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ROLE OF HIGH TEMPERATURE SUPERCONDUCTING MATERIALS FOR INNOVATIONS AND TECHNOLOGY

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ABSTRACT

Green energy is a need of present time. The development of any country largely depends upon the accessibility and convention for use of energy and its energy efficiency. No country can, therefore, afford to think of not using the energy. In related to efficiency of power generation, its transmission and distribution, improvement of power quality become priorities in the field of electric power industry in the today's time. Requirements to natural resource saving aspects at all phases of energy production, transmission and distribution are simultaneously raised. Continual improvement of technologies for the safe use of energy resources is a key to sustainable development of a human society. In particular, high temperature superconductivity (HTS) should be used to meet the growing needs of the energy industry. It is known that HTS power cables allow us to increase the level of transmitted power to several W at a voltage of 66-110kV. Technology of HTSing systems and equipment are characterized by high critical current carrying density (J_c), high critical temperature (T_c), minimum losses, high power transmission capacity and zero electromagnetic field radiations. In the present article it has been tried to analyse the various configuration of HTSrs, their properties as well as their special features available for use of HTSrs in various power applications.

Keywords**: *Critical Temperature, Energy, Transmission, Superconductivity*.**

I. INTRODUCTION

Energy is the primary and most universal measure of all kinds of works by human beings and nature. The per capita energy consumption in U.S.A is about 8000kWh per year whereas the per capita energy consumption in India is 150 kWh. U.S.A with 7% of world's population consumes 32% of the total energy consumed in the world, whereas India, with 20% of the world's population consumes only 1% of the total energy consumed in the world [1].

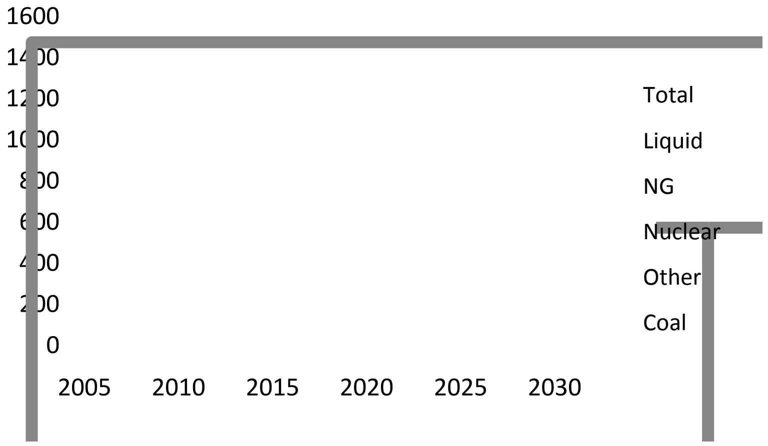

Fig.1 World's total energy consumption by fuels, in Quadrillion (10^{15}) kWh

Fig.2 Contribution of Natural Resources In The Electrical Power Generation In Trillion Kwh

Organization of Petroleum Exporting Countries and International Energy Agency (IEA) have estimated that global fossil fuels energy demand is increasing at the rate of 2% in the year 2006 to 23% in the year 2012 and it may increase to 40% more by 2020 than the exiting rate [2]. Super conductors are immune from the property of electrical resistance and hence Joule heating. Technological applications of HTSrs in various systems have vast intension for energy management which will reduce consumption of fossil fuels as well as environmental pollution alongwith greenhouse gases (GHGs). Technology of HTSing systems and equipment are characterized by high J_c, high T_c, minimum losses, high power transmission capacity and zero electromagnetic field radiations. In 1962, the first commercial Low T_c superconductor wire NbTi alloy was developed.

The purpose of the present article is to discuss a brief overview of the current status of the field of high temperature superconductivity. The emphasis is on recent developments on the HTSing material called T_c cuprates.

II. OVERVIEW ON HIGH TEMPERATURE SUPERCONDUCTORS (TYPE I AND II SUPERCONDUCTOR)

Loss of electrical energy in form of heat in conventional conductors like Cu or Al , resistance is accounted to more than 8% of total electrical generation that can be reduced easily by the LN_2 based HTSrs. Today, in the era of high temperature superconductivity, the drastic increase in T_c has been observed since 1986. Prior to 1986, the A15 compound Nb_3Ge with T_c ~23K held the record of highest T_c in superconductors [12]. After 1986, the range of superconductors has been increased at a very faster rate to its present value of ~133K for a compound in the Hg-Ba-Ca-Cu-O system and many more. Type II superconductors perform better to higher temperature and magnetic field in cryogenic conditions (4.2K and 77K). Most of the compounds and alloys are type II superconductors, they exhibit higher H_c and J_c.

High temperature superconducting power equipments such as transformers, fault current limiters, magnetic energy storage devices, generators, electrical machines etc. have been demonstrated and commissioned in the power grids and the super performance and capacity of fabricated new wires of HTSrs and LN_2 cooled HTSrs cables are giving new compact power T&D network, generator’s winding wires, compact and oil free liquid nitrogen (LN_2) based smaller transformers. They improve the performance, reliability, safety, environmental conditions and energy efficiency of power plants. The HTSing wires can help in delivering more power with greater voltage control and high current density with a negligible resistance in normal conditions and with zero resistance at LN_2 temperature (77K). Currently, the new technologies of HTSy are also being used from supercomputers to efficient brain imaging devices (MRI).

III. CATEGORIES OF SUPERCONDUCTORS [3]

Values of T_c above the boiling temperature of LN_2 are concerned with high T_c cuprates as beneficial elements for technological applications of superconductivity. The liquid helium (LHe) is currently employed to cool conventional superconducting materials (Nb, NbTi, and Nb_3Sn) into the superconducting state, whereas the cuprate materials have the advantage that they can be cooled into the superconducting state using LN_2. Cuprates such as the $LnBa_2Cu_3O_7$ compound (T_c in the range 92-95 K) have enormous critical fields ~10^2 Tesla that are more than satisfactory for technological applications. Epitaxially grown thin films of $YBa_2Cu_3O_7$ on single crystal $SrTiO_3$ substrates have critical current densities Jc ≈ 10^6A/cm^2 in zero field which decreases relatively slowly with magnetic field, making them suitable for technological applications. The $YBa_2Cu_3O_7$ is subjected to a melt textured growth process which yields values of J_c of ~10^5 A/cm at 77K that are not too low by an applied magnetic field. The classification of different materials as well as cuprate materials is made as under:-

3.1 Conductors and Low Temperature Superconductors

Since the discovery of superconductivity, many metals, alloys and compounds such as Cu, Al, Pb, Hg, C_{60}, $Nb_{0.6}Ti_{0.4}$, $C_{22}H_{14}$, Nb_3Ge etc. have many superconductive properties to flow of electricity without resistance and to develop high magnetic field.

3.2 Middle High Temperature Superconductors

HTSy was discovered in BaLaCuO at 35K having electrical resistance of superconducting material at high T_c and in YBaCuO at 93K under cryogenic (cooling) conditions of LN_2. Other middle high temperature superconductor Magnesium Diboride (MgB_2) is highly effective in high field magnetic applications like MRI, NDT, power cables and wire.

3.3 High Temperature Superconductor

In 1986, HTSr, BaLaCuO at 35K was discovered to initiate the innovations. In 1987, high temperature superconductivity on the YBaCuO was also discovered at 93K. Since the discovery of HTSy in many superconducting materials such as $YBa_2Cu_3O_7$, MgB_2, $Bi_2Sr_2Ca_{n-1}Cu_nO_{2n+4}$, $CuBa_2Ca_{n-1}Cu_nO_{2n+2}$, $Y_3CaBa_4Cu_8O_{18+}$, $TlBa_2Ca_{n-1}Cu_nO_{n+2}$, $Tl_2Ba_2Ca_{n-1}Cu_nO_{2n+2+\delta}$, $Ba_4Ca_2Cu_{10}O_y$, $AuBa_2Ca_3Cu_4O_{11}$, $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$, $Nd_{1+x}Ba_{2-x}Cu_3O_y$, InSnBaTmCuO, $YSr_2Cu_3O_7$ etc. has been reported as superconducting material between 35K and 371K. Some HTSrs work efficiently to carry large J_c at high H_c and T_c above the boiling point of LN_2, such as $YBa_2Cu_3O_7$ wires have T_c= 93K, J_c= 2x10^6Amp/cm^2, at cooling at 77K and 1.5x10^6 Amp/cm^2 in 1 Tesla at cooling 77K. BiSrCaCuO with Ag sheath wire T_c= 70-115K, I_c= 10^4Amp.

3.4 Room Temperature Superconductors

Till the discovery of many HTSrs, no any perfect room temperature superconductors are available on commercial level. RT superconductivity has been suspected in Tl-Be-hydride and Pb-Ag-carbonate compounds.

Some important high T_c cuprate superconductors alongwith the maximum values of T_c observed in each class of materials are shown in table 3 below and comparison of various compounds with their properties is shown in table 4 below [4].

Formula	Notation	T_c (K)	No. of Cu-O planes in unit cell	Crystal Structure
$YBa_2Cu_3O_7$	Y-123	92	2	Orthorhombic
$Bi_2Sr_2CuO_6$	Bi-2201	20	1	Tetragonal
$Bi_2Sr_2CaCu_2O_8$	Bi-2212	85	2	Tetragonal
$Bi_2Sr_2Ca_2Cu_3O_{10}$	Bi-2223	110	3	Tetragonal
$Tl_2Ba_2CuO_6$	Tl-2201	80	1	Tetragonal
$Tl_2Ba_2CaCu_2O_8$	Tl-2212	108	2	Tetragonal
$Tl_2Ba_2Ca_2Cu_3O_{10}$	Tl-2223	125	3	Tetragonal
$TlBa_2Ca_3Cu_4O_{11}$	Tl-1234	122	4	Tetragonal
$HgBa_2CuO_4$	Hg-1201	94	1	Tetragonal
$HgBa_2CaCu_2O_6$	Hg-1212	128	2	Tetragonal
$HgBa_2Ca_2Cu_3O_8$	Hg-1223	134	3	Tetragonal

Table 3: Critical temperature, crystal structure and notation of some high T_c superconductors

Sr. No.	**HTSrs compounds**	**Types of fabrication**	**J_c(Amp/cm^2)**	**H_c (Tesla)**	**Cryogenic (K)**	**T_c (K)**
	HTSrs					
1.	YBaCUO with $NdCaO_3$ substrate	Thin film	1.2x10^6	-	77	88.5
2	TBCCO with $LaAlO_3$ substrate	Thin film	5.8x10^6	-	77	91.8
3.	YBCO	Composite	8.6x10^4	0	77	93
4.	YBCO	Wire	>2x10^6	Self field	77	93
5.	Bi-2212/Ag	Tape	>10^7	5	77	-
6.	MgB_2	Sample	1.5x10^7	-	-	39.6
	LTSrs					
1.	Nb_3Sn	Wire	8x10^4	28	4.2	18.5
2.	NbTi	Wire	5x10^5	11	4.2	9.5
3.	V^3Ga	Wire	10^7	25	4.2	15
4.	8x104	Wire	8x10^6	105	4.2	9
5.	Nb_3Ge	Wire	4x10^6	5	4.2	-
6.	Pb	Wire	4.4x10^4	550	4.2	7.7
	Normal conductor					
1.	Cu	Wire	100-500	-	-	-

Table 4: J_c of conductors and high T_c superconductors

IV. STRUCTURE & CHARGE CARRIER DOPING IN HTSrs [4]

Doping density of HTSrs with high T_c cuprate superconductors plays a vital role in development of highly energy efficient technologies for energy conservation and upgrading the industrial technologies. For example, substitution of divalent Sr for trivalent La in the anti ferromagnetic insulator La_2CuO_4 dopes the CuO_2 planes with mobile holes and produces superconductivity in $La_{2-x}Sr_xCuO_4$ with a maximum T_c of ~40K at x ~0.17. Similarly, substitution of tetravalent Ce for trivalent Nd in the anti-ferromagnetic insulating compound Nd_2CuO_4 apparently dopes the CuO_2 planes with electrons, resulting in superconductivity in $Nd_{2-x}Ce_xCuO_{4-y}$ with a maximum T_c of ~25K at x ~0.15 for y ~0.02. The $La_{2-x}Sr_xCuO_4$ and $Nd_{2-x}Ce_xCuO_{4-y}$ systems have one CuO_2 plane per unit cell and are referred to as single CuO_2 layer compounds. Other superconducting cuprate systems have more than one CuO_2 plane per unit cell. $LnBa_2Cu_3O_{7-\delta}$ has two CuO_2 planes per unit cell (double CuO_2 layer compound), while $Bi_2Sr_2Ca_{n-1}Cu_nO_x$ has n CuO_2 layers per unit cell (n CuO_2 layer compound) and can be synthesized by conventional methods for n = 1, 2, 3.

V. PROPERTIES EXHIBITED BY HTSrs

Normal state properties and superconducting state properties of a material, which reflects the electronic structure that underlines high T_c superconductivity, are discussed below [5].

5.1 Normal State Properties

The electrical resistivity ρ(T) of many of the hole-doped cuprate superconductors has a linear temperature dependence between Tc and high temperatures ~1000 K, with an extrapolated residual resistivity ρ (0) that is very small; i.e., $\rho(T) \approx \rho(0) + cT$, with $\rho(0) \approx 0$ and the value of c similar within different classes of superconducting materials. The Hall coefficient R_H is inversely proportional to T and the cotangent of the Hall angle $\theta_H = R_H/\rho$ varies as T^2; i.e., $\cot(\theta_H) = AT^2 + B$.

5.2 Cuprates

The layers of ions such as lanthanum, barium, strontium, selenium, calcium, mercury or other atoms act to stabilize the structure and dope electrons or holes into CuO_2 layers. The copper-oxide planes are checkerboard lattices with squares of O^{--} ions with a Cu^{++} ion at the centre of each square. There are several families of cuprate superconductors and they can be categorized by the elements they contain and the number of adjacent copper-oxide layers in each superconducting block such as YBCO and BSCCO, referred to as Y123 and Bi2201/Bi2212/Bi2223 depending on the number of layers in each superconducting block (*n*) (ref. Table 3) [6].

5.3 Iron based Properties

These superconductors possess second highest critical temperature T_c, after the cuprates. This superconducting property exists in LaFePO at 4K as well as in material LaFeAsO or LaFeAsF with 43K temperature. The highest critical temperatures in the iron-based superconducting compounds exist in thin films of FeSe, where a critical temperature is reported more than 100K. Some other compounds possessing iron based properties as LnFeAs(O,F) or $LnFeAsO_{1-x}$ with T_c up to 56 K, referred to as 111 materials. Similarly, $(Ba,K)Fe_2As_2$ and related materials with pairs of iron-arsenide layers, referred to as 122 compounds of T_c values range up to 38 K. These materials also superconducting compounds when iron is replaced with cobalt.

5.4 Metallic hydrogen property

Theoretical work by Neil Ashcroft in 1968 predicted that solid metallic hydrogen at extremely high pressure should become superconducting at approximately room-temperature because of its extremely high speed of sound and expected strong coupling between the conduction electrons and the lattice vibrations, but unfortunately, no such work is verified in origin experimentally.

5.5 Magnetic properties

All known high-T_c superconductors are Type-II superconductors as mentioned above in table 4, whereas as already stated in the present article that ideally all the superconductors are diamagnetic in nature which are placed in category of Type-I superconductors, which expel all magnetic fields due to the Meissner effect, Type-II superconductors allow magnetic fields to penetrate their interior in quantized units of flux, creating holes or tubes of normal metallic regions in the superconducting compounds. Thus, high-T_c superconductors can sustain much higher magnetic fields.

VI. BASIC TECHNOLOGICAL APPLICATIONS OF HTSrs IN TRANSMISSION & DISTRIBUTION SECTORS

Various applications about the energy conservation technologies of HTSrs have been discussed as under:

6.1 HTSrs in Power cables and Winding Wires

Leading challenges in power T&D system will be solved by the HTSing technology where HTSing cables are highly capable to wear large J_C under cryogenic conditions (77K) with zero resistance, low impedance, zero electromagnetic radiation and free from hazardous cooling oil than conventional power cables and wires. Underground AC/DC power T&D network of HTSrs use inexpensive and environmentally safe LN_2 cooling core which provides cooling to the material to maintain the superconducting state [7]. In addition, the installation cost of underground and overhead power cables can be reduced more than 20%. In conventional overhead Cu based power T&D cable system, about 50kW/km of electrical energy is dissipated due to high resistance of conductor can be reduced by HTSrs High superconducting cable, characterized by high current densities and low transmission loss, shows promise as a compact low-capacity power cable that exhibits several environmental advantages such as energy and resource conservation as well as no external electromagnetic fields. HTS DC cable takes maximum advantage of the characteristics of superconductivity. Because they are absent of those problems unique to AC applications, HTS DC cables are expected to outspace HTS AC cables, in line with future performance enhancements and price reduction of converters [8].

6.2 HTSrs in Power Generation [9]

HTSrs in Power generation will reduce technical power losses, which are given conventional conductor and obsolete mechanical designs. Conventional conductor winding wires are heavy and oversize. So, excess load due to technical power losses discharges additional air, water and land pollution from thermal power generation units. The wastage of unit power by power energy efficiency of power utility and power generation process release about 1.5kg CO_2 and other pollutants. But superconductor wire, bars and tapes will reduce electrical losses, ground water and fossil fuels consumption and they may improve the power factor positively.

6.3 Super machine

The major components of a rotating machines employing HTS winding. Only the field winding employs HTS cooled with a cryocooler subsystem to about 35-40K. The cryocooler modules are located on the stationary frame and a gas such as helium is employed to cool the components on the rotor. The stator winding employs conventional copper winding but with a few differences. The stator winding is not housed in conventional iron core teeth but superconductor magnetic material.

6.4 Industrial Supermotors [10]

The world's most powerful Supermotor were developed American Superconductor's first generation HTS wire. American superconductor has demonstrated a 5000Hp, 1800rm synchronous motor in July, 2000. The rotor assembly includes the HTS field winding operating at cryogenic temperature (35K), its support structure, cooling loop, cryostat and electromagnetic shield. The stator assembly includes AC stator winding, back iron, stator winding support structure, bearing and housing. This motor has met all design goals by demonstrating HTS field winding, cryocooling system and a noval armature winding cooled with fresh water.

6.5 Superdrive for Ship Propulsion [11]

Modern electric drive has many advantages over competing mechanical systems. The advantages include redundancy, reliability, better fuel economy and reserve power when needed, better use of internal space allowing revenue producing space, quietness, easier maintenance and improved ship safety. A conceptual design has been developed under an Office of naval Research contract for a 25MW, 120rpm, HTS motor for ship propulsion. In order to demonstrate the key technologies employed for the 25MW motor, a 5MW motor preliminary design has been completed.

The 25MW 120rpm HTS Superdrive motor is 2.65m in diameter and 2.08m in length. It weighs 60kg and generates structure borne noise of 48dB at full speed. The motor employs a 6.6kV stator winding that is cooled with fresh water. The HTS rotor winding is cooled by off-the-shelf cryocoolers positioned in the stationary reference frame-a defective cooler could be replaced in less than 30 minutes without having to stop the motor. This motor has an overall efficiency of 97% at full speed and 99% at 1/3rd full speed.

6.6 HTSrs Transformers

Electrical transformers are major equipment in the power supply and utility system. Most of the present and conventional transformers use Cu winding and internal oil coolants, which sometimes create environmental contamination and heavy losses caused by the fire hazards. Furthermore, many conventional very large and high capacity transformers nay be difficult to transport and shift to the site. Because of higher J_C and zero resistance of HTSing winding (such as MgB_2, YBaCuO, $Bi_2Sr_2Ca_2Cu_3O_{10}$ etc.) superconducting transformers give much lower electrical losses, smaller size, require less expensive and environmental friendly coolant which reduce the overall cost of transformer. It also reduces the losses by 70% as compared to conventional designs. Today's power transformer loses about 1-2% of the total rating power in wasted energy. Losses in conventional transformers (63MVA) were about 839.7MWh and in same rated superconducting transformers, losses were about 160.3MWh.

For the boost up of windmills renewable energy generation, HTSing based generator has been developed to green energy generation. This reduction in weight would also allow an increase in blade size, efficiency, lower the cost of power generation and greater power output.

6.7 Superconducting Energy Storage

Today, this system is being used to enhance the capacity, reliability and stability of the grids. In this system, flywheels based on frictionless superconductor bearings can transform electric energy into kinetic energy (avoid metal to metal contact), store this energy in a rotating flywheel and use the rotational kinetic energy to regenerate electrical energy as needed. Superconducting magnetic energy storage (SMES) systems are being used in power T&D systems for many years. Conventional flywheels suffer energy losses of 3-5% per hour whereas new HTSrs ($Bi_2Sr_2Ca_2Cu_3O_{10}$) based flywheels operate at <0.1% loss per hour. Thus, a large magnet store electrical energy in an almost lossless manner for future use. Small and momentary fluctuations in electrical power can damage computers or shut down processing lines, but the rapid response of SMES control fluctuations and power quality for short duration.

VII. DISCUSSION AND RESULT

During the past decade, remarkable progress in the areas of basic research and technological applications has been made on the high T_c cuprate superconductors. The availability of high quality polycrystalline and single crystal bulk and thin film materials has made it possible to make reliable measurements of the physical properties of these materials and to optimize superconducting properties such as T_c, J_c, H_c etc. that are important for technological applications. These investigations have provided important information regarding the normal state properties, the symmetry of the superconducting compounds and dynamics in the cuprates. Now the next phase of research on the high T_c cuprate superconductors as well as other importantly noted superconducting compounds promises to yield significant advances toward the development of high temperature superconductivity as well as the realization of technological applications of these materials on a broad scale such as the applicable ability of HTSrs to conduct the electricity with zero resistance can be used in many applications. Scientists are working to take HTSrs at room temperature which can make many resolutions in the electricity generation, utilization and many other fields. Possibly in near future HTSrs will come to room temperature or ambient temperature and will serve in many applications. Growing demand of energy for the human needs have forced to develop energy efficient technologies to reduce environmental pollutions and to energy conservation. So, technological applications if the HTSrs help to meet in energy conservation and environmental pollution reduction targets. Despite their advantages, superconductors also suffer from a number of limitations. These include their restricted range of operating temperatures, brittleness, and sensitivity to changing magnetic fields. As previously noted, the world record for the highest Tc currently stands at 138K. Thus, there is still a long way to go before superconductors are available for applications such as consumer electronics. It is impractical for handheld consumer devices to have liquid nitrogen running through them.

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