SYNTHESIS REPORT

FOR PUBLICATION

Contract n°: **BRPR-CT98-0647**

Project n°: **BE97-4738**

Title: **SUPERPOLI** (**Super**conducting **Po**wer **Li**nk)

Project coordinator: **Alcatel and ZFW (last 9 months)** **FR/DE**

Partners:

Alcatel	**FR**
Nexans (prev. Aventis)	**DE**
Alstom	**FR**
Laborelec	**BE**
Tampere University of Technology	**FI**
ZFW	**DE**

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Starting date: June 1st 1998 **Duration: 42 months**

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1. SUMMARY

Keywords: High-Temperature Superconductors, Fault Current Limiters, Power Engineering.

The aim of this project is to realise a demonstrator, based on High-T_c Superconductors (HTS), which combines two devices, cables and fault current limiters, for which the industrial need has been clearly demonstrated. Such a link can find its application as a generator out-line or in the medium voltage power distribution system. Two alternative superconductors, Bi-2212 melt-cast bulk material and Y-123 coated tapes, have been considered as possible candidates for the power link.

As final application of the SUPERPOLI *an integration in the power grid* was considered as (i) a generator output and (ii) high density distribution network. A numerical simulation of the interaction of the power link with the grid was performed, and, as a result, a general specification for the HTS conductors was defined. In order to minimize the ac loss of the conductor a tubular co-axial structure of the link has been suggested. Stability and quench behaviour of SUPERPOLI functional model has been studied. The *safety aspects* of the power link are considered, particularly, with respect to "hot-spots" which appear in the HTS material. *A functional model link* (single phase, 2 meter long, normal operation 20 kV, 2 kA, fault conditions: 200 V, 5 kA) has been developed. The model link allows operation both with active elements based on Bi-2212 and on Y-123.

The essential part of the work has been devoted to the *development of well-specified superconductors* that are suited for the application in the power link. *The development of Bi-2212 conductor* included a study towards an increase of critical current density (by 30 %) and a homogenization of its distribution. A *melt cast tubular material with reduced current path* has been developed. The non-superconducting cross-sectional area in the tubes is based on secondary phases which formed during the controlled solidification process at the inner side of the tube. As a result, 650mm long tubes with 3 mm wall thickness, where the HTS layer does not exceed 2/3 of the wall thickness were developed. *Development of Y-123 coated conductors* included particular development of the conductor architecture and deposition techniques of particular layers. The finally developed *Y-123 conductor architecture* in based on a 0.1mm-thick stainless steel tape coated with a bi-axially textured yttria-stabilized ZrO_2 buffer layer, the Y-123 film (~1 µm thick) and, finally, a metallic shunt/protection layer. *A High-Rate Pulsed-Laser-Deposition (HR-PLD)* was developed for the Y-123 film processing; a method which allows an increase of the deposition rate by a factor of > 40. *The critical current densities* achieved finally in these tapes are >1.3 MA/cm^2, the critical current in these tapes corresponds to >165 A per cm width of the tape. Electrical contacts and shunting layers with well-specified parameters were developed for coated conductors. Y-123 tubular modules, with I_c > 2000A, enabling temperature compensation and double side cooling, were developed for the final power tests. For both Bi-2212 and Y-123 superconductors, 3 tubular modules with ∅50mm (Bi-2212), ∅55mm (Y-123), 650mm-long, with improved contacts have been delivered for the power tests.

An assessment of the superconductors has been performed with respect to the current limiting capacity, power losses, mechanical strains and current limitation capability. Measurements of $E(J,B,T)$ characteristics at high electric fields were done. *Data sheets of material properties* including stability under mechanical strain are provided for both superconductors. Means for *conductor protection* against shocks, thermal shrinkage and curvature are defined.

The final power tests were performed at the industrial site in a 600 MVA Power Laboratory for the Bi-2212 tubes and Y-123 modules (3 pieces of each connected in series). The performance of these materials was rather different. *The Bi-2212 tubes* yielded a high critical current of 17 $kA_{ampl.}$, a quenching time of 20 ms and a maximal voltage drop of 25 V. *The Y-123 modules exhibited* a critical current of 2.4-3.3 kA_{ampl}, a quenching time of 0.1-0.5 ms, and, under fault current (unlimited current of 50 kA_{ampl}), − a voltage drop up to 150 V with corresponding peak power loads up to 450 kW. These later parameters, indicating a high performance of Y-123 modules, were found to be sufficient to provide a reliable protection for both a grid and generator by a scaled-up power link.

Techno-economical evaluation of the SUPERconducting POwer LInk combining low loss power transmission (1 GVA) with fault current limitation, to be used typically between the generator and the step-up transformer in a power plant, exhibits significant economical benefits with a Y-123 link. A lower power application (bus bar coupling in the distribution grid) has also been studied, on the basis of a comparison with existing Duplex reactors. In lower power applications, the advantages in terms of dynamic performances of the network are considered. A large range of technical and technological results confirms *the high potential of SUPERPOLI for further industrial application*.

2. THE CONSORTIUM

2.1. Partner organizations

The partner organizations with their addresses, contacting persons, telephone and fax numbers, e-mail addresses are listed in Table 1.

2.2. Consortium Description

Laborelec, the technical competence center of the Belgian Electricity Industry focuses on all necessary scientific and technical research in order to improve the existing means of power generation, transmission and distribution of electricity and anticipate the future needs. The participation of Laborelec in this European project was important because it enabled to get more knowledge to such industrial partner in two promising fields: high temperature superconductors and the introduction of novel fault current limiters in future networks. The Laborelec played an important role in the SUPERPOLI project performing the tasks on integration (modelling, numerical simulations) of the superconducting power link in the power grid as well as techno-economical assessment of SUPERPOLI benefits.

Alcatel (finally *Alcatel CIT*, R&D group), the company with core business activities in communication systems; generation and transmission, control and storage of electric power, etc., was engaged to study the feasibility of the realisation of a superconducting power link concept within SUPERPOLI project, also as a coordinator. Main tasks of Alcatel in the SUPERPOLI were design of power link and realization of the functional model. In 2001 Alcatel CIT assigned all cable activities to Nexans and terminated its participation in the SUPERPOLI Consortium.

Zentrum fuer Funktionswerkstoffe gGmbH (ZFW), the technical competence center for advanced materials, is a government supported, non-profit organization. The ZFW develops functional materials for technical applications and closely cooperates with the University of Goettingen with respect to microstructural studies and material characterization.
Since 1991 the ZFW is involved in developments of high-T_c superconductors (HTS), especially of the HTS coated conductors. In the last 4 years ZFW succeeded in the development and processing of Y-123 coated conductors with the highest critical current density ever observed in long-length HTS coated tapes. At present ZFW, is focused on further development of efficient technologies for manufacturing of large-area Y-123 coated tapes and fault current limiting devices based on these tapes. In SUPERPOLI project, ZFW was, originally, responsible for the development of Y-123 coated conductors to be employed as a superconductor in power link. Nevertheless, in the course of consortium evolution the role of ZFW in the project was significantly enlarged. ZFW executed wider input to the project (as originally planned) developing not only coated tapes with a special architecture but also temperature compensated fault-current limiter modules based on these tapes. These modules exhibited an outstanding performance in the full power tests. In 2001 the function of the project coordinator was assigned to the ZFW.

Table 1. Partner Organizations

Partner	Address	Contact persons	Phone	FAX	e-mail
Alcatel CIT	Route de Nozay F-91460 Marcoussis, France	Dr. FOULON Nadine	+33 (0)1 6963-1279	+33 (0)1 6963 1977	Nadine.Foulon@alcatel.fr
Nexans Superconductor	Chemiepark Knapsack D-50351 Hürth-Knapsack, Germany	Dr BOCK Joachim Dr WOLF André	+49 2233 48 6658 +49 2233 48 6569	+49 2233 48 6847	Joachim.Bock@nexans.com Andre.Wolf@nexans.com
Nexans	72, Av de la Liberté F-92723 Nanterre 54, rue La Boëtie F-75008 Paris, France	Mr SAUGRIN Jean Maxime Mr PARASIE Yves	+33(0)155 5172 94 +33 (0)140 7628 96	+33 (0) 155 51 50 95 +33 (0)140 7614 23	Jean_Maxime.Saugrain@nexans.com Yves.Parasie@nexans.com
Laborelec	Rodestraat 125 B-1630 Linkebeek, Belgium	Mr EVEN André Mr PIERSON Etienne	+32 2 382 03 54 +32 2 382 04 92	+32 2 382 02 41 +32 2 382 02 64	Andre.even@laborelec.be Etienne.pierson@laborelec.be
Alstom	Alstom Transmission & Distribution 130, rue Léon Blum F-69611 Villeurbanne Cedex, France	Dr. KIRCHESCH Peter Mr COLLET Michel	+33 4 72 68 32 12 +33 4 72 68 35 70	+33 4 72 68 35 76	Peter.Kirchesch@tde.alstom.com Michel.Collet@tde.alstom.com
ZFW	Zentrum für Funktionswerkstoffe gGmbH Windausweg 2 D-37073 Göttingen, Germany	Prof Dr FREYHARDT Herbert C. Dr USOSKIN Alexander	+49 551 50 717 10 +49 551 399 727	+49 551 50 717 50 +49 551 50 717 50	Hfreyha@gwdg.de Usoskin@umpsun1.gwdg.de
Tampere University of Technology	P.O. Box 692 FI-33101 Tampere, Finland	Dr LEHTONEN Jorma	+358 3 365 2009	+358 3 365 21 60	Jlehtone@alpha.cc.tut.fi

Nexans, particularly *Nexans Superconductor*: Since Alcatel separated its cable business under the name of Nexans end of October 2000, the former Alcatel High Temperature Superconductors became Nexans SuperConductors. Alcatel High Temperature Superconductors (AHTS) emerged from Aventis Research and Technologies, a subsidiary of the former Hoechst AG. In October 1999 the Aventis HTS team was acquired by the Alcatel Cable group. The new company, Nexans SuperConductors GmbH, consolidated the activities of AHTS and the former Alcatel CIT to one site. For more than 10 years the group has been at the forefront of HTS development with patented melt cast material and outstanding commercial precursor powders and rods. Manufacture and development work takes place from highly equipped research laboratories and a state of the art manufacturing plant. *Role in the project*: development and manufacturing superconducting Bi-2212 tubes with integrated silver contacts. The specifications for this tubes are a well defined critical current for the transport of the nominal current as well as a defined quench behaviour for the limitation of the overcurrent in the case of a fault. In the future, the Bi-2212 tubular conductors can be produced, and commercialized for the needs of electrical engineering companies and large-scale applications in utilities.

Alstom (Alstom Transmission & Distribution), industrial company with R&D segments, particularly dealing with development and production of electric power equipment. In the SUPERPOLI project, Alstom was responsible for the development of testing equipment and testing programs as well as for the full power tests of the functional model with two alternative superconductors (Bi-2212 and Y-123) and, finally, for the assessment of the results of the full power tests. It is important that Alstom has a capacity to be the final producer of the self-limiting superconducting power link as well as to exploit fault current limiters developed within SUPERPOLI project as system elements. Alstom can perform also further industrial tests of power superconducting devices aimed for exploitation.

Technical University of Tampere (TUT) is responsible for scientific research, education in engineering and architecture based on this research, and training of researchers. Activities within the field of applied superconductivity are undertaken by the Laboratory of Electricity and Magnetism, which is one of 48 Institutes of the University. The superconductivity activities are backed by a group specialized on advanced computational electromagnetics. Within the SUPERPOLI project TUT had to solve the tasks concerning calculation of ac power losses, stability, carrying current capacity, overload conditions and safety of the superconducting power link. TUT was focused also on characterization of small HTS samples, study of intrinsic physical mechanisms, which are responsible for their quench behaviour.

3. TECHNICAL ACHIEVEMENTS

3.1. General description of the achievements

The aim of this project is to realise a demonstrator, based on High-T_c Superconductors (HTS), which combines two devices, cables and fault current limiters, for which the industrial need has been clearly demonstrated. Such a link can find its application as a generator outline or in the medium voltage power distribution system. Two alternative superconductors, Bi-2212 melt-cast bulk material and Y-123 coated tapes, have been considered as possible candidates for the power link.

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A functional model link (single phase, 2 meter long, normal operation: 20 kV, 2 kA, fault conditions: 200 V, 5 kA) has been developed. The model allows operation both with active elements based on Bi-2212 and on Y-123.

The essential part of the work has been devoted to the *development of well-specified superconductors* that are suited for the application in the power link. *The development of Bi-2212 conductor* included a study towards an increase of critical current density (by 30 %) and a homogenization of its distribution. A *melt cast tubular material with reduced current path* has been developed. The non-superconducting cross-sectional area in the tubes is based on secondary phases which formed during the controlled solidification process at the inner side of the tube. As a result, 650mm long tubes with 3 mm wall thickness, where the HTS layer does not exceed 2/3 of the wall thickness, were developed. *Development of Y-123 coated conductors* included particular development of the conductor architecture and deposition techniques of particular layers. The finally developed *Y-123 conductor architecture* in based on a 0.1mm-thick stainless steel tape coated with an yttria-stabilized ZrO_2 (processed by ion-beam assisted deposition) buffer layer, a Y-123 film (~1 µm thick) and, finally, a metallic shunt/protection layer. *A High-Rate Pulsed-Laser-Deposition (HR-PLD)* was developed for Y-123 film processing; a method which allows an increase of the deposition rate by a factor of > 40. *The critical current densities* achieved finally in these tapes are >1.3 MA/cm^2, the critical current in these tapes corresponds to >165 A per cm width of the tape. Electrical contacts and shunting layers with well-specified parameters were developed for coated conductors. Y-123 tubular modules, enabling temperature compensation and double side cooling, were developed for the final power tests with I_c > 2000A. For both Bi-2212 and Y-123 superconductors, 3 tubular modules with ∅50mm (Bi-2212), ∅55mm (Y-123), 650mm-long, with improved contacts have been delivered for the power tests.

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Techno-economical evaluation of the SUPERconducting POwer Link combining low loss power transmission (1 GVA) with fault current limitation, to be used typically between the generator and the step-up transformer in a power plant, exhibits significant economical benefits with a Y-123 link. A lower power application (bus bar coupling in the distribution grid) has also been studied, on the basis on a comparison with existing Duplex reactors. In lower power applications, the advantages in terms of dynamic performances of the network are considered.

A large range of technical and technological results confirms *the high potential of SUPERPOLI for further industrial application*.

The deliverables aimed for further exploitation are listed in Table 2.

3.2. Results aimed for industrial applications

The superconducting power link (SUPERPOLI) developed offers the opportunity for low-loss power transmission of high load currents and fault current limitation simultaneously in a single device. Its potential applications are in *generator out-lines* and in *medium voltage power distribution grids*. The main benefit of the SUPERPOLI concept is related to the fault current limitation: when the current rises, the superconducting link becomes resistive and the over currents are reduced to a pre-determined value.

Simulations have shown that, by modifying on the superconductor cross-section and on the working temperature, it is possible to adjust the response of the SUPERPOLI to take into account actual network situations and to introduce selectivity in fault current limitation. This can increase its domain of application.

However, the time for the development of marketable applications was estimated too optimistic and conductors suitable for power applications are just emerging. Now, for the first time both key requirements are fulfilled: the industrial need and the economic figures for superconducting power applications.

Table 2. Main deliverables of SUPERPOLI aimed for further exploitation:

No.	Item	Partner	Functionality	Specification
1	Superconducting power link (SUPERPOLI), further development is needed to achieve a full-scale functional prototype	Alcatel, Nexans (at present)	Low-loss power transmission of high load currents and fault current limitation simultaneously in a single device	➢ 3 phases ➢ nominal power: 1 GVA ➢ nominal current: 28 kA_{rms} ➢ phase-to-phase voltage: 20 kV_{rms} ➢ length of the link: 200 m ➢ operation temperature: (65-77) K ➢ refrigeration concept based on LN_2 circulation
2	Functional model	Alcatel, Nexans (at present)	Testing installation for high-T_c superconductors	➢ single phase ➢ max. current: 5 kA_{ampl} ➢ max. voltage: 20 kV ➢ active length: 2 m ➢ operation temperature: 77 K
3	Y-123 coated stainless steel tapes	ZFW	Flexible superconducting material with high current density	➢ critical current density: (17-30*) kA/mm^2 ➢ engineering current density: (170-340*) A/mm^2 ➢ nominal current in1cm-wide tape: (150-300*) A ➢ voltage drop at fault current: up to 100 V/m ➢ tape thickness: 0.1 mm ➢ tape width, max.: 50 mm ➢ operation temperature: (4-77) K
4	Fault Current Limiter based on Y-123 tubular modules	ZFW	Fault current limiter, component of superconducting power link	➢ single phase ➢ nominal current: (2-4*) kA_{ampl} ➢ unlimited fault current: 50 kA_{ampl} ➢ voltage drop at fault current: up to 50 V ➢ max. power dissipation at fault current: 150 kW_{peak} ➢ outer diameter: 55 mm ➢ length: 650 mm ➢ transition time: (0.1-0.4) ms ➢ operation temperature: (65-77) K ➢ module design: with temperature compensation
5	Fault Current Limiter based on Bi-2212 tubes	Nexans	Fault current limiter, component of superconducting power link	➢ single phase ➢ nominal current: (2.8-3) kA_{ampl} ➢ outer diameter: 50 mm ➢ length: 650 mm ➢ transition time: ~ 20 ms ➢ operation temperature: (65-77) K
6	Software for the design of HTS applications	TUT	Tools for analysis of performance ac loss and stability of superconducting power link	the software allows to calculate ➢ ac losses ➢ inner temperature of the link ➢ limits of stable operation ➢ database for Y-123 and Bi-2212 is available

Table 2 (continuation). Main deliverables of SUPERPOLI aimed for further exploitation:

No.	Item	Partner	Functionality	Specification
7	Method to measure the resistivity of HTS materials at high current densities	TUT	Characterization technique for superconductors	➢ temperatures: (2-300) K ➢ external magnetic field (0-12) T ➢ diameter: 50 mm ➢ length: 650 mm ➢ transition time: ~ 20 ms ➢ operation temperature: (65-77) K
8	Software for calculation of performance of SUPERPOLI integrated in the power grid	Laborelec	Computer tool for simulation of the interaction of the power link with the grid	two cases of applications are considered: ➢ generator output ➢ high density distribution network
9	High-rate pulsed laser deposition (HR-PLD)	ZFW	Efficient method for processing of Y-123 coated tapes	➢ highest critical current density: > 17 kA/mm^2 ➢ increase of film deposition rate by a factor of 30 ➢ capability of scaling-up of the tape length to > 100 m
10	Performance of superconductors under full power tests	Alstom, ZFW	Operation parameters to be used in design of large scale power link	➢ Bi-2212 tubes ➢ Y-123 modules
11	Techno-economical evaluation of HTS power link	Laborelec	Assessment of full-scale power link (installation, maintenance costs, etc.)	➢ 3-phased ➢ Power: 1 GVA ➢ bus bar coupling in the distribution grid ➢ link between generator and the step-up transformer ➢ comparison with Duplex reactors

* operation at temperature of 65 K

Superconducting devices for power transmission and for current limitation must be worked out now. A revolution is taking place in the world of power generation, power transmission and distribution and more generally in the business of utilities. This is true for the European utilities which, in the past have often been state owned companies with a monopoly-like position within their regions.

Deregulation is the new master word and this will change the structure of power transmission in Europe. The increasing competition should result in the shut-down of ineffective and expensive power generation plants and transmission systems. As a consequence, the whole power system will have to operate closer to its limit which makes it more fragile with respect to perturbations and short-circuits. Effective fault current limiting devices will therefore become necessary in power systems.

The aim of this project was to realise a demonstrator which combines two devices, cables and fault current limiters, for which the industrial need has been clearly demonstrated. Indeed there exist today a number of projects which are targeted either on power transmission or on current limitation which are pursued in Europe, in Japan and in the US. The first step towards this goal (this project) is a medium voltage self-limiting power link between power generation (generator) and high voltage transformation in an energy production plant. This application has been chosen by the consortium as a model application to study and to demonstrate the feasibility of the combination of current limitation and low loss power transmission. It is however seen that a similar system could also be introduced in the low voltage part of power system.

The final industrial objective will be a 1 GVA range high power link which demonstrates for the first time in one single device low loss power transmission of high nominal currents and current limitation. Such a link can find its application as a generator out-line or in the medium voltage power distribution system.

According to the assessment performed, the investment costs for a superconducting power link are comparable to the corresponding classical three phases link.

The main benefit of the SUPERPOLI concept is related to the fault current limitation: when the current rises, the superconducting link becomes resistive and the over currents are reduced to a predetermined value. System components for power transmission are today designed for severe fault conditions (over currents, heating and electro-magnetic forces). Current limitation will allow savings of 30 % for high cost equipment including generators and will improve the safety of the system.

An additional advantage concerns the low loss transmission of high nominal currents: the total room temperature losses for the SUPERPOLI system should represent only 1/7 of the ac losses in classical three phases busbar systems. This results in energy savings of ~ 260 kECU per year. As the cross sectional dimension of SUPERPOLI will be approximately 4 times smaller than in classical power links the civil engineering costs can also be reduced. Furthermore, the more compact design will strongly reduce the leakage of electromagnetic fields.

As a first step to achieve the double function of power transmission and current limitation SUPERPOLI was considered to be a milestone towards superconductivity systems in power applications, it is seen that the successful realization of this project and the amassed know how through this model application will bring the European industries in a very strong position, as well as for individual HTS power transmission or for power limitation systems. HTS cables and current limitation by HTS conductors will be pushed through this first application.

The use of the self-limiting power link will have a decisive impact on safety and will provide the following environmental benefits:

- Significant safety improvement of electric generators, transmission lines, transformers and consumer devices due to the self-limitation in the proposed power link which avoids accidental jumps of current over the safety level, especially in the case of short-circuits and, therefore, prevents disastrous fires and explosions.
- Conservation of raw materials as consequence of scaling down of the dimensions of electrical equipment like generators, secondary transmission lines, transformers, circuit breakers due to the reduction of their safety levels to over currents approximately by a factor of 2. The savings of raw materials is also achieved through the increase of the life time of these equipments reducing waste and improves the environmental quality.
- Reduction by, at least, 30 % of the areas required for all installations needed for the production and transmission of electric power due to the scaling factor mentioned above.
- Together these improvement will lower the price of electrical energy which favours the industrial sites in Europe by lowering production cost. It is seen that a reduction of the production cost of the manufacturing industry will increase the competitiveness and will thereby reinforce stability of employment, and even lead to the creation of new jobs in Europe.
- On a longer term time scale, superconducting power transmission cables can prevent environmental pollution caused by SF_6 gas or oil conventionally used for cooling of high voltage underground transmission lines. The SF_6 gas which is used when high heat exchange rates under high voltage are necessary contributes to the gradual destruction of the protecting ozone in the atmosphere of the earth. In Europe the annual production of SF_6 gas for power systems reaches 170 kg which could be avoided.

Further industrial applications of the deliverables of SUPERPOLI and their technological and commercial potentials are quoted in Table 3.

Table 3. Main industrial applications of deliverables of SUPERPOLI and their technological and commercial potentials.

No.	Item	Industrial applications	Technological and commercial potential
1	Superconducting power link (SUPERPOLI); further development is needed to achieve a full-scale functional prototype	Low-loss power transmission of high load currents and fault current limitation simultaneously in a single device; to be used in (i) generator out-line or (ii) in the medium voltage power distribution system	➢ savings up to 30 % for high cost equipment including generators ➢ improvement of safety of the system ➢ reduced ac losses ➢ 4 times smaller cross-sectional dimensions of the power link ➢ environmental benefits: - reduced leakage of electromagnetic fields - conservation of raw materials - preventing environmental pollution caused e.g. by SF_6 - reduction of the areas required for all installations needed for the production and transmission of electric power
2	Functional model	Testing installation for high-T_c superconductors and fault current limiters	➢ reduction of development costs for full-scale power links ➢ relevant characterization of superconducting elements
3	Y-123 coated stainless steel tapes	Flexible superconducting material with high current density	➢ replacement of copper conductors ➢ basis for compact designs of generators, transformers, cables, etc. ➢ reduction of power losses
4	Fault Current Limiter based on Y-123 tubular modules	Fault current limiter, component of superconducting power link	➢ improvement of safety of the systems ➢ reduced power losses ➢ fast conditioning of power distribution ➢ environmental benefits (see no. 1)
5	Fault Current Limiter based on Bi-2212 tubes	Fault current limiter, component of superconducting power link	➢ improvement of safety of the systems ➢ reduced power losses ➢ environmental benefits (see no. 1)
6	Software for the design of HTS applications	Tools for analysis of performance ac loss and stability of superconducting power link	➢ enabling the development of full-scale power links of different designs
7	Method to measure the resistivity of HTS materials at high current densities	Characterization technique for superconductors	➢ quality control of the superconducting components of power link ➢ basis for further development of the superconducting components for high power applications
8	Software for calculation of performance of SUPERPOLI integrated in the power grid	Computer tool for simulation of the interaction of the power link with the grid	➢ enabling the development of full-scale power links of different designs: - generator output - high density distribution network

Table 3 (continuation). Main industrial applications of deliverables of SUPERPOLI and their technological and commercial potentials.

No.	Item	Industrial applications	Technological and commercial potential
9	High-rate pulsed laser deposition (HR-PLD)	Method for processing of Y-123 coated tapes	➢ highest critical current density: > 17 kA/mm^2 ➢ increase of film deposition rate by a factor of 30 ➢ capability of scaling-up of the tape length to > 100 m
10	Performance of superconductors under full power tests	Operation parameters to be used in design of large scale power link for Bi-2212 tubes Y-123 modules	➢ method for industrial tests of the superconducting power link ➢ data base enabling the development of full-scale power links of different designs
11	Techno-economical evaluation of HTS power link	Assessment of full-scale power link (installation, maintenance costs, etc.)	➢ basis and method for technological and commercial assessment of the superconducting power link in different applications

Further development of industrial application for the full-scale superconducting power link is obviously needed. The benefits for such application are cited above. The technical risk lies at present mainly in the optimization of the heat balance in the large-scale system as well as in up-scaling of the refrigeration means. The risk to achieve the objectives is estimated low to medium during first 1.5-2 years period of the further development steps. The technical risk on the material side, which was initially considered as a high one, is estimated at present at the lower level, at least for Y-123 superconductors. A consortium which intends to perform this further development includes ZFW, Nexans, Alstom and TUT.

In other application areas, particular members of the former Consortium intend to continue with the following products: (i) Y-123 coated tapes (ZFW, Nexans, TUT together with c&ct GmbH[a]), (ii) fault current limiters based on Y-123 tubular modules (ZFW, Nexans, together with c&ct GmbH), (iii) software for the design of HTS applications and for calculation of performance of SUPERPOLI integrated in the power grid (TUT, ZFW, Nexans), (iiii) efficient technology and equipment for low-cost production of the HTS-coated tapes (ZFW together with c&ct GmbH).

[a] c&ct (c&c technologies GmbH) is a new technological company aiming at the to production of superconducting coated tapes and electrical elements based on these tapes.

4. EXPOILTATION PLANS AND FOLLOW-UP ACTIONS

Laborelec: The results of SUPERPOLI project will be considered in future studies comparing the different technical possibilities to answer the growing demand concerning electrical networks. These are many: higher capacity, more distributed generating units, higher reliability and power quality, no supplementary overhead lines, more international connections, ... There is no doubt that novel technical solutions such as fault current limiters will have to be introduced in future networks to fulfil all these requirements. Particular gains expected in the exploitation of the SUPERPOLI power link are:

- For the 1 GVA application such as between a generator and a transformer, significant financial benefits could be obtained with an Y-123 link on the basis of current estimations. For the BSCCO link, the economical benefits are reduced because of the higher AC losses. The combined fault current limitation effect also appears more efficient with the Y-123 variant. This actually brings limited benefits with the current network management system, but it could bring very large savings in future network systems managed in a different way. The fast recovery time of the Y-123 could be a supplementary advantage in this case.
- For lower power applications such as busbar coupling in the distribution grid, the most important advantages are not to be sought in the reduction of the losses or in the lower voltage drop in normal service conditions, but above all in the dynamic performances of the network in case of faults, (short-circuit limitation and mitigation of the voltage drops caused by faults in adjacent networks) compared to classical current limiters based on inductances. However, these technical advantages are difficult to translate in economical benefits that could then be compared to the supplementary investment cost of the SUPERPOLI solution.
- For the longer term, many other applications can be considered, and the intrinsic properties of superconducting fault current limiters make them serious candidates for new and innovative network configurations, especially for the Y-123 variant.

In the following years, Laborelec will closely monitor the progress in this field considering all possible implementations of SUPERPOLI devices at utility sites.

Zentrum fuer Funktionswerkstoffe gGmbH (ZFW), will be focused on further development of efficient technologies for manufacturing the large-area Y-123 coated tapes and fault current limiting devices based on these tapes, especially in the following fields:

- Implementation of the developed SUPERPOLI system based on Y-123 fault current limiter modules in real use
- Further development of market-oriented products, particularly, based on SUPERPOLI, i.e. the products which will be provided for the needs of power engineering and utility companies
- Triggering of a large-scale production activity by establishing strong links with specialized production companies, e.g. with c&c technologies GmbH which is aimed to the industrial production of the Y-123 coated tapes as well as related items for the electric power conditioning.

Nexans, particularly *Nexans Superconductor*, Nexans developed Bi-2212 tubular conductors for the needs of ac power applications. For example, conductors that incorporate insulation can readily be used for integrated busbar applications. The Bi-2212 tubular conductors will be produced, and commercialized for the needs of electrical engineering companies and large-scale applications in utilities. HTS materials and semi-finished parts are anticipated to become a new business for Nexans.

Alstom has the capacity to be the final producer of the self-limiting superconducting power link as well as to exploit fault current limiters developed under SUPERPOLI project as system elements. Alstom can perform also further industrial tests of power superconducting devices aimed for exploitation. Alstom will monitor further the developments in this field considering implementation of SUPERPOLI devices in the following years.

Technical University of Tampere (TUT) has a capability of further development of a software for analysis ac losses, safety aspects and overload behaviour of superconducting power links. This is basically needed for the next steps in design and realization of the full-scale prototype. TUT will use the additional expertise gained in low-scale measurements techniques and electromagnetic computation to provide high value technical education for its students. It expects also to benefit from the participation in other industrial research projects where low level measurements techniques and electromagnetic computation can be used to advantage.

Supplementary investments and further support is needed to speed up the implementation of the SUPERPOLI in a full-scale, especially at utility sites. As the SUPERPOLI enables not only the technical improvements but also valuable environmental and transnational impacts setting-up a further RTD project supported by EC is planned.

Main potential users of the SUPERPOLI are utility companies and industrial manufacturers of electric power equipment. To establish a relevant communication in the nearest future, the following means are considered:

- Presentations of SUPERPOLI at most important conferences and technical meetings
- Publications of SUPERPOLI results in the main technical journals focused on power engineering
- Development and distribution of software containing
  - knowledge about a self-limiting device for the medium voltage level which reduces efficiently short circuit currents.
  - numerical tools for the computation of the impact of current limitation in the electrical power grid
- Establishing an Internet page with current information on present and further developed state-of-art.

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6. COLLABORATION SOUGHT

Main data for the CORDIS Entry Form are listed in Table 4 and Table 5. The rest required information will be submitted electronically according to the actual rules of EC.

Table 4. Data for CORDIS Entry-Form on RTD-Results, page 1.

TECHNOLOGY DESCRIPTION

Title

Superconducting Power Link

Subject descriptors

B07	**E42**	**E39**	**E23**	**E08**

Innovative aspects

Within this project a demonstrator, essentially based on High-T_c Superconductors (HTS), which combines two devices, cables and fault current limiters, is realized and tested under industrial conditions. A power link based on such concept can find its application as a generator out-line or in the medium voltage power distribution system.

Current stage of development

Preliminary design, feasibility study	☐ (code 3)	Available for testing or assessment	X (code 6)
Intermediate design, research phase	☐ (code 4)	Tested, availible for demonstration	X (code 7)
Development phase	☐ (code 5)	Other	☐ (code 8)

Table 5. Data for CORDIS Entry-Form on RTD-Results, page 2.

Abstract

The aim of this project is to realise a demonstrator, based on High-T_c Superconductors (HTS), which combines two devices, cables and fault current limiters, for which the industrial need has been clearly demonstrated. Such a link can find its application as a generator out-line or in the medium voltage power distribution system. Two alternative superconductors, Bi-2212 bulk-material and Y-123 coated tapes, have been considered as possible candidates for the power link.

As a final application of the SUPERPOLI an *integration in the power grid* was considered as (i) a generator output and (ii) high density distribution network. *A functional model link* (single phase, 2 meter long, normal operation at 20 kV, 2 kA, fault conditions: 200 V, 5 kA) has been developed. The model allows operation both with active elements based on Bi-2212 and Y-123.

An assessment of the superconductors has been performed with respect to the current limiting capacity, power losses, mechanical strains and current limitation capability. *The final power tests* were performed at an industrial site in a 600 MVA Power Laboratory for Bi-2212 tubes and Y-123 modules (3 pieces of each connected in series). The performance of these materials was rather different. *The Y-123 modules yielded* a critical current of 2.4-3.3 kA_{ampl}, a quenching time of 0.1-0.5 ms, and, under fault current (unlimited current of 50 kA_{ampl}), - a voltage drop up to 150 V and peak power loads up to 450 kW. The high performance of the Y-123 modules (critical current of 2.4-3.3 kA_{ampl}, quenching time of 0.1-0.5 ms, and peak power loads of 450 kW under fault current) was found to be sufficient to provide a reliable protection for both a grid and generator by a scaled-up power link.

Techno-economical evaluation of the SUPERconducting POwer LInk combining low loss power transmission (1 GVA) with fault current limitation, to be used typically between the generator and the step-up transformer in a power plant, exhibits significant financial benefits with a Y-123 link. A lower power application (bus bar coupling in the distribution grid) has also been studied, on the basis of a comparison with existing Duplex reactors. In lower power applications, the advantages in terms of dynamic performances of the network are considered. A large range of technical and technological results confirms *the high potential of SUPERPOLI for further industrial application*.