 kW, R_2P_{2c}=294.37 kW. The total power loss of 35 kV conventional cables used in the selected region is 581.5 kW, whereas that of 10 kV HTS cables is 421.54 kW, which is 72.5% of that of using conventional cables. This result means when the capacity of the transmission lines in the selected region is expanded, the total power dissipated by using 10 kV HTS cables is much less than that dissipated by using 35 kV conventional cables.

3.2.3 Summary. According to strategy 2, it is found that either 35 kV or 10 kV HTS cables can show remarkable energy-saving advantages compared with the conventional cables in the selected region. In addition, when the HTS cables with larger capacity is adopted, the multiple of power expansion is greater than using HTS cables with smaller capacity, and the energy-saving effect is more significant.

3.3 Strategy 3

The T-joint of HTS cable is introduced in the design of HTS cable distribution network in strategy 3. The T-joint of HTS cable is a kind of multi-way joint used in superconducting cable system, which can realize the connection of multi-way superconducting cables [38]. Using HTS cable with T-joint for power distribution can not only solve the problem of shunting current during operation, but also optimize the layout of underground cable and remove unnecessary distribution lines, thereby alleviating the shortage of underground resources in metropolises. The length of HTS cable lines are no longer equal to that of conventional cables in the selected region by introducing the T-joint. The power loss of conventional cable and HTS cable is given by (1) and (2), when $P_s<P_c$, the criterion should be fulfilled as follows

$$\left[(\omega+\theta)l_s+2\tau_1+(2l_s-1)\tau_2\right]\rho+\omega l_s<I^2 r l_c \qquad (18)$$

With the introduction of T-joint, HTS cables may be able to achieve the advantages of energy conservation in the cases that they cannot realize energy-saving superiority otherwise.

3.3.1 Scheme 5. In this scheme, the T-joint and 10 kV HTS cables are used to renovate the 35 kV conventional cable in the selected region. The structure diagram after transformation is shown in figure 6. The renovated line 1 consists of a 10 kV HTS cable, which transfers all the required electric energy in this region from 110/10 kV substation to the factory town, and then the T-joint installed in the factory town is used to shunt the required power to the residential area through a 10 kV HTS cable.

For line 1 in this scheme, the length and power loss before and after transformation are same as that of line 1 in scheme 2. Whereas line 2 after transformation in this scheme is no longer the line from substation to residential area, but the line from factory town to residential area. The cable length for line 2 after transformation in this scheme is 3.24 km.

By substituting the parameters of line 2 before and after transformation into (1) and (2), it can be figured out that P_{2s}=131.25 kW. The power loss of line 1 before and after transformation and line 2 before transformation has been calculated in scheme 2. The results show that the total power loss of 35 kV conventional cables used in the selected region is 364.58 kW, and that of 10 kV HTS cables used in this case is 284.66 kW, which is 78.1% of that of using conventional cables. It means HTS cable can realize the energy-saving advantages by strategy 3.

3.2.3 Summary. By substituting the parameters of line 2

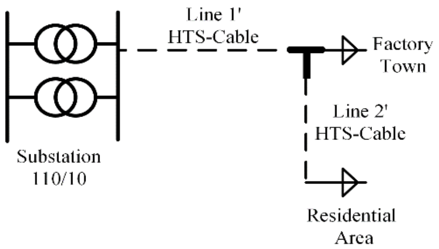

Figure 6. Structure of the selected distribution system renovated by strategy 3 (scheme 5).

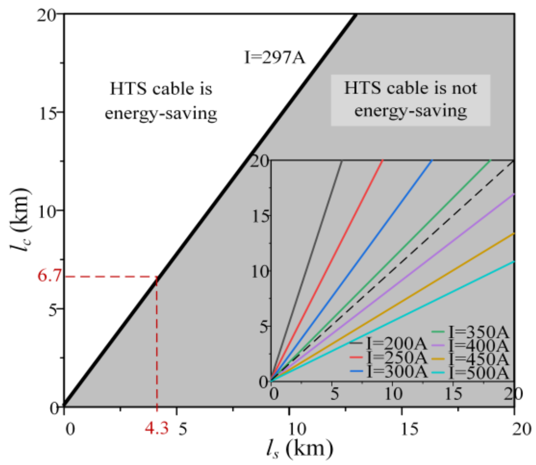

Figure 7. The relation curves between energy-saving length of HTS cable and conventional cable at different currents.

before and after transformation into (18), we can get

$$39.56l_s+3.08<I^2\times2.93\times10^{-4}\times l_c \qquad (19)$$

The relation curves between energy-saving length of HTS cable and conventional cable at different current can be obtained and shown in figure 7. Above the curve is the energy-saving area. Since the current of line 2 is 297 A, the relation curve in the case where the current is 297 A is enlarged in this figure. When the length of conventional cable before transformation is 6.7 km, the maximum energy-saving length of the HTS cable is 4.3 km, which is greater than the actual length of the HTS cable in scheme 5. Therefore, the HTS cable is energy efficient in scheme 5, as evidenced by calculation results above. Moreover, it also can be found that when the length of the conventional cable is determined, the larger the current, the longer the maximum energy-saving length of the HTS cable, the easier the HTS cable to realize the energy-saving advantages. It indicates that when the capacity demand is large enough, the distribution network renovated by HTS cable is energy-saving even if the length of HTS cable is longer than that of conventional cable before transformation.

4. Discussions

Based on the analyses of the above five schemes, a bar chart of operation power loss of HTS cable distribution network and conventional cable distribution network in five schemes can be obtained and shown in figure 8.

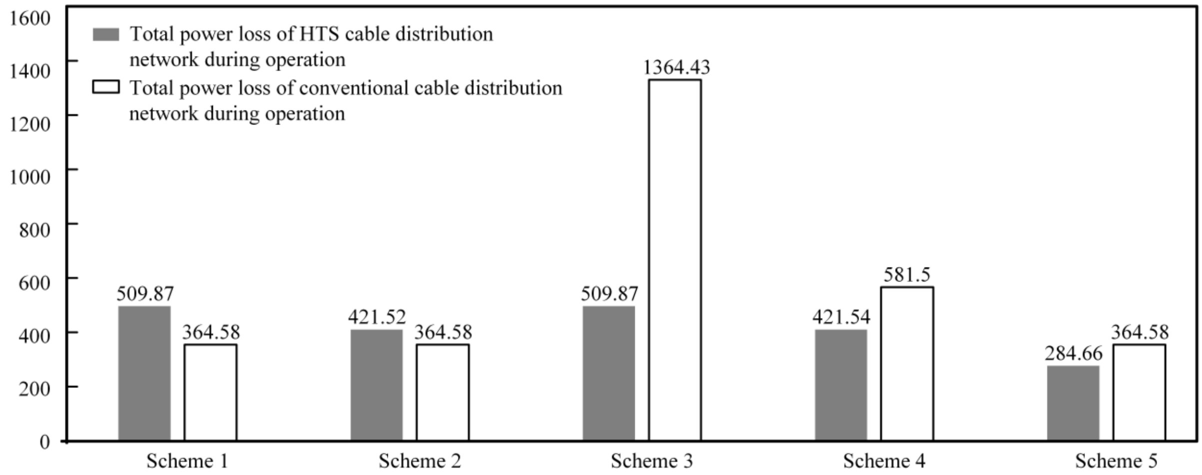

Figure 8. Total power loss of HTS cable distribution network and conventional cable distribution network in the five schemes.

According to the parts of scheme 1 and scheme 2 in this figure, it can be seen that the power dissipation of HTS cable distribution network is more than that of conventional cable distribution network by strategy 1. For the conventional cable distribution network, transmission lines tend to have higher voltage and smaller current in order to reduce power loss, and the transmission capacity of the conventional cable is usually smaller (much smaller than the transmission capacity of the HTS cable of the same voltage level). Moreover, the power consumption coefficient of cryocoolers used for HTS cables is generally high at present limited by manufacturing technology. All of these factors lead to the fact that replacement of conventional cables by HTS cables with equal capacity and length cannot save energy in the selected distribution system of this study.

When the power capacity of distribution network in the selected region is expanded, the conventional cable distribution network has to increase its transmission current or increase the number of cables, which makes its operation power loss greatly increased. However, the HTS cables selected in scheme 1 and scheme 2 can still meet the capacity demand in this case, which makes the energy-saving advantages of HTS cable distribution network significantly reflected in scheme 3 and 4. Moreover, the larger the capacity of the HTS cable are adopted, the more obvious the advantages of energy saving are.

In scheme 5, there is no power expansion for the distribution network in the selected region, so the power loss of conventional cable distribution network is the same as that in scheme 2. But in this scheme, the T-joint is used to optimize the route of the HTS cable distribution network. This transformation method shortens the length of the HTS cable, which can compensate for the power loss caused by the high power consumption coefficient of the cryocooler. It can be seen from the figure 8 that the power loss of the HTS cable distribution network in scheme 5 is less than that in scheme 2, and also less than the power loss of the conventional cable distribution network in this region, which means HTS cable distribution network renovated by strategy 3 is more energy-saving as compared with conventional cable distribution network. However, the technology for HTS cable T-joint is still immature now, and there is no application example in the world.

The region selected in this paper belongs to the Class A power supply section and the load growth rates of line 1 and line 2 are 5.2% and 4.8% respectively in 2017. These data show that although the load density in this region is large, the load growth rate is moderate. This may be due to the fact that the region is now in the adjustment stage after the explosive economic growth in China. By comparing the calculation results and considering the technical maturity of the three transformation strategies, it is most appropriate to use the strategy 2 to optimize the distribution network in the selected region. Power expansion by strategy 2 not only can satisfy the power demand in subsequent decades, but also can improve the energy-saving advantages of HTS cables greatly.

Considering the load growth rates of line 1 and line 2 in 2017, using 10 kV HTS cables to optimize the distribution network in the selected region can meet the power demand in the next 10 years [39]. In addition, reducing the voltage level of distribution network can cut down the investment of power equipment in high voltage level and simplify the structure of the power grid, which can save costs and improve the reliability of distribution network. Therefore, adopting 10 kV HTS cables to expand the power capacity of the distribution network in the selected region is a better optimization scheme.

5. Conclusion

This study focused on the feasibility of applying HTS cable to urban distribution network. Three strategies and five schemes are proposed for replacing conventional cables with HTS cables for a selected distribution network in Tianjin. The results show that:

1) At high current level and sufficient transmission length, HTS power transmission are energy saving.
2) In certain cases, transmission voltage can be lowered with the replacement of conventional cables with HTS cables at the same transmission capacity and lower transmission loss.
3) HTS cables may not energy-saving to replace conventional cables with equal capacity and length in some cases. However, under expanded capacity with increasing power demand, HTS cables can be beneficial.
4) T-joint connected HTS cables can optimize the underground structure and remove unnecessary lines, which not only reduce the power dissipation but also greatly alleviate the shortage of underground resources faced by most metropolises.

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