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TECHNICAL TREND OF SUPERCONDUCTING AND ELECTRICAL INSULATING MATERIALS FOR HTS POWER APPLICATIONS

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Summary

This paper describes the development and status of HTS (High temperature superconducting) materials and electrical insulation materials for electric power applications. First generation HTS wire is commercially available and second generation wires are making rapid progress. Prototypes of cables, rotating machinery and other power equipment have been designed, fabricated and tested. Based on recent technical trends for the individual power equipment, we discuss the technical targets for further development of HTS and insulation materials.

Keywords

High temperature superconductivity (HTS) – motor – generator – cable – current limiter – cryogenic insulation – materials

1. Introduction

We evaluate the current status of HTS materials and electrical insulation materials in the context of a technical review of HTS electric power applications. This includes the Bi-2212, Bi-2223 and YBCO materials in wire, film and bulk form. Secondly, an applications review, including cables, rotating machinery, transformers, current limiters and SMES defines further applications-specific development targets for HTS and insulating materials. The status of insulation and coil technology is also included. Finally, we describe future directions for the HTS materials and power equipment development.

2. Development Status of HTS Materials

2.1. Bi-2223: "First Generation Wire"

The high temperature superconductor (HTS) $(Bi, Pb)_2Sr_2Ca_2Cu_3O_{10}$, commonly called Bi-2223, forms the core of today's commercial HTS wire, which is known as first generation (1G) HTS wire. The composite structure of 1G HTS wire is composed of 30-40% Bi-2223 embedded in a silver alloy matrix. For some applications, the wire is laminated to stainless steel tapes on both sides for enhanced mechanical properties and protection from the environment. The wire is a flat tape-shaped product, typically 0.2 mm by 4 mm. 1G HTS wire is used today for a number of future potential applications, including power grid stabilization solutions, power cables, motors, generators, magnets, etc. World-wide gross production capacity exceeds one million meters per year.

Several 1G designs are available to meet the requirements of various applications. The critical stress at room temperature can vary from 65 to 265 MPa, critical tensile strain (77K) from 0.3-0.4%, critical compressive strain (77 K) from 0.15-0.25% and minimum bend diameter from 70-100 mm.

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The critical current density performance of 1G HTS wire has been a focus of R&D efforts for 16 years. Long-length wires now achieve an average of about 150 A in end-to-end I_c at 77 K and self-field (sf) in 0.21 x 4.2 mm wire. The maximum I_c corresponds to an engineering critical current density of close to 18,000 A/cm^2, and a j_c of 45,000 A/cm^2. Bi-2223 wire also shows good performance in higher fields at lower temperatures. For example, at a temperature of 30 K and 2 T, the current density is about double the 77 K (sf) current density.

2.2. Bi-2212 Wire

A Bi-2212 round wire of high critical current density (j_c) in high magnetic field has been developed. It can carry more than 200 kA/cm^2 in a magnetic field of 10 T and 180 kA/cm^2 in a magnetic field of 20 T at 4.2 K, which exceeds the current-carrying capability of all conventional metallic superconductors.

The round wire was sufficiently ductile to be handled with ease during cabling. 500 m long 1+6 type stranded cables for large-scale superconducting devices have been manufactured successfully, as shown in Fig. 1. It consists of a single Ni-based reinforcement wire surrounded by six Bi-2212 round wires. The I_c value of these cables was 2.5 kA at 4.2 K in self field [1]. Moreover, Rutherford type cables using Bi-2212 round wires have been manufactured, as shown in Fig. 2. The maximum current-carrying capacity achieved to date is 12,000 A at 4.2 K in a back-up field of 0.6 T [2].

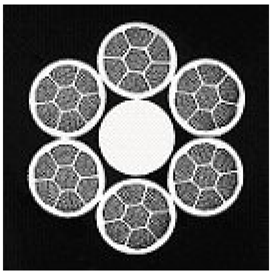

Fig. 1: Bi-2212 stranded cables with I_c=2.5 kA at 4.2 K, self field.

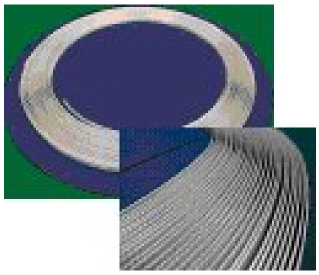

Fig. 2: 0.8mm, φ-30strand Rutherford cable with 70 m length.

2.3. Bi-2212 Bulk

The most striking property of bulk materials, which distinguishes them e.g. from tapes or wires, is their lack of flexibility. Bulk materials typically come in the shape of rings, plates, rods or pellets. Due to their high rigidity the range of possible applications for bulk materials is rather limited. They can be suitable for fault current limiters, current leads, hysteresis or reluctance type motors, and levitation applications, like magnetic bearings e.g. for fly-wheel energy storage systems or for liquid hydrogen storage tanks. State-of-the-art materials are produced in form of plates [3] or tubular parts [4] in a partial melt or by a melt cast process, respectively, yielding a polycrystalline non-textured ceramic. The material thickness: is typically in the range of 0.1 to 5 mm with j_c(77 K) = 2000 to 5000 A/cm^2.

2.4. YBCO Wire

The high temperature superconductor $YBa_2Ca_3O_{7-x}$, commonly called YBCO, is the superconducting material used in second generation (2G) HTS wire. Thin YBCO coatings on metal tapes are developed in a worldwide effort as an alternative to the well established powder-in-tube Bi-2223 1G wires. To achieve high critical current densities in the YBCO layer, the grains have to be in-plane-aligned to a high degree.

2G wire is a composite structure comprising 1) a biaxially-textured template consisting of a tape-shaped metal substrate with multiple buffer layers, 2) an epitaxial YBCO layer applied to the template, 3) a thin silver passivation layer and 4) a thick electrical and mechanical stabilization layer which also provides environmental protection. The wire is typically 0.15-0.30 mm thick, and 4 mm wide, making it a form, fit, function replacement for 1G wire. 2G wire is currently under development in a number of laboratories and companies around the world. 2G wire is expected to provide similar or improved electrical properties at 2-5 times lower cost than 1G HTS wire. This price advantage is expected to significantly expand the number of HTS applications and markets.

There are a number of 2G manufacturing processes under development. These include Rolling Assisted Bi-axially Textured Substrate (RaBiTS), Ion-Beam-Assisted Deposition (IBAD), and Inclined Substrate Deposition (ISD) for the textured buffered substrate. For deposition of the HTS coating, development is focused on Metal-Organic Deposition (MOD), Metal-Organic Chemical Vapor Deposition (MOCVD), multiple-stage chemical vapor deposition, Pulsed Laser Deposition (PLD), and electron beam deposition.

Progress on developing 2G wire has been accelerating and results are now approaching the performance levels required for commercial applications. For example, 10 m long wires with up to 180 A/cm-width (77K, sf) using a low-cost MOD/RABiTS process that can be readily scaled for commercial-volume production are reported [5]. Using the PLD/IBAD process a length of 100 m has been achieved with a 38 A/cm-width performance, and over a length of 6.1 m 357 A/cm-width (77K, sf) have been reached. With MOCVD/IBAD an 18 m long 2G wire with 110 A/cm width has been reported. Using a six-stage CVD system a 100 m long YBCO tape with 70,000 A/cm^2 was successfully fabricated [6].

Early test results show that the mechanical properties of 2G wire may be superior to those of 1G HTS wire. 2G wire research continues to focus on achieving lower alternating current (AC) losses and operation at higher temperatures in the presence of magnetic fields. The industry is now working toward adding conductive stabilizer materials to the 2G wire architectures. In 2G wire the stabilizer material, typically copper or silver, is applied by lamination, electro-deposition, or vapor deposition techniques. 2G wire can be produced using a low-cost, high volume manufacturing technique known as “wide-web coating”, which produces multiple wires mechanically-sheared from a wider strip.

In July 2003, a sub-scale multi-strand, 2G cable conductor achieved 4200 A_{dc}(77K, sf), which is transmission-level performance. Demonstrations of small 2G HTS coils have also been made. Initial preparation for and investment in pilot manufacturing for 2G wire is expected to begin as early as one year from now. Commercial quantities of 2G wire are expected to be available in 3-5 years. Typical target values for length are 500 m and for I_c 300 A/cm-width.

2.5. YBCO Films

YBCO thin films have become commercially available from a variety of vendors in the last years. The films are generally grown epitaxially by physical vapor deposition methods like pulsed laser ablation (PLD) [7], MOCVD, sputtering [8] or reactive thermal coevaporation [9]. The substrates used for the film growth are polished single crystal oxides such as MgO, $LaAlO_3$ or sapphire. The YBCO layers have a black to greyish appearance, are typically 0.2 – 2 µm thick and single crystalline allowing critical current densities beyond 1 MA/cm^2 at 77 K. The homogeneously coated wafers are typically 10.20 cm diameter or rectangular in sizes of up to 100x200 mm^2. To ensure low resistivity contacts, e.g. to current leads, the films are typically covered with a thin in-situ Au layer.

For power applications resistive-type superconducting fault current limiters of a 1-MVA-class have been built from YBCO thin films patterned to strip structures on sapphire. The main requirement for this application is the ability of YBCO films to carry high current levels in the superconducting state (up to 100 A/cm strip width) without losses although the films are only 0.3 µm thin. The YBCO films do not influence the electrical circuit during normal (superconducting) operation, but turn resistive on high fault currents and efficiently limit the current levels in the power grid. The demonstrators have been successfully tested both for medium voltage three-phase AC configurations [10] and low voltage DC circuits.

While most YBCO films are still grown on expensive single crystal substrates, the development of ion beam assisted deposition (IBAD) of biaxially textured YSZ buffer layers has opened up a way to use cheaper and more economical substrates like glass, ceramics or sheet metals as substrate for YBCO thin films with properties comparable to single crystal architectures [11].

3. Applications

3.1. Cables

HTS Cable characteristics of interest include high current carrying capacity, low impedance, zero dc resistance, and low thermal and electromagnetic impact on the environment. System benefits will include high power transfer capability, lower voltages, siting and permitting advantages, reduced network congestion, and reduced overall system losses.

Technical challenges are currently being addressed in cable demonstration projects. To date these projects have included both distribution and transmission voltages, warm and cold dielectric designs, and development of support equipment such as refrigeration, terminations, and splices. Two demonstrations have been successfully operated within existing distribution systems. A 12.4 kV, cold dielectric cable serving an industrial customer has been operating for over 3 years in the US. A 30 kV, warm dielectric cable serving 50,000 customers was operated for two years in a European substation before decommissioning for analysis.

At least nine HTS Cable projects are planned for implementation over the next two to three years. In addition to improving designs and gaining experience in real world situations, these new demonstrations will address areas such as higher voltages (138 kV), longer lengths, elevation changes, fault current protection, and a new tri-axial cable design that could reduce costs for cables with voltages up to 69 kV. Examples of the major projects include:

Super-ACE project in Japan that consists of a 500 m long single-core HTS cable operating at 77 kV constructed with 1G wire. The field test will be carried out in 2004 [12]. The cable has the configuration that is installed in an actual cable duct with a 10 m vertical rise, few meter high gradual slope and 5 m radius curves. During the test operation cooling, dielectric and current carrying tests are planned.

LIPA project in the United States that consists of three 600m long single-core HTS cables operating at 138kV with a power transfer capability of 600 MVA constructed with 1G wire. The field test is planned for 2005. The cable is designed for high system fault currents, triplex duct installation, and operation in the live grid.

3.2. Motors and Generators

The development of superconductor rotating machines has been pursued since low temperature superconductors (LTS), which operate at 4 K, became available in the mid-1960s. The small thermal margin and the complex and expensive cooling systems of these early LTS devices prevented market acceptance. It was not until the advent of HTS, which operate at 30-40 K and have simpler cooling systems, that economically viable superconductor rotating machines became possible.

In the last few years, a number of HTS rotating machines have been demonstrated in the US and Europe (see Fig.3) and several other projects are currently in advanced development stages. Today, large, high-torque ship propulsion motors (36.5 MW, 120 RPM), large turbo-generator prototypes (100 MVA, 3600 RPM) and grid stabilization devices (10 MVAR, 1800 RPM dynamic synchronous condensers) are under development and are expected to become commercially available over the next 1-3 years. High power density, smaller size, lower weight, higher efficiency and greater durability are among the expected benefits driving the development of these HTS machines. For example, a 36.5 MW, 120 RPM HTS ship propulsion motor has a 5 times weight and size advantage compared with conventional motors of the same power rating, which makes more onboard space available for passengers, cargo, etc.

HTS rotating machines use coils made with 1G HTS wire and operate at around 35 K. The coils in an HTS rotating machine are designed to ensure that the majority of the conductors experience field parallel to their ab-plane; exposure to the c-planes is minimized to achieve higher operating current with minimum losses. Research continues to further enhance the price-performance of HTS wire and to develop rotating machines that operate at around 55 K, which will reduce costs further still and help expand the markets and applications for these new devices.

FiFig.3 : HTS machines built in US and Europe

3.3. Fault Current Limiters

There is a big demand for Fault Current Limiters (FCL), which under normal operation have negligible influence on a power system, but in case of a fault will limit the short circuit current to a value close to the nominal current I_n. Attempts to realise FCLs, have been based on fast (< 1 msec) current interruption (e.g. explosive fuses, or power electronics), on detuning LC-resonance circuits (only applicable for AC-applications), or on components with strongly non-linear I(V) characteristics (e.g. semiconductors, iron-core reactors, superconductors).

Among the non-linear materials, superconductors (SC) stand out because of their unique transition from zero to finite resistance. Here we concentrate on FCLs, which utilise this transition, and refer to them as SCFCL. There are essentially two concepts of SCFCL, namely, the “resistive” and the “shielded core” or "inductive" concept. In the resistive SCFCL the SC is directly connected in series to the line to be protected whilst in the shielded core concept the SC is magnetically connected into the line. A common feature is, that a superconductor during quenching with $I > I_C$ develops an electric field $E = V/L$ (V: voltage drop across the quenched superconductor; L: length of the superconductor) causing dissipation. Considering the resistive state after quench, the required superconductor length of a current limiter can be dimensioned with an applied maximum voltage V by $L = V/E_s$, where E_s is a specific value depending on the material. Currently, the inductive type concepts are not pursued any more because of the increased mass and volume, mainly caused by the iron core, in comparison to the resistive type. Resistive type SCFCLs with rated power between 1 and 6.4 MVA have been demonstrated based either on Bi-2212 (plates [3] or tubular parts [4]) or on YBCO-films [10].

For current limiter applications the SC-materials have to meet three requirements: (1) low AC-losses in normal operation to minimise cooling costs, (2) high mechanical strength to withstand the thermo-mechanical and magnetic forces during the current limitation process, and (3) good thermal stability to avoid excessive heating at "hot-spots", which may develop during the current limitation process and can lead to a burn-through of the superconductor.

Due to the ceramic nature of the HTS, conductors with sufficiently low AC-losses for arbitrary directions of the magnetic field have not been demonstrated. AC-losses are usually minimised by decreasing the conductor dimensions transverse to the local magnetic field (e.g. choosing an arrangement of tape- or plate-like conductors so that the resulting magnetic fields are parallel to the plate surface).

The rather brittle HTS needs to be mechanically stabilised, e.g. by supporting substrate, which might be metallic or insulating. HTS, in contrast to LTS, are very poor thermal conductors, and at 77 K have rather high specific heat, thus, hot-spots spread very slowly or even contract if j drops below j_c. In such a case, the whole grid voltage would drop across a decreasing part of the conductor, which eventually will lead to a burn-through in the HTS. A common measure to reduce the problem is the application of a normal conducting “electrical bypass”, thus allowing the current to bypass the hot-spot. Most HTS components for SCFCL are composites, comprising the HTS, a mechanical substrate or support, and an electrical bypass.

A 3-phase, 6.25 kVA, 275/105 V HTS fault current limiting transformer with functions of both SC transformer in normal operating condition and SC current limiter in fault condition was developed by using MCP (melt cast processed) Bi-2212 composite materials [13].

3.4. SMES

A MJ-class HTS SMES for bridging instantaneous voltage dips using Bi-2212 wire has been developed. The Bi-2212 cable used for the SMES coils achieves high performance conductive characteristics that do not deteriorate in high magnetic fields beyond 10T. Thus the compactly arranged HTS SMES coils can be operated in a high magnetic field. And the coils of Bi-2212 cable can be insulated enough due to a high critical temperature. Therefore it is possible for the HTS SMES coils to enhance output power and dielectric strength. The isolating, cooling and conductive characteristics of 4 unit coils (Outer diameter: 700 mm, height: 127 mm, stored energy

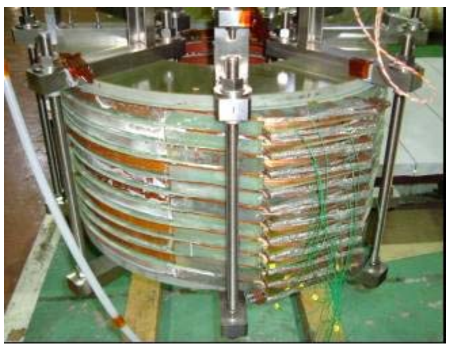
Fig. 4: Outlook of the stacked coil

90 kJ) were checked in a variety of conditions. 11 unit coils (Outer diameter: 700 mm, height: 390 mm, stored energy 560 kJ) shown in Fig.4 were also stacked and tested in liquid helium. Moreover, fundamental performance tests for bridging instantaneous voltage dips using a 125 kW resistance and a 50 kW motor as imitation loads were checked. Testing showed that the HTS SMES operated reliably [14].

4. Cryogenic Electrical Insulation

Electrical insulation at cryogenic temperature has been recognized as one of key technologies for the practical development of superconducting power apparatus. Dielectric characteristics of cryogenic liquids such as liquid nitrogen (LN_2) have been so far investigated. Recent trend on research activities in this field seems to be shifted from low-temperature physics to practical application to superconducting power apparatus for their electrical insulation design. Especially, composite insulation system composed of LN_2 and solid dielectrics such as paper and epoxy has recently been employed as the test electrode for high temperature superconducting (HTS) transmission cables and coils of transformers and fault current limiters. In addition, partial discharge (PD) characteristics leading to breakdown (BD) have been investigated for the enhancement of insulation reliability and economic benefit of HTS power apparatus.

4.1. Discharge Physics

Fundamental electrical insulation characteristics of LHe and LN_2 were reviewed [15]. Dielectric measurements with different classes of LN_2 purity were done and a comparison to mineral oil was given [16]. Prebreakdown phenomena in LN_2 were investigated in point-plane geometry [17]. Fig.5 shows an example of the streak photograph of filamentary streamer propagation up to the plane electrode and the corresponding signals associated with its propagation. Experimental results revealed that the transition from slow to fast positive streamers (velocity: about 10 km/s) was observed at a threshold voltage below the breakdown voltage. The fast positive streamers in LN_2 were able to propagate at rather low voltage and induce breakdown.

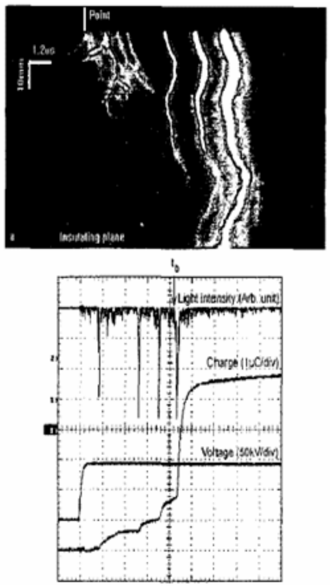

Fig. 5: Prebreakdown in LN_2 in point-plane system [17]

4.2. Application to HTS Coils

Bubble contamination and epoxy-impregnation in LN_2 are focused on in order to ensure the insulation reliability of HTS coils. Influence of the shape of vapor bubbles on breakdown in LN_2 was investigated under DC and AC voltage applications [18]. Ice-paper composite insulation system immersed in LN_2 was proposed as an all-solid electrical insulation system at cryogenic temperature [19]. In addition, the life time behavior of cryogenic insulation systems was tested at an electrical insulation model designed with solid (PET), liquid (LN_2) and gaseous (GN_2) insulants arranged in cylinder coaxial position [16]. Fig.6 shows the life time curve with the exponent of 40, which expects a longer life time period compared to conventional insulation systems.

4.3. Application to HTS Cables

For the development of HTS cables, LN_2/paper composite insulation has been regarded as the promising insulation system and its electrical insulation characteristics have been investigated [20-25].

4.3.1. Volume effect on partial discharge (PD) inception strength

PD inception characteristics of LN_2/polypropylene (PP) laminated paper composite insulation system were investigated in terms of volume effect on PD inception electric field strength (PDIE) under AC voltage application at atmospheric pressure [24]. Experimental results revealed that PDIE decreased with the increase in the butt gap number under a fixed PP laminated paper layer and electrode size. On the other hand, PDIE also decreased with the increase in the PP laminated paper layer and the electrode size under a fixed butt gap number. These results proved that PDIE cannot be evaluated only by butt gap volume and suggested the presence of weak points for PD inception other than the butt gaps in LN_2/PP laminated paper composite insulation system.

Supposing the existence of LN_2-impregnated thin areas between PP laminated paper layers associated with the surface roughness on the papers, statistical stressed liquid volume (SSLV) was defined on the basis of the discharge probability with consideration of electric field distribution in the electrode system. As the result, SSLV between layers was found to be larger than that of butt gaps for different layer-configurations. PDIE decreased with the increase in SSLV, as shown in Fig.7, for different butt gap numbers, PP laminated paper layers and electrode sizes, which corresponds to the volume effect of PDIE. Through the optical observation using the transparent electrode system, PD light emission was verified to occur between layers, as shown in Fig.8, in addition to that in butt gaps. The regression line in Fig.7 can be expressed as follows:

$$\mathrm{PDIE} = 90.1 \times \mathrm{SSLV}^{-1/2.5} [\mathrm{kV_{rms}/mm}]$$

The above equation can be regarded as a universal expression for the volume effect on PDIE in LN_2/PP laminated paper composite insulation system for HTS cables. Such concept of volume effect on PDIE was applied to the electrical insulation design of a 66 kV/77 kV class HTS cable [21].

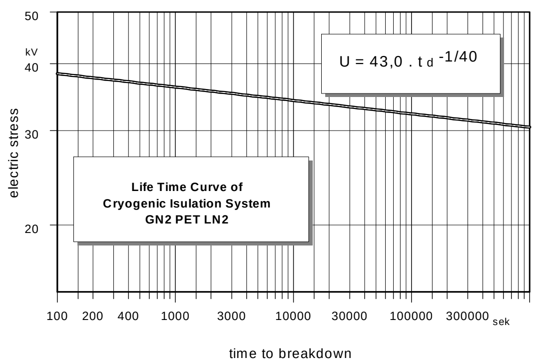

Fig. 6: Life time curve of GN_2/PET/LN_2 composite insulation system arranged in cylinder coaxial position [16]

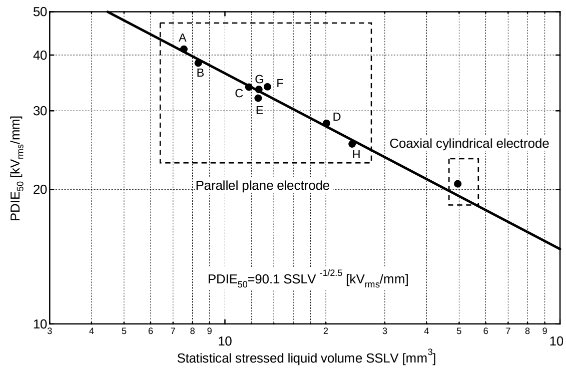

Fig. 7: Volume effect on PD inception electric field strength (PDIE) for LN_2/PP insulation system [24]

4.3.2. V-t characteristics at partial discharge (PD) inception

V-t characteristics are quite important for the reliable insulation design and the testing for life-long operation of the HTS cables. V-t characteristics at BD in LN_2/PP laminated paper composite insulation system have already been investigated. However, few studies have so far focused on V-t characteristics at PD inception as the precursor of BD, which can be more crucial to understand the insulation deterioration mechanism of the HTS cables.

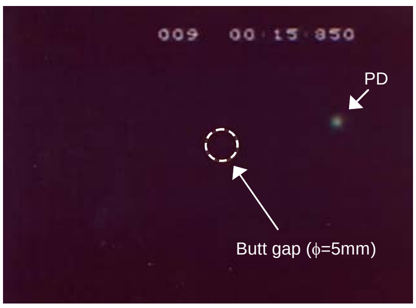

Fig. 8: PD inception between laminated paper layers of LN_2/PP insulation system [24]

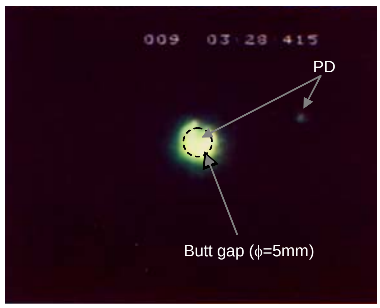

Fig. 9: PD after inception in LN_2/PP system [25]

V-t characteristics at PD inception under AC voltage application were recently reported in LN_2/PP laminated paper composite insulation system [25]. According to the experimental results, lifetime indices n of V-t characteristics at PD inception were as high as 80-100, irrespective of the butt gap conditions. In addition, n values decreased slightly under the pressurized condition. On the other hand, n values at PD inception were higher than those at BD; e.g. n=26.2 at BD was reported [20]. The lower n values at BD was interpreted by the intensified PD development in thermal bubbles in the butt gap after PD inception. PD behavior leading to BD was investigated, as shown in Fig.9 [25]; the PD behavior would highly be influenced by the withstand ability of layer-configurations. Thus, the electrical insulation design should be based not on BD strength, but on PD inception strength. V-t characteristics at PD inception were also theoretically verified by the extended Weibull distribution with consideration of location parameter.

5. Conclusions

In this paper, the recent activities and the future trends of HTS materials and electrical insulation materials for commercial and pre-commercial electric power applications are described. Electric power applications currently under development using BSCCO 1G wire and will provide the basis for future applications using YBCO 2G wire. The target YBCO 2G wire performance requirements by application are described in Fig.10 showing the need to continue research and development on these materials to meet the needs of equipment manufacturers and system suppliers.

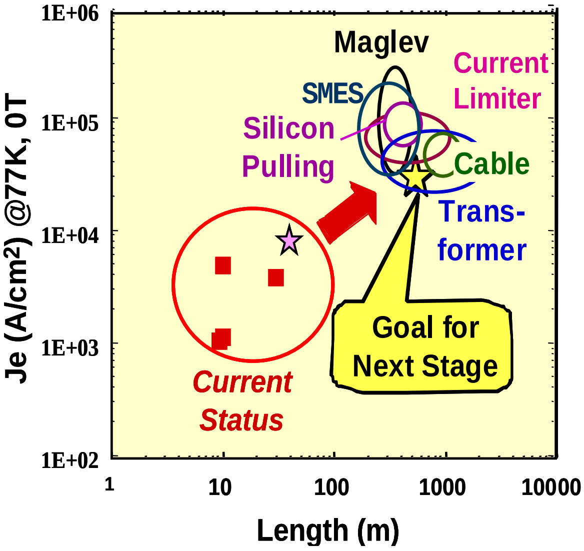

Fig. 10: Development target of YBCO 2G HTS wires for different power equipment [26]

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