APPLICATION OF HIGH TEMPERATURE SUPERCONDUCTORS IN
DESIGNING EFFICIENT POWER TRANSMISSION SYSTEM

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Abstract- Nowadays electricity serves a very important role in human life. There is need of efficient generation, transmission, distribution with a surety of effective response and good workability. Performance of power system is depended upon the transmission. From studies done, it is observed that about 10-17% of power generated is lost during transmission in India. So there is a need to look for solutions for a better efficient and reliable network of transmission system that can serve high power delivery at HV levels. The option of HTS cables as retrofit element is gaining popularity for densely populated urban areas; High temperature superconducting (HTS) wire, holds enormous promise for the efficient and reliable supply of electricity. Standardizing manufacturing processes and implementing constant improvements in productivity can provide a good cost effective system.

Keywords- High temperature superconductors, cryogenic cooling, Superconducting power cables, fault current limiter

I. INTRODUCTION

The performance of power system is dependent on transmission lines. The important considerations in the operation of the transmission lines are voltage drop and power losses occurring in the line and efficiency of transmission. The performance of transmission line is governed by parameters like resistance, inductance, capacitance and conductance. The resistance R is due to the fact that every conductor offers opposition to the flow of current. For discussing the performance of the overhead transmission line they are classified into short, medium, long transmission line. In short transmission line due to smaller distance and lower line voltage, the capacitance effects are extremely small and therefore can be neglected. Hence the performance of short transmission line is depends on resistance and inductance. But the loss takes place due to resistance only. Therefore, the use of HTS, or high temperature superconducting transmission line will be useful at short distance, low voltage, high current and high power networks at urban zones.

The call for underground transmissions systems increases because of the rapid development of industries and the high density of the residential areas. Many utilities are forced to go for underground cabling because of expansion of urban area and increasing concerns about electromagnetic fields. From an economic point of view, underground cables are less attractive than overhead lines. However, in cases where overhead lines are not feasible due to some nontechnical and non-economical reason, the evaluation of alternatives is important.

In this review paper, I have tried to evaluate the chances of HTS conductors as a good underground power transmission option for cities in India based on studies done worldwide and relating them with Indian context.

II. SUPERCONDUCTIVITY

“Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic fields occurring in certain materials when cooled below a characteristic critical temperature”. This quantum mechanical phenomenon was discovered by Heike K. Onnes in 1911 in Mercury, at temperature of liquid helium, 4 K, it’s resistance suddenly disappeared. The electrical resistivity of a metallic conductor decreases gradually as temperature is lowered and at the same time its conductivity becomes infinite. Thus a current in a superconductor flows without any change in magnitude. In ordinary conductors, such as copper or silver, this decrease is limited by impurities and other defects. Even near absolute zero, a real sample of a normal conductor shows some resistance. In a superconductor, the resistance drops abruptly to zero when the material is cooled below its critical temperature. An electric current flowing through a loop of superconducting wire can persist indefinitely with no power source.

In superconducting materials, the characteristics of superconductivity appear when the temperature T is lowered below a critical temperature (Tc). The value of this critical temperature varies from material to material. Conventional superconductors usually have critical temperatures ranging from around 20 K to less than 1 K. Similarly, at a fixed temperature below the critical temperature, materials cease superconduction when an external magnetic field is applied which is greater than the critical magnetic field.

For AC cables, the superconductor will take the form of a thin surface layer on a normal metal substrate, necessary for structural and other purposes. The superconductor then acts as an electromagnetic screen for the normal metal, and ensures that no transport or eddy currents, due to AC or ripple in DC flow in the
normal metal and generate heat. Current density, \( I \) measured at the surface perpendicular to the direction of current flow, and hence is identical to the surface magnetic field.

Some properties of superconductivity phenomenon is as given the following points:

1. Zero resistance allows large and heavy conventional cables to be replaced with small, light superconducting cables.
2. Meissner effect allows magnetic levitation
3. Flux quantization in superconducting ring.
4. A macroscopic quantum phenomenon.

### III. HIGH TEMPERATURE SUPERCONDUCTORS

In 1986, a breakthrough discovery, Alex Muller and Georg Bednorz, Switzerland, created a brittle ceramic compound that superconducted at a temperature of 30K. This lead to the creation of a new class of superconductors whose critical temperature was more than 30K, and the name HTS was given to them. HTS have been observed with transition temperatures as high as 138 K. Until 2008, only certain compounds of copper and oxygen (so-called "cuprates") were believed to have HTS properties, and the term high-temperature superconductor was used interchangeably with cuprate superconductor for compounds such as Bismuth Strontium Calcium Copper Oxide (BSCCO) and Yttrium Barium Copper Oxide (YBCO). However, several iron-based compounds (the iron pnictides) are now known to be superconducting at high temperatures.

The first superconductor found with \( T_c > 77 \) K (liquid nitrogen boiling point) is yttrium barium copper oxide \((\text{YBa}_2\text{Cu}_3\text{O}_7-x)\); the proportions of the 3 different metals in the \(\text{YBa}_2\text{Cu}_3\text{O}_7\) superconductor are in the mole ratio of 1 to 2 to 3 for yttrium to barium to copper, respectively.

Iron-based superconductors contain layers of iron and a pnictogen—such as arsenic or phosphorus—or a chalcogen. This is currently the family with the second highest critical temperature, behind the cuprates. This material gained much greater attention in 2008 after the analogous material LaFeAs was found to superconduct at up to 43 K under pressure. Fulleride superconductors where alkali-metal atoms are intercalated into \(\text{C}_{60}\) molecules, conducts around 38 K for \(\text{Cs}_8\text{C}_{60}\).

### IV. DEVELOPMENT OF HTS CONDUCTORS

With development in the area of HTS materials, the next important stage is to put that material to use. Many companies across the world are working on various designs of underground cables to involve the use of HTS for developing lossless power transmission system. To design a HTS based transmission underground cable, many auxiliary systems are required, among which the most important component is the cooling system.

Superconducting High Power Transmission Cable can transmit 5-10 times the electrical current of traditional Cu or Al cables with improved efficiency. HTS power cable systems consist of the cable, which is comprised of 100s of strands of HTS wire wrapped around a copper core, and the cryogenic cooling system to maintain proper operating conditions.

HTS power cables are particularly suited to high load areas such as the dense urban business districts of large cities, where purchases of easements and construction costs for traditional low capacity cables may be cost prohibitive. At this time, the cost and performance of HTS Wire are major limiting factors for broad commercialization.

HTS power cables act as a bridge between electric energy transmission and distribution. Transmission voltages range from 60 kV to 765 kV and distribution voltages range from 5 kV to 46 kV. The primary application is for a medium voltage feed to load pockets in dense urban areas. In these high demand zones the grid is often saturated with aging infrastructure. HTS technology brings a considerable amount of power to new locations where the construction of additional transmission to distribution substations, with major transformer assets, is simply not feasible. Another potential use of HTS power cable is to improve grid power transmission by connecting two existing substations. In dense urban environments many substations often reach capacity limits and require redundant transformer capacity to improve reliability. HTS cables can tie these existing stations together, avoiding very costly transformer upgrades and construction costs.

### V. DESIGN OF HTS CABLE

Many designs have been put forward for superconducting cables, embodying different kinds of conductor and different dielectrics. Most early designs assumed the use of helium or vacuum as the dielectric, the conductors then take the form of rigid tubes to contain the helium, or to separate helium from vacuum. In an AC cable the tubes can be arranged in several different ways, of which three are shown schematically in figure. In each case three phases of the cable are enclosed in a single 'cryogenic envelope' which provides the thermal insulation separate envelopes for each phase would be too costly. The envelope contains a screen to absorb the radiation and conduction down supports from 300 K in this case the screen is cooled by liquid nitrogen. Between the screen and the outer pipe there is a 10 mm layer of 'superinsulation', many layers of aluminium Mylar sheet, to reduce the radiative heat leak in leak. The supports for the screen and for the assembly of conductors should have minimum cross section to reduce conduction, and the envelope is kept...
at a vacuum of $\leq 10^{-2}$ Pa to prevent convection. Heat in leaks to the screen and to the conductor assembly can be reduced to about 2Wm$^{-2}$ and 0.1Wm$^{-2}$ respectively. The loss in the conductors should be kept below 0.1Wm$^{-2}$, though higher losses could probably be accepted for a few hours if it was required to temporarily overload the cable. The heat inleak to the conductors, and the dielectric AC and losses, are removed by the helium streams, of which there must be at least two one 'go' and one 'return'. The go and return streams must be thermally isolated from each other to prevent temperature peaking effects between refrigerator stations. The all-coaxial conductor arrangement of third figure is the most compact, but would be difficult to assemble.

The inner conductor is laid on a helical non-conducting former, and the outer on the outside of the dielectric held down with skid wires. This construction is flexible, would accommodate thermal contraction, and could be pulled into the helium pipe in long lengths. The lapped tape also offers about three times the electric strength of helium alone, and hence a higher working voltage, a more compact cable, and lower total cost. The conductor plus dielectric would be very light, but would also be a mechanically weak structure.

The dielectric is polyethylene tape, and each phase of the cable is cooled by a flow of helium through the pipe in which it sits. The two smaller pipes carry the go flow, and the larger pipe, which absorbs most of the heat inleak, carries the return flow. The screen is cooled by liquid nitrogen in eight ducts, four 'go' and four 'return', and the whole is enclosed in a single steel pipe of 465 mm o.d. All the interior pipes and ducts are straight tubes made from low thermal contraction alloy with bellows at joints. They are held in place by straps and spacers at intervals along their length, and are supported by studs which rest on the outer steel pipe. The go and return helium streams are in separate pipes, though in some cases the solid dielectric may be able to provide the thermal isolation, giving only one helium pipe. The electric stress at the inner conductor is 20 MVm$^{-1}$, and the current density 120 Amm$^{-1}$. If fault currents are taken by the normal metal, smaller thicknesses are obtained, the current is 17.4 kA. The absence of stress inversion effects in the dielectric and the ability of superconductors to carry very large DC currents gives

![Figure-1- Three designs for an AC superconducting cable with tubular conductors: (a) All-coaxial design. (b) A trefoil design (c) Multitube design.](image)

The trefoil design is with good reason the most popular. Here each phase of the cable consists of a coaxial pair; the inner carries the phase current at the phase voltage and has superconductor on its outside, while the outer is grounded, carries equal and opposite current and has superconductor on its inside. The outer wall acts as an electromagnetic screen and as the helium wall.

In the third design there are four tubes per phase and a common surrounding neutral screen. This design is not very practical, because large sideways electromagnetic forces act between the conductors during fault currents. Even in the other designs, slight axial misalignment of the conductors causes vibratory forces which during faults are several times the weight of the conductors, and these have to be considered when designing the spacers. Tubular conductors must be assembled in lengths of 15m or less, which entails many joints. However, a greater problem is the on cooling, while typical strains at the elastic limit are 0.06 and 0.1%. To allow for contraction the tubes must be continuously corrugated, must follow a helical path, or must have large n bends at intervals along the conductor route. Satisfactory designs for aluminium are particularly difficult to obtain.
a most compact cable. The DC to AC, power ratio for similar cables is therefore about 9, compared with between 2.5 and 3 for conventional cables.

VI. DESIGN OF CRYOGENIC ENVELOPE

There are two concentric longitudinal welded and corrugated stainless steel tubes. In these two tubes there is a multilayer superinsulation in between them. There is low loss spacer to avoid contact between inner and outer tube. Vacuum to avoid convection heat losses (10-5mbar). These are quality control type in Helium leak test of all welds and pieces to ensure long term vacuum tightness.

The helium would be pressurized to avoid 2-phase flow conditions and the rapid changes in properties which occur just above the critical pressure. Refrigeration is cheaper than the larger refrigerator size, and hence the further they are apart. However, for a given helium temperature rise between refrigerators, the flow velocity, and hence pipe friction, also increases with refrigerator spacing. The major problem with refrigeration and thermal insulation is one of reliability. Considerable spare refrigeration capacity has to be provided, even if it is assumed that improvements are made over the reliability of present plant. Within the cable, a single leak to the vacuum space will put the cable out of commission, and during cable construction elaborate testing of all pipe and ducting will have to be carried out to ensure vacuum tightness. Gross damage to the outer steel pipe could lead to bursting of the helium pipes, and loss of much helium, even if stop joints are installed at intervals along the cable route. Following figure shows Refrigeration system.

VI. DVANTAGES

A detailed review of many papers available on the topic and a thorough thought process during the period of my study, it was very clear that the system in todays have some basic advantages of savings in power loss, and a good life time, but along with positive the idea has many limitations for extensive use, especially for power transfer over a longer distance. But still, following positives can be shorted out in favour of such project:

a. High temperature superconductor transmission lines have current carrying capability 3-5 times that of conventional cable.

b. This transmission line generates essentially no waste heat or electrical losses.

c. It uses of environmentally benign liquid nitrogen for cooling.

d. Can be installed into existing infrastructure.

e. This transmission cable takes up less space than conventional cables, leaving room for future expansion.

CONCLUSION

At the end of this review paper, I would like to conclude by saying that a gradual step should be taken in this direction so that such systems can be established at LV distribution level urban zones. As the cost of the setup is too high presently, its application for long distance is not suggested. The main benefit of HTS lines is the possibility to transmit high power densities at lower voltage. Transmission at the generation level would avoid numerous power transformers. Another solution is found out the problem of economical electrical energy transmission by sketching a design for large capacity, long distance superconducting line and estimating the capital and operating costs for such line.

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