# Next Generation of DC Power Transmission Technology Using High $T_c$ Superconducting Cables

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***Abstract*****--High $T_c$ superconducting (HTS) cables and their application to develop a DC electrical power transmission system with the advantages of high transport current capability, low resistive loss, and compact systems have been studied and verified. Technical assessments of DC transmission behaviors with the use of the HTS DC cable technology have been carried out with the HTS DC cable and the system models built. The analysis results are presented in this paper, as well as discussion of economical benefits of this new technology.**

***Index Terms*****--High $T_c$ superconducting (HTS) cables, DC electrical power transmission, power system, power system analysis.**

## I. Introduction

THE 21st century is the age of superconducting cable, according to the forecast of the World Bank Institution, 80 percent of the traditional grounding cables could be substituted with high $T_c$ superconducting (HTS) cables in 2020. Using the mechanical distortion and heat treatment to obtain preferably crystalloid tropism Bi HTS tapes, physical and chemical deposition to obtain long film tapes, there is the ability to volume-produce a few kilometers long HTS wires for a single length in the United States, Japan, China and Germany. The resistive energy losses consumed on power transmission lines become enormous as the high capacity delivery power required by the dramatically developed society. Using HTS technology is an alternative way to resolve the principal technical difficulties to achieve high efficiency in power transmissions [1]. The HTS cable will especially benefit to DC power transmission due to zero resistive loss and lowering voltage levels [2], [3]. The DC networks can operate with low voltage and high current allowing direct connection of the generators to the rectifiers, eliminating the need for high voltage insulation and transformers.

The development of HTS tapes and cables, and a conceptual superconducting DC cable model will be presented in this paper. Power transmission performance studied by numerical simulations using the Matlab/Simulink, and analysis of the system loss and economical benefit will also be presented.

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## II. Development of Superconducting Cables

HTSs have been developed since 1986, the successfully produced HTS wires, with long length, high critical current density and mechanical flexibility, have the capability to be operated at 77 K liquid nitrogen temperature for electrical applications. The R&D of HTS power applications has included many fields, however among all possible power applications of HTSs, the power transmission cable is more significant. There are a few countries which have initiated HTS cable development programs, the world's first applicable HTS cable 30m/12.5kV/1.25kA with three single phases [4] developed by the Southwire, were constructed during the first two quarters of 1999, installed by the third quarter of 1999, energized on Jan. 6, 2000, and inauguration on Feb. 18, 2000. The second superconducting 30m/30kV/104MW cable system [5] designed with a room temperature dielectric and based on a HTS Bi-2223 tape technology has been developed, installed and operated in the public network of Copenhagen Energy in a two-year period between May 2001 and May 2003. The third HTS cable project for a 30m/35kV/2kA, 3 phases, warm dielectric HTS power cable system [6] is operated in China, which has been installed in the China southern power grid at the Puji substation in Kunming, Yunan province, in 2004. Fig. 1 is the 30 m HTS cable operated at the Puji substation, the loads of the cable are the company's production workshops. Table I shows the parameters of the first three HTS cables running in practical networks. American, Japan et al plough into the investigation of HTS AC cables, their object and hope is to realize short distance (<500m), low loss, and high capacity power transmission. AC electric power transmission currently is the main way of power delivery and commonly used, which somehow results to HTS DC cable investigation lagged to HTS AC cables. The HTS zero resistance is observed only in DC currents, therefore a HTS DC cable and its DC transmission has better performance than for the AC case in which HTS AC loss exists. With the use of HTS DC cables, the transmission line voltages can be lower than conventional cables when the same power is transmitted because of the greater transmitting current capability, and also the AC/DC convertors on the termination of DC transmission cable become simple and low cost consequently.

Fig. 1. HTS cable site at Puji substation in China.

TABLE I
PARAMETERS OF THE FIRST THREE HTS CABLES RUNNING IN NETWORKS

| Nations | America | Denmark | China |
|---|---|---|---|
| Rating voltage | 12.5kV | 36kV | 35kV |
| Rating power | 26MW | 104MW | 121MW |
| Refrigeration structure | CD double channel | WD single channel | WD double channel |
| Running temperature | 70~80K | 76.5 ~79.5K | 70~76K |
| Bending radius | -- | <1.5m | <1.5m |
| Termination loss | 230W/each | 150W/ea. | 108W/ea. |

HTS cables can not completely avoid transmission resistive loss in AC cases. Moreover it is necessary to take measures to solve the problems inherited to HTS AC cable, such as protecting against short circuit current and solution to avoid unbalanced AC current in each HTS conductor tape. The HTS DC cable, on the other hand, is a cable that utilizes the advantages of superconductivity most effectively and shows no problem inherited to HTS AC cables.

## III. SUPERCONDUCTING TAPES AND PERFORMANCES

The Bi-based HTS wires, especially the metal (Ag) clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_{10+x}$ (Bi-2223/Ag) wires, have achieved high critical current $I_c$ under low magnetic fields, long length with flexible mechanical property, and have reached the requirement of some electric applications [7], [8]. The critical current density $J_c$ of the HTS wires operated at liquid nitrogen temperature 77 K (1μV/cm and self field) can reach to $J_c = I_c / CS_{HTS} \approx 7 \times 10^4$ A/cm$^2$, where $CS_{HTS}$ is the cross section of the HTS material. When taking the whole HTS wire as a conductor, worked at 77 K, the engineering current density $J_e = I_c / CS \sim 10^4$ A/cm$^2$, where CS is the whole cross section of the whole wire. It was a few decuple times as the traditional copper conductor's rating current density $J_{Cu} \approx 3 \times 10^2$ A/cm$^2$. But the high cost of Bi-based HTS tapes about a few times as the copper conductor, and some other performance problems such as its poor mechanical flexibility and its $J_c$ attenuation sharply on magnetic field made it difficult to take domination position in transmission systems at present. Compared with Bi-based HTS tapes - the first generation (1G) HTS wire, the Yttrium based oxide $Y_1Ba_2Cu_3O_{6+x}$ tapes - the second generation (2G) HTS wires, its anisotropism is relatively infirmness and have higher $I_c$ near liquid nitrogen temperature with higher magnetic field tolerance. The $I_c$ of the 2G HTS tape produced has reached uniform high $J_c$ with applicable long lengths. According to the preparation process of the 2G HTS tapes, leaving out noble metal silver used to produce Bi-based HTS tapes, the cost is lower than the 1G Bi based HTS tapes, meanwhile the carrying capacity is higher than the 1G HTS tapes, and the superconducting performance is better at high magnetic field than the 1G HTS tapes. The 2G HTS tapes made in United States have reached to a kilometer level in a single length, and also a few hundred meters in a single length in Japan [9]. The HTS wire production cost has been reduced, but the practical HTS application cost still needs to add up the HTS material and its refrigeration cost. The price predominance of new $MgB_2$ superconductor worked at 20-30 K is distinct. In recent years, some methods have been used to prepare $MgB_2$ tapes or wires, U.S., Japan and Europe have made some excellent work in producing $MgB_2$ and have the ability to produce long wires. China is also undertaking the investigation of producing $MgB_2$ wires.

The HTS tape's DC *I-V* characteristic is important for DC power applications; it can be described as the following exponent hypotaxis

$$V = V_0 \left( I_{\mathrm{HTS}} / I_0 \right)^{\mathrm{n}} \quad (1)$$

where $I_{HTS}$ is the current flow through the HTS conductor, and $I_0$ is the current when the voltage is $V_0$. n reflects the *I-V* curve's shape and the HTS conductor quality, which can be calculated by electro-intensity criterion $E_{c1} = 0.1$ μV and $E_c = 1$ μV, the critical current $I_{c1}$ and $I_c$ obtained through electro-intensity criterion $E_{c1} = 0.1$ μV and $E_c = 1$ μV, so n can be described as

$$n = \frac{\log E_c - \log E_{c1}}{\log I_c - \log I_{c1}} \quad (2)$$

For the Bi-2223/Ag compound HTS tapes, when used to produce a DC cable, which is under the conduction of the frequency of chord current being zero, the current distribution between conductor core and metal silver harness can be expressed as

$$I = I_0 \left( V/V_0 \right)^{1/\mathrm{n}} + V/R_{\mathrm{s}} \quad (3)$$

where $I$ is the total current of HTS wire, and $R_s$ is the metal sheath resistance outer the superconductor that is silver. If AC ingredient in a DC system is taken into account, and considering the HTS worked under the above critical magnetic field $B_{c1}$, the flux would penetrate to the superconductor, and produce AC losses. Based on Bean model, when the environment field is less than the penetrated field $B_p$, the AC loss can be shown as

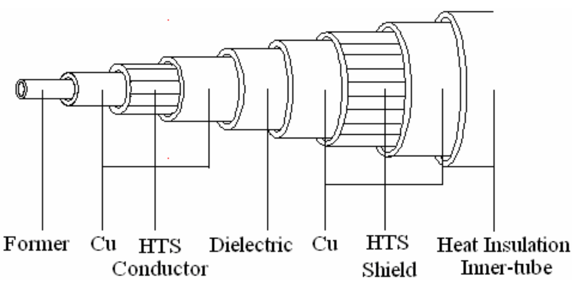
$$P = \frac{4\sqrt{2}}{3}\mu_0\left(\frac{I}{p_e}\right)^3 p_e f / J_c \qquad (4)$$

where $P_e$ is the perimeter of superconductor, $f$ is the frequency of the AC current.

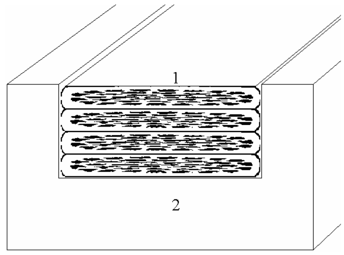
## IV. A CONCEPTUAL HTS CABLE MODEL

The HTS DC cable design has a concentric structure shown in Fig. 2, cold dielectric was used, and the main body of this cable from inner to outer is former, compounded conductor that is copper composite with parallel placed HTS tapes, dielectric, compounded shield, and then the whole cable core covered by a thermally insulated double wall cryostat. The liquid nitrogen goes through the hollow former and returns at the other end in the space between the outer layers of HTS tapes and below the cryostat. The configuration of this cable can be used as the DC line of monopole or double pole DC power transmission. The HTS conductor and the HTS shield act as guide line and circumfluence line respectively. The magnitude of current that flows in HTS conductor and HTS shield is equivalent, but the orientation is contrary, so there is no current flow through grounding site and mother earth in the double pole DC transmission system. The shield's current shields the magnetic field effectively. The Bi-2223/Ag HTS tapes are used which can be produced commercially as cable conductors, the $I_c$ of each tape is over 100 A in a typical cross section about 3 mm × 0.2 mm. An inner stainless steel former, which design to contain liquid nitrogen flowing at a rate appropriate to cool the cable conductor, is surrounded by HTS tapes were placed parallel in specially designed copper rectangular grooves, the copper acting as both a mechanical support and as a potential current shunt for fault conditions. It is that the composite of copper and HTS tapes are used as the cable conductor, at the same time, the composite of copper and HTS tapes are used to be cable shield, and the fill in coefficient of the conductor layer and the shield layer is small.

Recently, a 0.5 m long experimental HTS DC cable has been built by the author's group with the 2G HTS wires for technical verification, which has 1.6 kA transport current capability in total and its $J_e \sim 10^4$ A/cm$^2$ operated at 77 K.




(a) A HTS DC cable physical model




(b) A practical HTS conductor model
1 - HTS element wires; 2 – A reinforced protection coat

Fig. 2. A HTS DC cable physical model.

## V. SUPERCONDUCTING DC TRANSMISSION SYSTEM ANALYSIS AND SIMULATION

Most of DC transmission systems adopt 12-pulse current convertors using two 6-pulse thyristor bridges connected in series. The converted current transformer provides current, reactive power required by the convertors is provided by a set of AC filters used to prevent the odd harmonic currents 11th, 13th and high pass filters from spreading out on the AC system on each side, and on the each side of the DC line has a smoothing reactor. Fig. 3 illustrates a DC power transmission system using a HTS cable. Matlab/Simulink has been used to set up a model to analysis the performance of a high-voltage direct current (HVDC) transmission system. The example in this section is modeling a HVDC transmission line using 12-pulse thyristor convertors. Perturbations can be applied to examine the system performance. A 1000 MW (500kV, 2kA) DC interconnection is used to transmit power from a 500 kV, 5000 MVA, 60 Hz system to a 345 kV, 10000 MVA, 50 Hz system. The AC systems are represented by damped L-R equivalents with an angle of 80 degrees at fundamental frequency (60Hz or 50Hz) and at the third harmonic.

Fig. 4 shows the sending power and receiving power of the DC transmission system, the front segment of the curve corresponds to the ramped start-up, and the middle pulse segment of the curve corresponds to the DC line fault and AC grounding fault and the resuming process. The power obtained in simulation is from measuring the active power at the sending AC and receiving AC system. Nominal voltage and current were taken in the all analysis and calculation. The sending power subtracted by the receiving power gives the transmission system total power losses which include the loss consumed by transformers, filters, convertors and transmission lines.

Fig. 5 shows the simulation results, where

(i) Curve 1 is the transmission energy loss of 400 kV, 2.5 kA, R = 0.015 Ω/km DC line.
(ii) Curve 2 is the transmission energy loss of 500 kV, 2 kA, R = 0.015 Ω/km DC line.
(iii) Curve 3 is the transmission energy loss of 400 kV, 2.5 kA, R = 0.00015 Ω/km DC line.
(iv) Curve 4 is the transmission energy loss of 500 kV, 2 kA, R = 0.00015 Ω/km DC line.

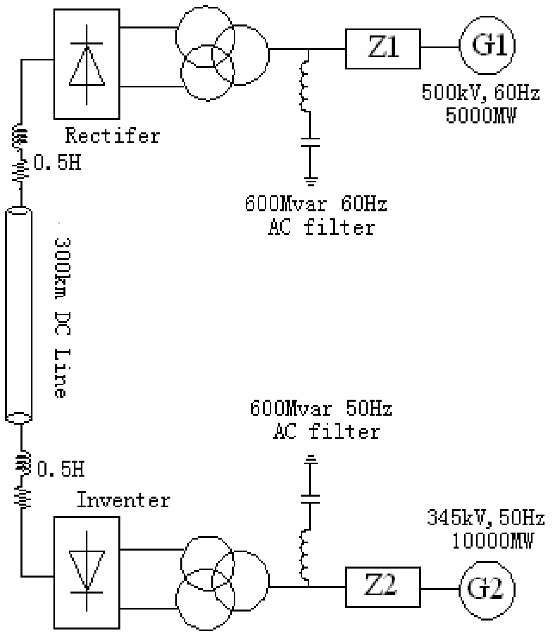



Fig. 3. A thyristor-based 12-pulse HVDC link using a HTS cable.

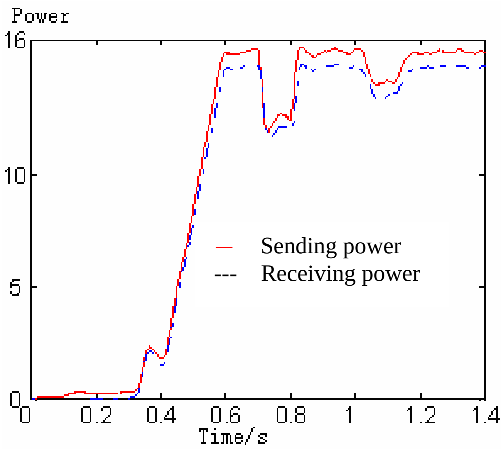



Fig. 4. Sending and receiving power (p.u.).

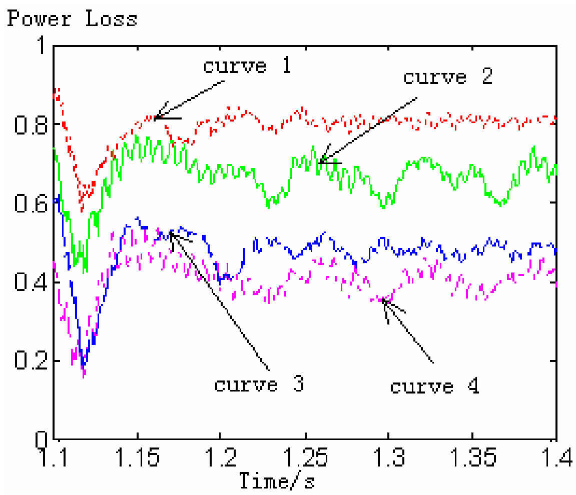



Fig. 5. Power loss comparisons (p.u.).

The simulation results show that the loss of the system increases with the increase of resistance on transmission line and the decrease of transmission voltage level. When the line resistance keeps unchanged, reduces the voltage level, the loss of the system increases in the meantime. If superconducting technologies are used to the DC transmission system, even if at a lower voltage level, the energy loss is still lower than that of the common DC transmission system worked at a higher voltage level.

## VI. Loss Analysis of the Transmission System

There are three components, i.e. convertor station, HTS cable system and grounding system, which are mainly included in the HTS DC transmission system. Therefore the total loss includes the convertor station loss on each side of the cable system, the loss of the cable system itself and grounding system.

The main equipments of the convertor station include convertor transformers, smoothing reactors, AC/DC filters, reactive power compensation and so forth. The loss mechanism of these equipment are different between each other, the characteristic harmonics are produced both on the AC sides and on the DC sides, which would produce some additive losses through convertor transformers, smoothing reactors and AC/DC filters, when the system working on different loads, the losses would be different. Hence, a few charge points between zero charge and full charge are selected to calculate the loss to obtain the convertor station loss, which at the same time can be divided into heat standby loss (zero charge loss or fix-up loss) and running loss including heat standbys loss and charge loss. The loss of convertor station can be obtained by calculating the loss of each component in the convertor station and then all the losses are added up, rather than measuring it directly. Table II summarizes the percentages of different loss items of convertor station [10]; it shows that convertor transformers and thyristor take up the principal loss of the convertor station. So reducing the loss consumed by convertor transformers and thyristors is critical to decrease the total convertor station loss.

The principal purpose of using HTS cables as transmission conductors in DC transmission systems is to reduce energy loss on the power transmission process. The energy loss in a DC HTS cable is negligible when operated below its critical current; the only energy is for cooling, used to keep the low temperature for the superconducting system and the refrigeration medium supply. The loss of the transmission line normally is described by the percentages of the total transmitted power. There are three principal loss contributions: HTS material, insulation, and cryostat to the total loss; and reactive power of HTS cables [11], HTS DC cable has no reactive power and virtually no loss in the insulation, leaving only the heat leak as a loss source. This makes the design and optimization of DC HTS cables much less complex than in the AC case.

TABLE II
LOSS DISTRIBUTION OF CONVERTOR STATION

| Item | Loss percentage |
|---|---|
| Convertor transformers | ~50% |
| Thyristor valves | ~35% |
| Smoothing reactors | ~5% |
| AC filters | ~5% |
| Other losses | ~5% |

The grounding system is one of the critical parts of HVDC transmission system, which contains grounding line loss and grounding pole loss. On the normal condition, the voltage of the grounding line is low enough that it need not take the loss about voltage into account, but only consider the loss in accordance with the current flow into the resistance, therefore, grounding loss is the grounding resistance consumed Joule heats, and the small grounding resistance leads to small grounding loss.

## VII. ECONOMIC BENEFITS OF HTS DC POWER TRANSMISSION

There are two principal technologies used to construct the major components of the convertor station which costs take the major percentage in a DC transmission system, the first one is based upon the classic thyristor current source convertor technology and the other one is based upon voltage source convertor technology. The switching components (valves) in the convertor station consist of individual power electronic components arranged in series-parallel arrays to meet station voltage-current specifications but valves in a convertor represent 20% of the total station cost and the convertor transformers and ac filters represent 16% and 10% respectively. If a HTS cable is used, the valve cost can be further reduced by 50% with a lower voltage level and possible cryo-cooling of the switching components to have higher current capacity; and the lower voltage operation can reduce the transformer and filter costs by 25%. Consequently, the reduction about 15-25% of the convertor station costs could be expected from the lower voltage designs. A conventional voltage source convertor station costs 160-170 $/kVA, and the cost of thyristor based HVDC inverters for overhead transmission is about 175 $/kVA [12].

A bipolar superconducting DC cable system could be easily designed to carry 10-50 kA [12] in principle after estimating the cost of the HTS cable and its refrigeration system, however, in practice, a lower operating current and higher operating voltage base has to be compromised by the fact that electrical insulation is effectively less expensive than superconducting materials.

The HTS cable, characterized by its ultra-high current density and super-low transmission loss, is a promising compact power cable with high transmission capacity, and has a variety of environmental advantages such as energy saving, resource conservation, zero electro-magnetic irradiation, non-explosiveness, non-flammability, and non-toxicity with the liquid nitrogen to act as refrigeration medium [13].

The transmission loss of a conventional cable takes up almost 7% of the total power transmitted, but only 0.5% does a HTS cable. If considering the energy consumed by refrigeration system, then the energy can be eventually saved up to 60%. If at the same size, the transmission power of the HTS cable can rise to 3 to 5 times, the loss can decrease 60% and weight can reduce over 80%. It can be used for short length and high current power transmission such as big city centre power distribution, or electroplate and electrolysis industry, power plant and transformer substation. Cable industry has been at inferior position for a long time, but superconducting technology provides cable industry another chance to bloom. If the grounding cable is changed to HTS cable, the total cost will reduce 20%, thus on the process of rebuilding and increasing the present city electricity network establishment, and the HTS cable would be a good substitute. In China, the demands of polypropylene laminated paper (PPLP) cable over 10 kV reached to 70,000~80,000 kilometer each year, if 5% of them can be replaced by HTS cables, then the total demands of HTS cables each year can reach 3,500~4,000 kilometer; supposing the cable costs ~200 $/meter, then it is close to one thousand million dollars, i.e. if in 2010 the HTS cables possess a 5% Chinese cable market, the total production value can reach about $10^9$ dollars a year. HTS cables can be used to change the traditional power transmission manner, adopt low voltage and high current to transmit electric power. It improves the efficiency, reduces the total transmission system loss, and provides a considerable economical benefit.

## VIII. SUMMARY AND CONCLUSION

The HTS cable used for DC power transmissions has supreme electricity performance. It can be concluded that based on the high $J_c$ HTS conductors and cables, the power capacity of a HTS DC transmission system can increase more than ten times, or use a much lower voltage level to deliver the same energy because of the high current capability of HTS cables. The simulation results have shown that the HTS DC cable exhibits significance to lower energy loss. DC transmission current $I_d$ leads to $R_L I_d^2 = 0$ under liquid nitrogen temperature avoiding the energy being consumed on the transmission line, where $R_L$ is transmission line resistance. As analyzed using Matlab/Simulation, the loss of a 500kV/ 1,000MW/300km/0.015Ω/km traditional DC transmission system is 18 MW. There aren't Joule loss and voltage loss on the HTS DC transmission line, which lead to a lower transmission voltage level that means a lower cost of transmission system including the lower cost for convertor station and electrical insulation materials. Applications of HTSs to power systems have a number of possible advantages in economy, and also reliability and stability, especially for the low-voltage high-current DC transmission.

By using the developed HTS cable and its *I-V* characteristic, a HTS cable model for the DC transmission has been built conceptually. A 1,000 MW (500kV, 2kA) DC interconnection has been used to transmit power from a 500kV /5,000MVA/60Hz system to a 345kV/10,000/MVA/50Hz system. Matlab/Simulink has been used to analyze the performance under different DC transmission cases having different voltage levels, and results proved that the HTS cable DC transmission system has substantial advantages compared to the AC cases. When the superconducting technologies are used to the DC transmission systems, even if at a lower voltage level, the energy loss is still lower than that of the common DC transmission system worked at a higher voltage level. With regard to the economic benefit, there is no conductor loss, dielectric loss, induced heat loss and other AC losses existed in AC cases. The only loss is the heat leak from the heat insulation tube. Therefore the cable configuration for the DC transmission becomes simple in design.

## IX. Acknowledgment

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