# Development and Application Trend of Superconducting Materials and Electrical Insulation Techniques for HTS Power Equipment

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**SUMMARY**

Technical reviews of the current status on the superconducting materials and electrical insulating techniques for HTS (High Temperature Superconducting) power equipment including cables, current limiters, rotating machines, SMES, etc., are carried out to summarize the state of the art in this area, and highlight milestones of their development, and to clarify the requirement of HTS materials and electrical insulation techniques for the future.

First, the development status of technically relevant materials, like 1G of Bi-2212, Bi-2223 and 2G of YBCO in relation to the application equipment is reviewed and investigated in the different phase of wires, bulks, films, tapes, etc. Secondly, based on the investigation results of the world-wide HTS power application projects and the field testing experiences, horizontal analyses of HTS materials are carried out to extract the common techniques among the different power applications, such as HTS cables, SMES and current limiters, as well as to distinguish the individual techniques. The requirements for the development of HTS materials are also evaluated. Finally, the discussions from the electrical insulation techniques are carried out based on the future HTS power applications.

**KEYWORDS:** High temperature superconducting (HTS) power applications, 1G and 2G materials, superconductors, electrical insulation, electric power equipment, cables, fault current limiters, SMES, rotating machines

## 1 Introduction

In recent years, the development of high temperature superconducting (HTS) materials has been actively extended and significant technical progresses are reported [1]. At the same time, the world-wide application projects for power engineering are aggressively introduced. Actually, in the USA, HTS power cable, transformer, current limiter, and rotating machine projects are on-going. In Europe, HTS cable, fault current limiter projects are taking place. In Japan, cable and SMES projects are reported. In addition, in China and Korea, big projects for HTS application have extensively progressed. Particularly, not only the development of 1G (BSCCO) materials but also 2G (YBCO) materials are actively developed and obtaining a sufficient level of properties for application to actual power equipment.

However, the development goals of HTS materials are different from the individual application equipment, making it very important to point out the target values of material development based on the comparative discussions of different power equipment. In addition, the electrical insulation techniques become more and more important for the development phase of the actual application of

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HTS power equipment. In the trend of HTS power application to the actual operating power grid, the applied rated voltages of the equipment are going to be upgraded, and then the insulation coordination techniques are to be key factor for HTS power application. The DOE in the USA reported the future application of HTS transformers will have high voltages of 138kV in 2008, 345kV in 2012, and HTS power cable as 138kV in 2007 [2]. According to the development phases of HTS power applications, the rated voltages are becoming higher, thus making the role of electrical insulation more important in the future.

# 2 HTS cables

The HTS wire and dielectric insulation requirements of HTS power cables can be distinguished with regard to the different types of cable designs as well as with regard to the voltage classes. The two main types of designs are the warm- and cold-dielectric designs. HTS power cables can be distinguished by the voltage classes they are designed for, e.g.:

- Medium voltage range cables (up to 35 kV)
- Lower high voltage range cables (up to 72 kV)
- High voltage range cables (>72 kV)

The main difference regarding the development goals is represented by the dielectric requirements coming from the voltage classes that are defined in various standards. Beside this the current related requirements such like fault current or rated current can be similar between different voltage classes and sites however the rated power can vary as well as the cable system lengths. The application requirements of HTS power cable are listed in Table 1.

Table 1 Application requirements of superconducting power cables

| | Rated voltage | Rated power | Cable length | Remarks |
|---|---|---|---|---|
| Medium voltage range | < 35 kV | 50 – 120 MVA | Short lengths up to few hundred meters | Possible without joints |
| Lower high voltage range | 35 – 72 kV | Up to 350 MVA | Several hundred meters up to km lengths | Joints required |
| High voltage range | > 72 kV | Up to 800 MVA | Multi kilometre connections | Various cooling systems required |

## 2.1 HTS wire development goals

The requirements for superconducting wires for HTS power cables are driven by the electrical and mechanical aspects of cable manufacturing, laying and operation. These requirements are independent from the type of wire (BSCCO or YBCO) and can be described as follows:

***(a) Electrical requirements:***

Typical cable designs done in various projects reflect the needs of utilities with regard to this new technology. The transport current of these cables is in the range of 1000-3000 $A_{rms}$. This specification drives the requirement for critical current in the single tape of the cable. As the development goal is also a simplification of the cable design, which can be achieved with the reduction of tape layers, this results in an $I_c$ per tape in the range of 250-350 A per cm tape width. The magnetic field dependence of the wire is not very critical due to the rather low magnetic field in the cable during operation in the range of several mT parallel field. Although higher $I_c$ is generally considered advantageous, an improvement in critical current cannot immediately result in less tape amount for the cable as a tape layer always needs to be fully covered. Sufficient over-current carrying capabilities are required in order to withstand fault currents that drive high currents in the superconducting layers of a cable parallel to the stabilization layers.

An important requirement for superconducting tapes is low AC-losses. Some work has been done on 1G BSCCO wire to improve the AC loss behaviour of tapes using resistive barriers or by twisting filaments. In addition to the wire properties the cable design also has a large impact on the cable AC-losses. Due to the smaller tape thickness, 2G YBCO wires are expected to improve AC loss in cables. Tape splices can be used in cables. The resistance, however, should be as low as possible.

***(b) Mechanical requirements:***

Superconducting tapes need high mechanical strength to withstand the stresses during cable manufacturing and installation. In particular, the cable bending results in tensile stress and strain for HTS tapes. A common goal for superconducting wire development therefore must be the improvement of mechanical strength that can be characterized as maximum stress and strain at a given residual critical current. The criteria usually taken for that is 95 % of the original $I_c$. The stress applicable to a single tape for HTS cable applications should be in the range of >200 MPa whereas the maximum strain should be around 0.2-0.3 %. In terms of cable application, it is very important that the wire be able to withstand this multiple times as such cycling happens during cable bending operations.

Superconducting wires are commercially available in the tape width of around 4 mm. This has somehow became a standard for 1G wire material. In terms of replacement, the development of 2G wire is focusing on similar width. The tolerance of tape width is a critical parameter for cable manufacturing and should be as low as possible. Tape thickness plays a minor role in cable design and is therefore usually not considered critical besides the impact on AC-losses. For cable manufacturing, HTS tape needs to be available in piece length of multiples of cable unit lengths. A unit length usually defined by the transport capacity of the final cable is in the range of 500-700 meters.

As described above, HTS wire development for cable applications should be related in terms of $I_c$, $J_c$, AC-loss, production length, conductor length, production homogeneity, mechanical forces, cooling and cost. HTS tape requirements for power cable applications are listed in Table 2.

Table 2 HTS tape requirements for power cable applications

| **Requirement** | **Status** | **Development Goal** |
|---|---|---|
| Critical Current (77K self field) | 270 A/cm (width) | 350 A/cm (width) |
| n-value | >20 | >15 |
| Maximum tensile stress (95% Ic) | 150 – 200 MPa | >200 MPa |
| Maximum strain (95% Ic) | 0.3 % | 0.3 % |
| Minimum bending Diameter (95% Ic) | 30 mm | 70 mm |
| Tape piece length | 1000 m | 1000 m |
| Tape splice resistance | 200 – 400 nΩ | 400 nΩ |
| Number of splices per km tape length | 1 – 5 | 1 |
| Cost | ~150 $/kAm | <10 $/kAm |

## 2.2 Electrical insulation for HTS HV cable

Superconducting power cables with cold-dielectric insulation rely on the combination of a lapped dielectric impregnated with the cooling fluid usually liquid nitrogen ($LN_2$). During the various on-going and completed projects with cold-dielectric cables material investigation was done with regard to basic dielectric properties as well as partial discharge(PD)-behavior and life-time investigations of these dielectric systems. On the material side, Polypropylene Laminated Paper (PPLP) seems to be the most suitable material to be used as a cable dielectric. The general dielectric requirements such like high dielectric withstand values at AC- and impulse voltage stress, high PD inception field or low dielectric losses are already met by PPLP material. Besides these dielectric properties, once more the mechanical properties play a major role for the material being used in superconducting cable applications given the fact that different from conventional cable manufacturing the HTS cable dielectric must withstand multiple mechanical bending steps without any impregnation fluid.

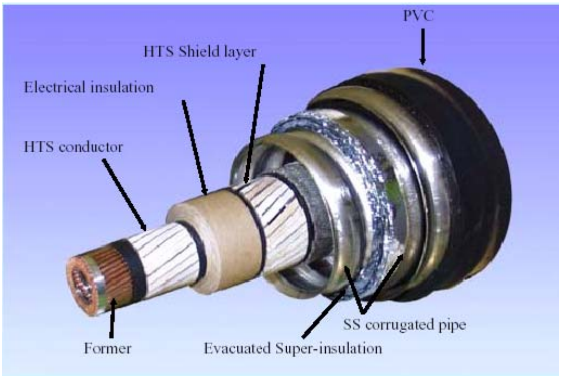


Fig.1 HTS cable of cold dielectrics with $LN_2$ impregnated PPLP [3]

In Japan, an HTS power cable project of 77kV, 1kA, 500m long, single core with a pressurized $LN_2$ cooling system was conducted and successfully tested. The cable configuration is shown in Fig.1, and the electrical insulation thickness of the $LN_2$ impregnated PPLP layers is determined to be 8mm [3]. The AC design stress is obtained as 15$kV_{rms}$/mm, from the experimental results of partial discharge inception and the tolerance of the life-time coefficient. The impulse design stress was calculated as 88kV/mm from the lightning impulse withstand voltage (LIWV) of 400kV. From the above discussions, 6mm thickness is sufficient, but 8 mm thickness was finally adopted as the optimum, by considering the mechanical stress, etc. In the field test, 95$kV_{rms}$ with 10min. and 70$kV_{rms}$ with 1000A 30days, and finally 150$kV_{rms}$ over-voltage with 10min. were applied and all of the requirements were passed without any partial discharge generation.

# 3 Superconducting fault current limiter (SCFCL)

## 3.1 SCFCL development target

SCFCLs are presently not commercially available, but considerable progress in research and development of first prototypes and demonstrators has been achieved in the past [4]. A first successful field test of a 10 MVA, 10 kV resistive type SCFCL in power system in Germany underlined the technical feasibility and reliability of SCFCLs [5]. Among the various types of SCFCLs, the resistive type seems currently the most attractive type, because of the simple design with low volume and weight [6]. The development target for SCFCLs and the application prospects depend very much on the voltage level because in each voltage level different conventional measures are taken to cope with short-circuit currents. Table 3 summarizes the development targets for SCFCLs.

***(a)Low voltage level (<1 kV):*** SCFCLs are presently not required for low voltage application because of inexpensive conventional alternatives (e.g. fuses), whereby these conventional alternatives contain a couple of disadvantages compared to a SCFCL solution (i.e. fuses must be exchanged manually, whereby an SCFCL can limit and withstand a short circuit current practically unlimited times maintenance-free). From the technical point of view, electrical insulation is simple, but rated currents and prospective short-circuit currents can be very high.

***(b)Medium voltage level (6-36 kV):***In medium voltage levels, fuses and $I_s$-limiters are conventional measures to handle short-circuit currents. Therefore, an inexpensive (<100-200 k€) and simple SCFCL concept is mandatory for a widespread medium voltage application. In niche applications, somewhat higher cost can be accepted. The electrical insulation concept with $LN_2$ is technically feasible even in case of bubbles during quench condition [7].

***(c)High voltage level (60-150 kV):*** The application of SCFCLs at high voltage levels seems very attractive because at this voltage level there is no conventional counterpart. In addition, high savings (> 1 Mio€) are expected for many applications [8, 9]. A reliable electrical insulation concept needs further development.

***(d)Higher voltages (> 150 kV):*** SCFCLs for voltage higher than 150 kV seem attractive in some applications [10] but it is extremely challenging to develop a reliable electrical insulation system. Currently, no effort is undertaken to develop SCFCLs for this voltage level.

Table 3 Summary of SCFCL development targets

| | Voltage | Current | Electrical insulation | Development target | SCFCL application prospects |
|---|---|---|---|---|---|
| Low voltage | < 1 kV | 1-6 kA | Solved | Depending on special customer evaluation | Special application cases |
| Medium voltage | 6-36 kV | 0.1-4.5 kA | Solved | < 100-200 k€ | + |
| High voltage | 60-150 kV | 0.1-4.5 kA | Needs R&D | < 1-2 Mio € | ++ |
| Higher voltage | > 150 kV | No information | Extremely challenging | No information | Special application cases |

## 3.2 HTS material requirements

Since the discovery of high temperature superconductivity in 1986, there is constant and fast progress in material research and development for all superconducting power system applications. In contrast to superconducting transformers, cables and rotating machines, most types of SCFCLs utilize the quench of the superconductor for their main function. Nowadays, the most attractive material options for SCFCLs are Bi-2212 bulk and YBCO coated conductor material. Bi-2212 bulk material and YBCO thin films have proven their feasibility in several successful demonstrator tests [4, 5, 10] up to the medium voltage level. YBCO coated conductor material promises a cost effective solution in the near future and offers a flexible wire to make compact and low impedance structures. For the most promising SCFCL material candidates, the major data is summarized in Table 4.

Table 4 HTS material data for SCFCL applications (* future target)

| | BSCCO2212 tubes | BSCCO2212 plates | YBCO thin films | YBCO coated conductor |
|---|---|---|---|---|
| Critical current density | 1.4 kA/cm$^2$(77 K)<br>3.5 kA/cm$^2$(65 K) | 3-5 kA/cm$^2$ (77 K) | 1-2.5 MA/cm$^2$ (77 K) | 0.5-3 MA/cm$^2$ (77 K) |
| Current per element | > 2 kA | ~ 150 A | 50-80 A/cm | 200-400 A/cm-width |
| Max. electric field during limitation | 6 V/cm | 0.5 V/cm | up to 10 V/cm | 0.5-2 V/cm |
| Rated power per element (typical values) | 450 kVA* for tube length of 30cm | 64 kVA for plate 40x25cm$^2$ | 70 kVA for substrate 10x20 cm$^2$ | 480 kVA * for coil 50cmx1cm |
| AC loss | ~ 5 W/MVA* | - | 0.5 W/MVA | few W/MVA |
| Cost | 1-3 k€/MVA* | - | 2.7 k€/MVA* | 400 €/MVA* |
| Selected reference | [5] | [11] | [6] | [12] |

## 3.3 Electrical insulation requirements

General requirements for any electrical insulation in a power systems apparatus are no aging over lifetime, no environmental hazards and low cost. The most attractive electrical insulator for SCFCLs is $LN_2$ because it fulfills the requirements and has, in addition, a dual function of cooling fluid and insulator with good insulating properties. With respect to electrical insulation properties, two operating conditions have to be distinguished.

***(a) Normal operation:***

During normal operation, the SCFCL has to withstand AC and lightning voltages from phase to phase and from phase to ground. The test voltages can be chosen according to IEC 71 insulation coordination standards. The voltage across the elements is negligible. The rated current causes no major bubble development in $LN_2$.

***(b)Quench condition:***

During short-circuit and quench conditions many bubbles are created instantaneously, and due to worse electrical properties of $N_2$ in comparison to $LN_2$, the electrical insulation is weakened [12]. This is the worst case for the electrical insulation and a short-circuit at rated voltage is recommended as a standard test procedure for all SCFCLs. The maximum test voltage for one phase should be the rated 3-phase voltage times 1.05, i.e. SQRT(3) times 1.05 = 1.8 times the rated voltage per phase. Depending on application, tests with additional lightning pulses during quench may be required. Test standards for SCFCLs need to be developed because the present standards for switchgear components do not reflect the function of the SCFCL properly. To ensure reliable electrical insulation for SCFCLs, a comprehensive test schedule including pre-tests of the different SCFCL parts (e.g. current leads) and final tests of the whole system is mandatory and needs to be developed.

## 3.4 Summary

In recent years, the development of HTS material for SCFCLs and suitable electrical insulation concepts and test procedures have made substantial progress. For medium voltage levels, first field tests have proven the technical feasibility of SCFCLs. For high voltage systems, the development of a reliable electrical insulation system is a challenging task for the future. Fig.2 shows the present state of the art of major SCFCL projects and the development targets for SCFCL application.

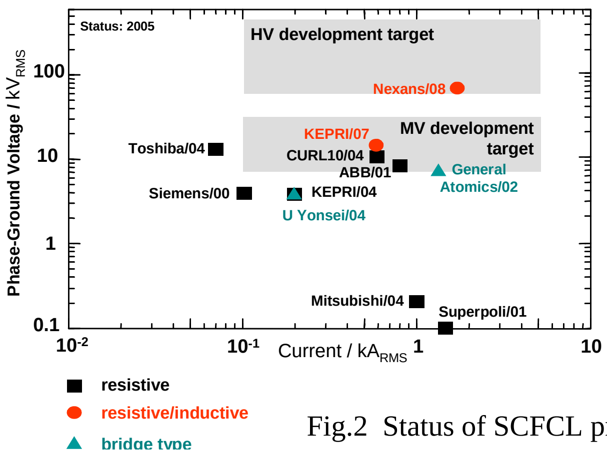


Fig.2 Status of SCFCL projects and development targets of CURL10 [5]

# 4 Superconducting magnetic energy storage (SMES)

## 4.1 Development target

As for SMES, there is 10 MJ LTS system working at a field test site in Japan (shown in Fig.3), and 2.6 MJ commercial LTS systems working in the USA and Europe, as well. The development targets of SMES for different purposes are summarized in Table 5 [14]. HTS SMES for bridging instantaneous voltage dips, power system stabilization, frequency control, load fluctuation compensation and so on, are being developed and the most critical item to be considered is the cost, compared with the other solutions, like NAS batteries, etc. SMES has no standard in test conditions up to now, but the standard for SMES is under discussion in a national project in Japan, and will be finalized in FY 2007. It is needed to establish the reliable and high efficient SMES for the future.

Fig.3 10 MJ SMES

Table 5 Target values of SMES developments

| Purpose | Output power | Operating time | Utilized energy | Cost |
|---|---|---|---|---|
| SMES for bridging instantaneous voltage dips | 10 MW | 1 s (output only) | 10 MJ | – |
| SMES for power system stabilization | 100 MW | 1 s×4 cycle (output & input) | 50 MJ | $690 /kW (*$1= 100yen) |
| SMES for load fluctuation compensation | 100 MW | 18 s (output & input) | 1.8 GJ | $1,970/kW (*$1= 100yen) |

## 4.2 HTS material requirements for SMES

The requirements of HTS materials for SMES development are summarized in Table 6. The most important key word for commercialization is cost, because SMES has to be lower in total (initial and life-cycle) cost than other energy storage systems. This target cost is very difficult to achieve using a 1G materials Bi-system, but the cost of a 2G materials Y-system is estimated to be lower than that of a 1G materials Bi-system in several years [15].

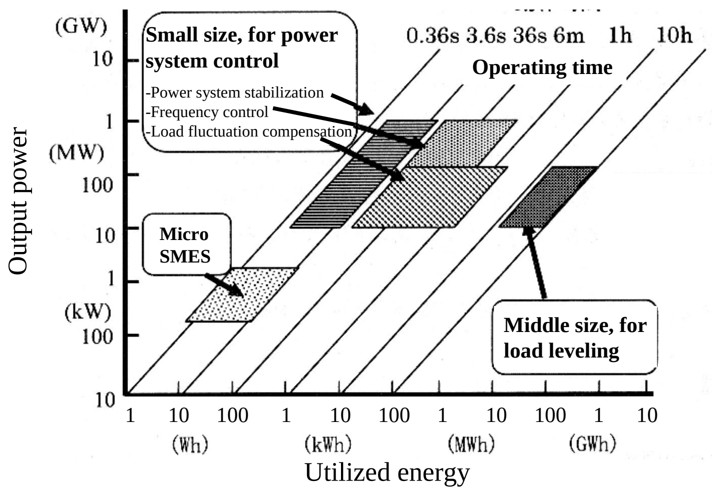


Fig.4 Target capacity of SMES

Table 6 HTS materials requirements for SMES

| Key word | Target | Requirement |
|---|---|---|
| Low cost | $10/A km (*$1= 100yen) | Lower cost than LTS on condition that HTS does not have lower performance characteristics than LTS |
| Large output power | 10 - 100 MW | Higher conductive characteristics and temperature margin for enough insulation to output large power (I×V) |
| High Ic in high B | ～10 T level | Higher conductive characteristics in high magnetic fields to make a compact coil by enhancing magnetic density and to reduce quantity of a coil and installation space |
| High Ic in high T | 20-50 K level (Y-system only) | Higher conductive characteristics in high temperature for high efficiency of a cooling system and cost reduction |
| Mechanical strength | 300 MPa level | Stronger mechanical property with or without support to endure electromagnetic stress such as hoop force |
| Reliability | No quench<br>No fault<br>No degradation | Higher temperature margin and thermal conductivity to provide enough thermal stability and enhance reliability<br>No fault and no degradation to avoid an accident and enhance reliability |
| Long life | Semi-permanent | Long life without degradation to reduce a life-cycle cost |
| Power lead | 1.5 - 3 kA level | Higher electrical conductivity<br>Lower thermal conductivity |

### 4.3 Electrical insulation requirements

The requirements of electrical insulation for SMES development are summarized in Table 7. Coil insulation level depends on a DC circuit switch of a SMES system such as a chopper circuit, because a coil receives high voltage in turn-off. In the case of the 10-100 MVA SMES coil, its targets of rated voltage and peak voltage in turn-off are 6.6-15 kV and 8.1-30 kV level, respectively. Rated voltage target of the power lead is 6.6-15 kV level.

Table 7 Electrical insulation requirements for SMES

| Key word | Requirement |
|---|---|
| Low cost | Not expensive |
| High Withstand voltage | Higher dielectric strength to enlarge output power and to endure over voltage in an accident |
| Thin insulation | Thinner electrical insulation to make a compact coil by enhancing engineering current density (magnetic density) and to reduce quantity of a coil and installation space |
| Reliability (No quench, no fault, no degradation) | Higher thermal conductivity to provide enough thermal stability and enhance reliability<br>No fault and no degradation to avoid an accident and enhance reliability |
| Long life (Semi-permanent) | Long life without degradation to reduce a life-cycle cost of a coil |
| Power lead | Higher electrical insulation<br>Lower thermal conductivity |

## 5 Rotating machines

Superconducting rotating machines have been looking promising since multifilamentary Niobium-Titanium (NbTi) superconductors became available in the mid-1960s. Both DC homopolar and AC synchronous machines were successfully demonstrated from the 1970s to 1990s. Three 70 MW generator were demonstrated by SuperGM project in Japan. However, economically attractive machines did not emerge due to a small thermal margin of Low Temperature Superconductor (LTS) NbTi winding operating at 4.5 K and a complex cooling system. On the other hand, High Temperature Superconductors (HTS) operate at much higher temperature (30-40 K), provide a much larger thermal margin and require simpler cooling systems. This has provided new impetus to the development of such machines for commercial applications. In last few years, a number of superconducting rotating machines with HTS field windings have been demonstrated, and several projects are currently transitioning to advanced development stages [23]. HTS machines in rating from a few kilowatts to several megawatts have been demonstrated in the USA and Europe. Currently, large high-torque ship propulsion motors and large generator prototypes are under development and are expected to be commercially available in the next few years. Improved life, smaller size, less weight, and higher efficiency benefits are providing incentive for development of these larger rating HTS machines.

### 5.1 HTS materials

Two types of HTS wires are being developed. Fig.5 shows the two basic HTS wire architectures: multi-filamentary composite (MFC), or 1G wire, and coated conductor composite (CCC), or 2G wire. The current commercial wire product is an MFC wire made from the Bi-2223 compound as the superconductor material. 1G high strength HTS wire shown in Fig.6 is made on the commercial scale and is available from several sources. This wire can handle high tensions necessary for producing high quality coils for motors and generators. Since 1995, An intensive R&D program on 2G HTS wire made from the Y-123 compound as the superconductor material has been conducting. The second generation wire is being designed to be a form, fit, function replacement for 1G MFC wire when it is commercially available in 2-3 years. It is expected that the cost of 2G wire will be two to five times lower than 1G wire. As a form-fit-function replacement for 1G wire, 2G wire will require no re-engineering of applications developed and commercialized using 1G wire. Fig.7 illustrates expected cross-over points for 1G, 2G and copper wires.

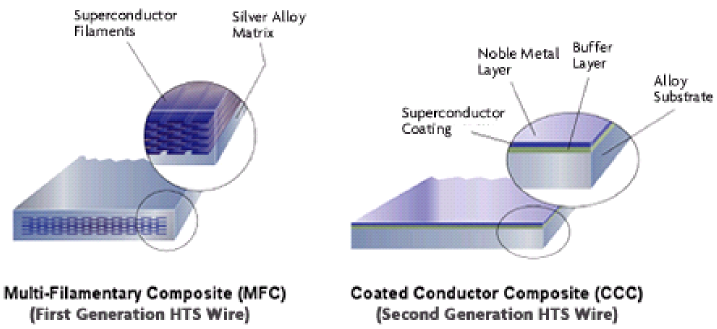


Fig.5 1G and 2G HTS wire architecture

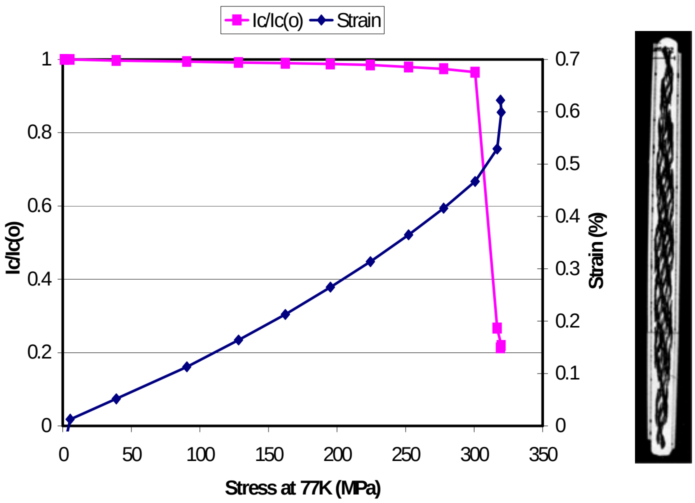


Fig.6 HTS wire reinforced with stainless steel tapes

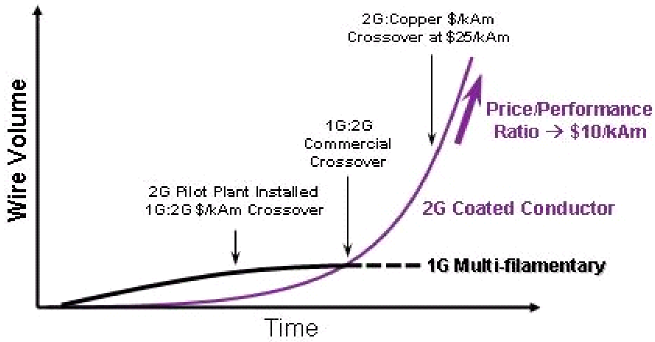


Fig.7 Cross-over points among 1G, 2G and copper wires

### 5.2 Electrical insulation

Superconducting rotating machines usually employ HTS only in the DC field winding. The DC field winding constructed from an HTS wire which is individually insulated with 30-50 micron thick paper or spray coated with a suitable polymer. Field winding coils wound with insulated HTS wire are epoxy impregnated to create final coil assembly. Usually these coils experience relatively low voltage, perhaps <800V, during initial charge and discharge cycles. The biggest challenge to insulating such coils stems from transition of current leads from room-temperature to cryogenic temperature. During this transition, a part of the lead is exposed to a partial vacuum which limits the highest voltage that can be imposed on the coil. On the other hand, the armature winding is AC and is built with copper using conventional techniques. These windings can be built up to 24kV and are cooled with air or a suitable liquid.

## 6 Electrical insulation techniques

The focus on the developments for cryogenic insulations systems falls to insulation systems of HTS wires for cables and other applications. Several cable projects with different insulating technologies and materials have been taking place. The demands to the insulation systems can be summarized:

- The dielectric should be fabricated with desired purity and homogeneity

- The purity of $LN_2$ and the maintenance during operation has to be defined. The nominal operating conditions can be fitted according to the technical requirements of transformer oil.
- Satisfactory cable performance at operating temperature has to be found after fabrication at ambient temperature despite various changes in size and shape with different contractions of cable conductor and dielectrics.
- The construction of the terminations should be able to handle the cable system at both temperatures.
- For long cable lengths, a concept for cooling stations should ensure a permanent penetration of the dielectric and not make the cable vulnerable to ground faults.

Most of the recent superconducting cable projects use industrially produced HTS tapes, which are insulated with solid tapes and impregnated with $LN_2$. The electrical insulation of the HTS wires were made from foil or PEEK with 4-40 µm thickness [17]. Many different types of tapes were tested and used in prototype cables, and synthetic polymer was also used. One of the most successful tapes is Polypropylene Laminated Paper (PPLP) which is constructed like a sandwich [3]. It joins the electrical, mechanical and thermal advantages of paper and the polymer PP with low dissipation factor and high electric strength, good flexibility at $LN_2$ temperature [18]. The PPLP is wounded on the conductor, and among other things for mechanical flexibility butt gaps were necessary. Under normal operating conditions these butt gaps were also filled with $LN_2$, but in case of hotspots partial discharges can occur [16,19]. The probability of partial discharges can be reduced by higher operating pressure of $LN_2$ [19]. Fractures in the PPLP were filled with $LN_2$ and show a kind of self-healing effect. Comparing the life-time of impregnated tapes with all-dielectric polymer insulation systems, the impregnated dielectrics show due to this self-healing effect, a much higher life-time exponent [20]. The partial discharge inception and breakdown strengths were investigated using coaxial cylindrical model and were found to show the volume effect of stressed $LN_2$ impregnated layers [21].

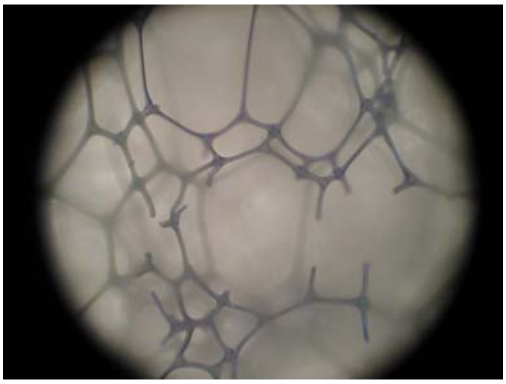

Fig.8 $LN_2$ impregnated open cell foam [19]

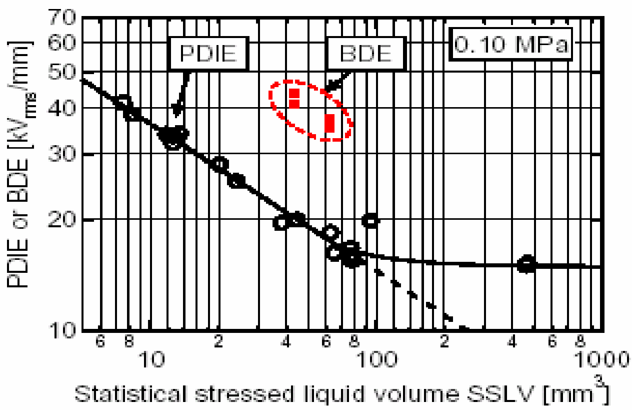


Fig.9 Volume effect of partial discharge inception and breakdown strength for coaxial cable model [21]

Apart from the aforementioned insulation systems, a special kind of open cell foam was investigated for the applications as electrical insulation or spacer. This foam shows good electrical properties because of the full saturation with $LN_2$. Due to its structure, it also takes over cooling purposes, and can easily be run through by $LN_2$. First tests have shown a sufficient dielectric strength for the application in power equipment [22].

## 7 Conclusions

In this paper, the development status of technically relevant materials is firstly reviewed and investigated in the different phase of wires, bulks, films, tapes, etc. Secondly, based on the investigation results, horizontal analyses of the HTS materials are carried out to extract the common techniques among the different power applications, such as HTS cables, SMES and current limiters, and to distinguish the individual techniques. Also, the requirements and the goals for the development of the HTS materials are evaluated. Finally, the discussions from the electrical insulation techniques are carried out based on future HTS power applications.

## BIBLIOGRAPHY


[1] H.Okubo, M.Lakner, M.McCarthy, S.Nagaya, C.Sumereder, O.Tonnesen, B.Wacker, “Technical Trend of Superconducting and Electrical Insulating Materials for HTS Power Applications”, CIGRE D1-403, 2004

[2] DOE FY 2005 Congressional Budget Request, “Energy Supply / Electric Transmission and Distribution Overview”, Feb, 2004

[3] T.Takahashi, “Tests for HTS Power Cable”, Workshop on Cryogenic Dielectrics, Nashville, USA, 2005

[4] W. V. Hassenzahl, D. W. Hazelton, B. K. Johnson, P. Komarek, M. Noe, T. R. Reis, “Electric power applications of superconductivity”, Proc. IEEE, Vol. 92, No. 10, pp.1655-1673, 2004

[5] J. Bock, F. Breuer, H. Walter, S. Elschner, M. Kleimaier, R. Kreutz, M. Noe, “CURL10: Development and field test of a 10 kV/10 MVA resistive current limiter based on bulk MCP BSCCO2212”, IEEE Trans. Appl. Supercond., Vol. 15, No. 2, pp. 1955-1960, 2005

[6] H.-P. Krämer, W. Schmidt, B. Utz, B. Wacker, H.-W. Neumüller, G. Ahlf, R. Hartig, “Test of a 1 kA Superconducting Fault Current Limiter for DC Applications”, submitted to IEEE Trans. Appl. Supercond. 15, 2005

[7] M. Noe, K.-P. Jüngst, S. Elschner, J. Bock, F. Breuer, R. Kreutz, M. Kleimaier, K.-H. Weck, N. Hayakawa, “High voltage requirements and test of a 10 MVA superconducting fault current limiter”, IEEE Trans. Appl. Supercond., Vol. 15, No. 2, pp. 2082-2085, 2005

[8] C. Neumann, J. Bock, “Three phase resistive fault current limiter – impact on system design”, IEEE ASC, Jacksonville, USA, 2004

[9] M. Noe, O.-B. Hyun, Y. Yoon, H. Jagels, “Investigation of the feasibility of superconducting fault current limiters in Seoul and Berlin”, No.181, Proc. EUCAS Sorrento, pp. 682-689, 2003

[10] EPRI report, Survey of fault current limiter (FCL) technologies“ , EPRI 1010760, 2005.

[11] W. Paul, M. Chen, M. Lakner, J. Rhyner, D. Braun, W. Lanz,“ Fault current limiter based on high temperature superconductors – different concepts, test results, simulations, applications”, Physica C 354, pp. 27-33, 2001

[12] W. Prusseit, H. Kinder, J. Handke, C. Hoffmann, G. Sigl, M. Noe, A. Kudymow, W. Goldacker, “Switching and quench propagation in coated conductors for fault current limiters”, Int. Symp. Supercond., Tsukuba, 2005

[13] J. Gerhold, “Crygenic Liquids – A prospective insulation basis for future power equipment”, IEEE Trans. Dielectrics and Electrical Insulation, Vol. 9, No. 1, pp. 68-75, 2002

[14] Irie chart, Journal of the Cryogenic Society of Japan, Vol.30, No.6, pp.5-15, 2005

[15] Cost Estimation of HTS wire from DOE report, 2005

[16] D.J. Swaffield, P.L. Lewin, Y. Tian, G. Chen, S.G. Swingler, “Partial discharge characterisation in liquid nitrogen composite systems”, ICDL 2005, Coimbra, pp.139-142, 2005

[17] www.trithor.de, product information 2005

[18] Y.Yamada, S. Isojima, T.Masuda, K. Hayashi, K. Sato, R. Hata, “Recent Development of HTS Cable in Sumitomo Electric Industries”, LTD, CIRED, 2005

[19] H. Okubo, M. Nagino, H. Kojima, N. Hayakawa, T. Takahashi, K. Yasuda, “Impulse and ac pd inception characteristics of $LN_2$/polypropylene laminated paper composite insulation system”, ICDL, Coimbra, pp.429-432, 2005

[20] C. Sumereder, “Dielectric investigations at cryogenic insulation systems”, Doctoral Thesis, Graz University of Technology, 2003

[21] N. Hayakawa, K. Sahara, H. Kojima, F. Endo, H. Okubo, “Partial Discharge Inception and Breakdown Characteristics of $LN_2$ / Polypropylene Laminated Paper Composite Insulation System for HTS Cables”, IEEE CEIDP, 2005

[22] M. Mifka, “Application of an Open-Cell Foam as Insulation Material for Superconductors”, Diploma Thesis, Graz University of Technology, 2005

[23] S.S.Kalsi, K.Weeber, H.Takesue, C.Lewis, H.W.Neumueller, R.D.Blaugher, “Development Status of Rotating Machines Employing Superconducting Field Winding”, Proc. IEEE, Vol.92, No.10, pp.1688-1704, 2005