New Generation of DC Power Transmission Technology Using HTS Cables

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Abstract -- **High T_c superconducting (HTS) cables and their application to develop a DC power transmission system with substantial advantages have been studied. Technical analysis of the HTS DC electrical power transmission system behaviours have been carried out with the HTS DC cable technology employed and the system models built.**

Index Terms -- **High Temperature Superconductor (HTS), HTS Cable, DC Transmission System, Power System Analysis, Simulation Model, MatLab.**

I. INTRODUCTION

The 21 century is the age of superconducting cable, according to the forecast of the World Bank Institution as an example, 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, there is the ability to volume-produce a few kilometers long HTS Bi tapes 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 our dramatically developed society. Using HTS technology is an alternative way to resolve the principal technical difficulties to achieve high efficient power transmissions [1]. The HTS cable will especially benefit to DC power transmission due to zero resistive loss and lowering voltage levels [2]. 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 will also be introduced.

II. DEVELOPMENT OF SUPERCONDUCTING CABLES

HTSs have demonstrated a great potential to be operated at 77 K liquid nitrogen temperature for electrical applications. Among all possible power utility applications of HTSs, the HTS power transmission cable has greater importance. There are a few countries which have started HTS cable development program, a 30m/12.5kV/1.25kA HTS cable developed by the Southwire [3], was 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. Then the second superconducting 30m/30kV/ 104MW cable system [4] 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 [5] is operated in China, which has been installed in the China southern power grid at the Puji substation in Kunming, Yunan province, in 2004. Figure 1 is the 30 m HTS cable operated at the Puji substation, the loads of the cable are the company's production workshops. Table 1 gives out the parameters of the first three groups of HTS cable running in network. Recently, 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. The AC electric power transmission is the main way of power delivery, which results to HTS DC cable investigation lagged to HTS AC cables. The zero resistance of HTS material is observed only in DC currents, while transmission loss is commonly generated by AC currents. The DC transmission line voltages can be lower than conventional cables when the same power is transmitted because of the greater current, and also the AC/DC converters on the termination of DC transmitted cable become simple and low cost consequently.

HTS cables can not completely avoid transmission resistive loss in AC cases. Moreover it is necessary to take measures to solve the problems inherented 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, utilizes the advantages of superconductivity most effectively and shows less problem inherented to HTS AC cables. Therefore, the DC application of HTS cables can be designed with optimizing the HTS tapes.

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

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

Figure 1 HTS cable site at Puji substation in China

III. HTS WIRES AND PERFORMANCES

The metal clad Bi-based HTS wires, especially the 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 [6-11]. 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, which 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, which 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 not yet to take dominant position in transmission systems at present.

Compared with Bi-based HTS tapes, the Yttrium based oxides $Y_1Ba_2Cu_3O_{6+x}$, generally called 123 material, the anisotropies are relatively infirmness and have higher I_c near liquid nitrogen temperature with higher magnetic field tolerance. The second generation (2G) YBCO-123 HTS tape has been prepared to build a DC cable. As shown in Figure 2, A 2G HTS experimental cable has total DC transport current capability of ~1.6 kA with 16 unit tapes having average I_c of 105 A and $J_e \sim 10^4$ A/cm^2.

2G wires have been produced by a few groups around the would, such as by Japan ISTEC company has reached to 245 A with 212 m in length [12]. According to the preparation process of Yttrium based HTS tapes, leaving out noble metal silver used to produce Bi based HTS tapes, the cost is lower than the first generation Bi based HTS tapes, meanwhile the carrying capacity is higher than the first generation (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 and Germany have also reached to a few hectometers in a single length. The practical HTS application cost 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 has made some excellent work in producing MgB_2 and has the ability to produce hectometer long wires. China is also undertaking the investigation of producing MgB_2 wires.

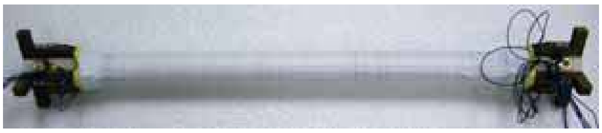
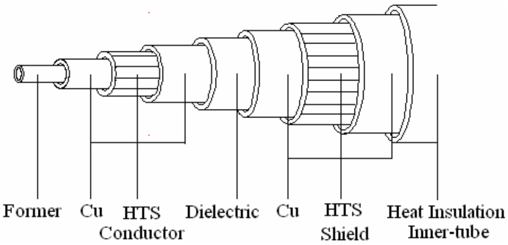


Figure 2 A 1.6 kA experimental DC cable made using 2G HTS wires

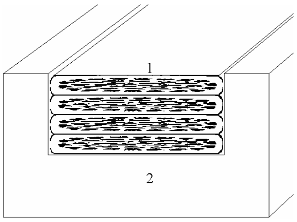
The HTS tape's DC I-V characteristic is important for DC power applications, it can be described as: $V = V_0(I_{HTS}/I_0)^n$, where I_{HTS} is the current flow through the HTS conductor, and I_0 is the current when the voltage is V_0. n reflects the I-V curve's shape and the HTS conductor quality, which 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: $n = (\log E_c - \log E_{c1})/(\log I_c - \log I_{c1})$.For the Bi-2223/Ag compound HTS tapes, when used to produce a DC cable, that 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: $I=I_0(V/V_0)^{1/n}+V/R_s$, 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 less than the penetrate field B_p, the AC loss can be expressed as: $P = [(4\sqrt{2})/3]\mu_0(I/P_e)^3P_ef/J_c$, 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, the configuration of the conductor and shield layer shown in Figure 3, cold dielectric was used, 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, then the whole cable core covered by a thermally insulated double wall cryostat. The liquid nitrogen goes through the hollow former and return 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 was no current flow through grounding site and mother earth in the double pole DC transmission system. The shields current shield 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 4 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.



(a) A HTS DC cable physical model



(b) A practical HTS conductor model

Figure 3 A practical HTS conductor model
1 - HTS element wires; 2 – A reinforced protection coat

V. HTS DC TRANSMISSION SYSTEM ANALYSIS AND SIMULATION

A. A DC Power Transmission System Using a HTS Cable

Most of DC transmission systems adopt 12-pulse current converters using two 6-pulse thyristor bridges connected in series. The converted current transformer provides current, reactive power required by the converters 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. 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 illustrates modeling of a HVDC transmission line using 12-pulse thyristor converters as the model shown in Figure 4. A 1000 MW (500 kV, 2 kA) 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. The system is programmed to start and reach a steady state. Then a step is applied first to the reference current and later to the voltage reference to observe the dynamic response of the regulators. Finally, a stop sequence is initiated to bring the power transmission smoothly down before blocking the converters.

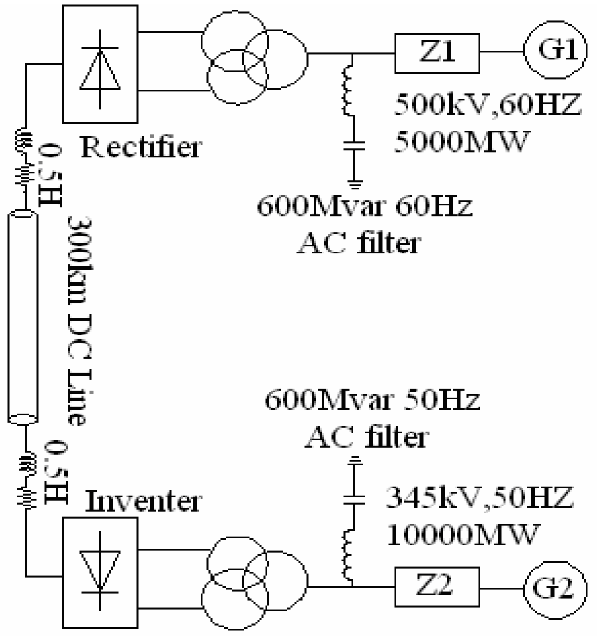


Figure 4 A practical DC power transmission system model

B. Frequency Response of the DC system

System frequency performance is important for a HVDC system filter design. The measurement library of the Powerlib in Matlab/Simulink contains an impedance measurement block that measures the impedance between any two nodes of a circuit. The frequency response of the DC system with different transmission line resistance. As shown in Figure 5, where Z1 is for the line having 0.015 Ω/km and Z2 for 0.00015 Ω/km, the series resonance at 240 Hz corresponds to the main mode likely to be excited on the DC side under large disturbances. The figure shows that the transmission line resistance has little influence on the frequency characteristic, because the impedance proportion of the resistance to the inductance are small under different transmission resistance during the simulation process, therefore the frequency characteristic of the DC system mainly decided by the inductance L and capacitance C of the transmission line, the magnitude of the response pole become bigger following with the decrease of resistance. Therefore the HTS technology does not influence the system frequency performance significantly due to large percentage of L and C. Surges at low frequency could happen because of insufficient damp.

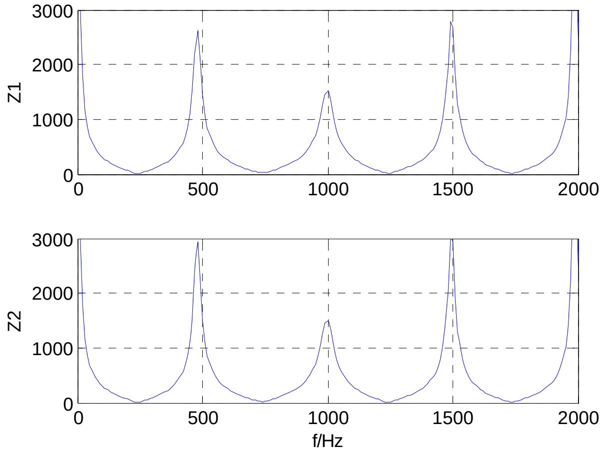


Figure 5 Frequency response of the DC system (Z/Ωm)

C. Power Loss Analysis

Figure 6 is the sending power and receiving power of the DC transmission system, the front segment of the curve correspond to the ramped start-up, and the middle pulse segment of the curve is correspond to the steps applied on the current reference and on the voltage reference in the master control and in the inverter control and protection respectively. At t = 0.7 s, the reference current decreases from 1 p.u. to 08 p.u.; and at t = 0.8 s, the reference current increases back to 1 p.u.. The reference voltage decreases from 1 p.u. to 0.9 p.u. from t = 1.0 s to 1.1 s, so the sending and receiving power is decreased following with the step change of the reference current and voltage. 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 subtract the receiving power equal to the power losses which includes the loss consumed by transformers, filters, convertors and transmission line, that is the total power losses of the whole power transmission system. On the condition of zoom in statement, there are pulses on the figure, because of the harmonious current and voltage on the DC line.

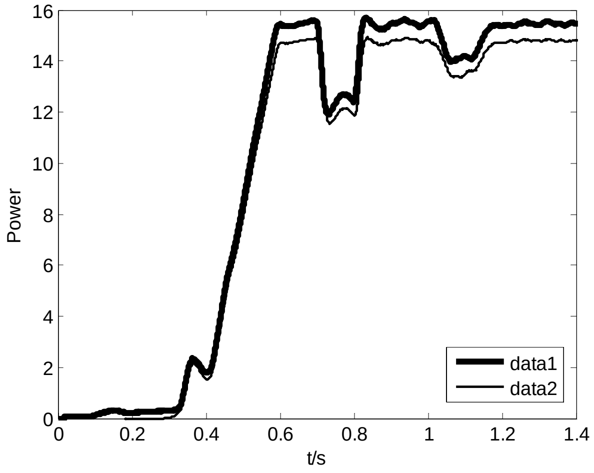


Figure 6 Sending (data1) and receiving (data2) power (p.u.)

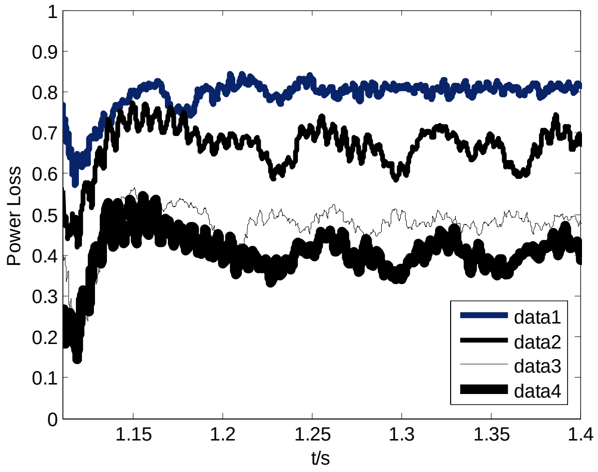


Figure 7 Power loss comparison (p.u.)

Figure 7 shows the simulation results, where

(i) Data 1 is the transmission energy loss of 400 kV, 2.5 kA, R = 0.015 Ω/km DC line.

(ii) Data 2 is the transmission energy loss of 500 kV, 2 kA, R = 0.015 Ω/km DC line.

(iii) Data 3 is the transmission energy loss of 400 kV, 2.5 kA, R = 0.00015 Ω/km DC line.

(iv) Data 4 is he transmission energy loss of 500 kV, 2 kA, R = 0.00015 Ω/km DC line.

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 lower than that of the common DC transmission system worked at a higher voltage level.

VI. CONCLUSION

The HTS cable used for DC power transmissions has supreme electricity performance identified both from the experimental cable built and the DC power transmission system Matlab/Simulink analysis.

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