Advancements and Impediments in Applications of High-Temperature Superconducting Material

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Abstract— **High-temperature superconductor (HTS) has proved to offer devices with higher efficiency due to its higher current density and higher power density. It has widespread applications in electrical power sector such as motors, transformers, fault-current limiters, energy storage devices and offshore wind turbines. All of these applications are still in progression. Still the mass commercialization of these applications has not been observed. This paper outlines a brief review of the development of HTS applications, their current status of development and the challenges.**

Keywords-component; High Temperature Superconductor (HTS), HTS applications, HTS devices

I. INTRODUCTION

Recently, there have been advancements in manufacturing and commercial availability of long lengths of HTS wires and tapes. This has triggered the use of HTS material in various large scale power applications. HTS material enables an increase in the efficiency of machines along with the massive reduction in size and volume, and hence it is possible to design compact, lightweight and efficient electrical machines. Superconductivity also empowers some novel features such as superconducting fault current limiters and magnetic energy storage [1].This paper outlines a brief review of various HTS applications along with basic concepts, status, opportunities and challenges in HTS power system applications.

II. HTS MATERIAL PROPERTIES

HTS materials has proved to be an economical superconductor compared to low Tc materials and, due to the economical cryogenic cooling, it has increased its prospects in to the practical power applications. In terms of material properties, high critical current density, high irreversibility field and high mechanical strength are some of the major advantages. HTS have the ability to carry higher current with almost zero losses in DC and lower losses in AC conditions. The copper coil in conventional machines typically operates with a current density of 3-5 A/mm^2, on the other hand the wire in the HTS coil can be operated at 200 A/mm^2 [2]. These characteristics make HTS material feasible to develop electric devices with smaller dimensions, reduced weight and high efficiency. Continuous research on material properties and advancements in the manufacturing technologies have led the market availability of high quality HTS wire in long lengths from a number of manufacturers. This achievement has triggered the efforts in commercialization of HTS devices. Some of the properties and benefits of HTS material against individual applications are highlighted in Table I.

TABLE I. HTS PROPERTIES AND BENEFITS AGAINST APPLICATIONS [3]

Benefits	Property	Application(s)
Higher Efficiency	R=0	Motors, Generators, Cables, Transformers
Higher Power Density	J_c	Motors, Generators, Cables, Transformers
Novel Opportunities	R=0	SMES
	Dm/dB<0	Magnetic Bearings
	Transition	Fault Current Limiters, Switches

III. HTS IN POWER SYSTEMS APPLICATIONS

A. *HTS Fault Current Limiters*

In any power system, there are high chances of short circuits. HTS fault current limiter (HFCL) effectively reacts to limit the fault with various additional features such as automatic recovery, automatic protection, no over-voltage and low resistance during routine operation. It maintains its superconducting state during the normal state of operation, while it returns to the normal state in case of any surge or fault where the current flow is reduced passively. HFCL has two main categories: resistive type HFCL and inductive type HFCL, which offer high resistance and high impedance respectively as per the operational demand. HFCL enables the innovative design of electric grids exploiting the sudden transitions of superconducting material from no-resistance or negligible impedance to instantaneous limitation.

With the commercial availability of the HTS material, development of large scale HFCLs has been possible. Many prototypes and samples have been designed and tested including medium voltage and high voltage, but the first commercial resistive HFCL was developed by Nexans in 2009 [4]. Recently a 220 kV/1.5 kA resistive type fault current limiter has been developed and tested limiting the current up to 63 kA$_{rms}$ up to duration of 100 ms [5].

B. *HTS Transformers*

The HTS transformers are differentiated from conventional counterparts in terms of their winding characteristics, where HTS wires or tapes are used instead of copper or aluminium.

HTS transformers bring the benefits of being lighter in weight and considerably smaller units along lower life cycle cost, less hazards and reduced environmental pollution. Furthermore, they also offer the novel features such as overload ability and fault current limiting function [6].

Research on HTS transformer is mainly focused on reducing the AC loss, which is the main impediment to fulfil higher efficiency because of the cooling penalty. A number of power transformers have been built and tested. A 24.9 kV/4.16 kV, 5/10 MVA utility power transformer was tested by Waukesha Company in year 2005. A three phase HTS power transformer was manufactured with ratting of 630 kVA, 10 kV/0.4 kV and it has been in the operation at HTS power substation in Baiyin, China since 2011 [7].

With the novel features like high current density and low energy loss in the superconducting state along with the feature of self-acting resistance in quenching state, HTS windings enable the possibilities of various special transformers such as hybrid transformers, traction transformers, pulse transformers and fault current limiter transformers.

C. HTS Power Transmission

With the growth in the population, the current power system will require further extension in order to meet the load requirements of the future. HTS cables have been in spot light to respond to such requirement. The superconductors can carry very high current with low resistance which allows to transmit more power than conventional cable. A number of demonstration projects have been executed to promote superconducting technology in transmission system [8]. In early 2000s, Korea initiated the research on the development of superconducting cables. Consequently, they were able to develop and conduct the successful tests on 23 kV to 154 kV superconducting cables for AC as well as DC [9, 10]. Furthermore, KEPCO, Korea's electric utility company initiated its first commercial project using a 23 kV three core tri-axial superconducting transmission cable [11].

Superconducting cables have the ability to transmit up to six time more power than conventional transmission cables with similar capacity. In spite of such advantages, HTS cables require massive capital investment, which is a major obstacle in their commercialization. A recent study was carried out on the economic feasibility study for using HTS cable in UK's electrical distribution network, which showed that HTS power transmission solution required 75% more investment than conventional cables [12]. However, various studies are still being conducted to further evaluate the feasibility and to enable the market penetration of superconducting cables.

D. Superconducting Magnetic Energy Storage (SMES)

There are various problems in the transmission lines, such as the surge current due to lightning, inrush current due to switching of electrical equipment or a simple bird short circuit creating instability in the overall power system. In order to improve the ability to exchange active power and reactive power in conventional power system, energy storage systems are incorporated in the system. The examples of such energy storage systems are fly wheels, super capacitors, batteries and most recent SMES. These devices are used to create the stability in the system having the ability to absorb/transfer large power [13]. Availability of superconducting material in recent years has encouraged the development of SMES. Although its development seems expensive as it is required in large quantity to manufacture SMES coil but it has good prospects in terms of power system stability. Hybrid SMES is also under investigation where superconducting and conventional energy storage systems are combined to decrease the overall capacity cost [14].

IV. HTS Rotating Machines

A. HTS Motors

HTS motors have been considered for wide range of applications, and experimental works have been carried out on aerospace, naval as well as on industrial applications mostly of synchronous type. Most of the HTS motors are designed with superconducting material in their rotor part in order to supply high air-gap magnetic flux density which brings high power density in motors. However, machines with HTS brings challenges such as manufacturing, maintenance, and refrigeration. Apart from the mechanical characteristics, the high magnetic flux density in the rotor coil will disturb the critical current of HTS tapes which results in reduction of operational temperatures to 20-30 K causing a massive additional cooling cost.

There have been significant progresses in research on HTS synchronous motors over the past years. Doosan Heavy Industries designed and fabricated 1 MW HTS synchronous motor, and its performance test was reported in [15]. General Electric also tested 1 MW HTS machine for Air Force Research Lab (AFRL) [16]. A 36.5 MW HTS motor for ship propulsion was manufactured in United States, and the machine successfully passed factory tests at no load as well as on full load [17]. A concept design of linear synchronous motor (LSM) to for high speed railway application was presented in [18], while a small scale HTS LSM prototype has been installed in railway bogie [19].

Apart from the synchronous motors, there have been significant works in the induction motors as well. HTS induction motors overcomes problems such as integrity of rotor dynamic seal and mechanical strength especially at high speed operation [20]. A Japanese group developed a 20 kW induction/synchronous fully superconducting motor having HTS windings in stator as well as in rotor part to achieve maximum torque density and power, and the motor realized the record speed of more than 1000 rpm [21].

B. HTS Wind Generators

Conventional generators with copper winding in the rotor and stator part face problems in terms of low output power density and low efficiency especially when high capacity power generation is considered. Since HTS offers much higher critical current density and power density, the weight and volume of large scale power generators can be reduced significantly by incorporating HTS windings in stator as well as rotor parts.

Copper coils in conventional machine usually have current density between 3 and 5 A/mm^2, while in superconductors, that current density may be increased up to 200 A/mm^2 [2]. As a result higher induction current can be drawn in HTS coils which leads to the possible axial dimension reduction of generator of the same power.

A lot of research is being carried out to investigate the HTS wind power solutions in terms of conceptual designs, component demonstration and prototypes. However, a complete setup of full scale operational HTS wind generator demonstration has not been reported. A demonstration of pole pair segment of MW class direct driven HTS wind turbine was conducted in HTS-GEN project [22]. Most recently, the EcoSwing project was launched which was funded by EU Horizon 2020 program. In this program the world's first MW class direct driven HTS generator was manufactured and the generator was installed in a commercial wind turbine near the western cost of Denmark, and the project is under basic experimental stage [23].

V. MODELING OF HTS APPLICATIONS

Modelling and simulation of HTS applications have been the key subjects of study. The modelling is usually carried out in the means of integral equations to provide the estimate for various arrangements. These arrangement may consist a couple of conductors, periodic arrays, infinite stacks, infinite bifilar stacks of thin films, quasi-variational inequalities. The modelling targets the actual layout of few conductors and partial differential equations and provides approximations of anisotropic homogenous-medium for arbitrarily large stacks.

Numerical models are very popular tools for the investigation of electromagnetic and thermal behavior of HTS applications. Particularly the models dedicatedly for electromagnetic behavior of HTS have evolved in recent years. This is because the HTS technology has become matured with many applications in its pre-commercial developing stage. Consequently, there is strong desire for the tools that can optimize their design and predict their performance. Furthermore, the electromagnetic behavior of HTS is very complicated to simulate, particularly for the applications characterized by the presence of time varying magnetic fields.

The first numerical model that was able to systematically investigate current and field distributions inside HTS tape and could calculate AC losses in various working conditions was proposed by Amemiya in 1998 [24]. That model was based on finite element model (FEM). FEM is used for simulations of HTS as it has the ability to handle complicated geometrical structures along with rigorous mathematical framework. There exist many formulations to compute the AC losses and they are characterized in three forms based on the variables used in the corresponding partial differential equations (PDEs): the $A-V$ formulation [25] based on magnetic vector potential, the $T-\emptyset$ formulation [24] based on current vector potential and the most commonly used magnetic field based H- formulation [26]. There is also a combined $H-\varphi-\omega$ formulation FEM [27] in which co-homology basis functions are used in the dielectric region allowing the air as zero conductivity region. Variational method is an alternate method of FEM which is compatible for all current density-electric field relations and it has several formulations: H - formulation [28], T - formulation [29] and $J-\emptyset$ formulation [30]. All the above techniques use finite elements to solve different types of time-dependent Maxwell's equations having a nonlinear resistivity in order to describe the electrical behavior of HTS. A summary of the different formulations is given in Table II [31]. The most common is the H-formulation based FEM which has the advantage of dealing with the boundary conditions in the model and offers the direct solution of the magnetic vector potential [32]. External magnetic field is established by stating the boundary conditions of the magnetic field, however, the currents in the HTS device can be applied by using Ampere's Law.

TABLE II. DIFFERENT FORMULATIONS COMMONLY USED TO SOLVE MAXWELL'S EQUATIONS WITH NUMERICAL MODELS [31]

Formulation	Equations	Definitions
$\boldsymbol{A-V}$	$\nabla^2 A=\mu\sigma\left(\frac{\partial A}{\partial t}+\nabla V\right)$ $\boldsymbol{\nabla\cdot\left(\sigma\frac{\partial A}{\partial t}+\sigma\nabla V\right)=0}$	$B=\nabla\times A$ $E=-\frac{\partial A}{\partial t}-\nabla V$ $\boldsymbol{\sigma=\sigma(E)}$
$\boldsymbol{T}-\emptyset$	$\boldsymbol{\nabla\times\rho\nabla\times T}$ $\boldsymbol{=-\mu\frac{\partial(T-\nabla\emptyset)}{\partial t}}$	$J=\nabla\times \mathrm{T}$ $H=T-\nabla\emptyset$ $\boldsymbol{\rho=\rho(J)}$
$\boldsymbol{E-field}$	$\boldsymbol{\nabla\times\nabla\times E=-\mu\frac{\partial(\sigma E)}{\partial t}}$	$\frac{\partial B}{\partial t}=-\nabla\times E$ $\boldsymbol{\sigma=(\sigma E)}$
$\boldsymbol{H-field}$	$\boldsymbol{\nabla\times\rho\nabla\times H=-\mu\frac{\partial(\sigma H)}{\partial t}}$	$J=\nabla\times \mathrm{H}$ $\boldsymbol{\rho=\rho(J)}$

VI. CONCLUSION

HTS has edge over low temperature superconductors (LTS) where liquid nitrogen can be used for the cooling which is less expensive than helium but there still needs to have significant amount of work on cryogenic cooling cycle which is a major problem in terms of technical as well economic viability of HTS application.

The cost of the material is still a challenge which is a major hurdle in the development and commercialization of HTS technology. Economic feasibilities and case studies are required for individual applications.

Apart from the engineering prospective, environmental part of HTS applications must be studied. HTS offers potential benefits in energy conservation and emission reduction as compared to the conventional machines.

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