Two Examples of Efficient Superconducting Cable Applications

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Abstract. Within the scope of the Supercable project granted by ENDESA, we have study some possible applications of the superconducting cable on linking of sub-stations. One of them considers the possibility to link two sub-stations at the medium voltage level (25 kV) by both, a standard set of copper cables and their equivalent superconducting cable. The second case establishes a comparison between a medium voltage superconducting link and the high voltage, 220kV, counterpart. As in the first case, the energy and emissions savings are clearly coming from the lower impedance of the SC cable, in the second case the benefit is clearly due to the absence of transformers. Although superconducting cable benefits are not only related with efficiency or environmental impact, the higher efficiency could be an added value when considering a SC cable installation.

1. Introduction
The successful development of HTS tapes with a critical current large enough to be operative, has created great expectation for the development of applications in the electric power distribution. Superconductivity can play a very interesting role to achieve new strong requirements for the electric networks, which constitute a very important challenge for the actual technological developments. Increasing of demand in places were the capacity for new lines is nearly saturated, introduction of fluctuating loads as electrical cars, power generation dispersed along the distribution grid, fluctuating power generation as is the case of wind based renewals, intensive use of electronic converters introducing a high content of harmonics, the environmental impact that the huge consumption of energy that our world-wide connected urban society claims for, and security required in the regular supplying of power are, among others, items which push for introducing new concepts leading to a new paradigm in the electric power distribution.

Contributions of superconductivity in this changing framework, considered for industrial level development effort, have been cables, fault current limiters, transformers, SMES’s, motors, generators, flywheels and synchronous condensers, being all of them, with the exception of motors and generators, especially considered for the transport and distribution business, for the new grid. The environmental impact of the energy needs of our life system becomes so huge that it is affecting, not only the landscape of the globe but also the life conditions derived from the emissions associated
to the generation of energy, so much that specific world-wide regulations have been needed in order to consider energy consumption as an important item to be considered when designing energy related systems or devices\cite{1}, from buildings to computers, from industrial plants to domestic devices. Efficiency is the new word pushing us to adapt for the new designing concerns leading to a smart use of energy.

In Europe, especial regulations will impose a short time horizon for energy consumption rationalization: the so called 20-20-20 target by 2020 \cite{2}, just concerning a reduction of 20\% on primary energy, a 20\% reduction of the greenhouse emissions and a 20\% increasing of renewals. If the savings objective of 20\% is met, the EU would not only use about 400 Mtoe less primary energy but it would also avoid the construction of about 1000 coal power units or half a million wind turbines. CO$_2$ emissions reduction would be about 860 Mt. According to that, Efficiency using energy is a critical point concerning all the new designs in energy distribution or, simply, in any new device requiring powering.

Despite its need of development, superconducting materials are mature enough to be considered in the manufacturing of devices for electrical power distribution, not only due to its higher capacity for transporting energy but also for its higher efficiency. A good proof is just the large number of projects for development of cables, SMES’s and limiters, running nowadays.

In this work we will deal about the comparison between the efficiency of a well made conventional solution and the efficiency when superconducting solution is adopted, in two cases. In the case of a medium voltage link for high current, with a set of conventional cables, compared with a superconducting one, and a second case of linking with a 220 kV system between two substations or using a HTS line at 25kV, at the distribution level.

The work we are reporting on is a part of an ambitious prospective project which has been started with the construction of 30m of a superconducting cable, for 3200A and 25kV, by NEXANS, designed for the distribution level, to be delivered at the starting of the next year 2010, in order to study the possible contribution to improve distribution efficiency and its near future expectancies related with the expected improvement of the superconducting tapes in energy losses and cost. The project has been funded by ENDESA in the scope of the NOVARE price 2007 on energy efficiency.

2. Losses in conventional undergrounded cables

At the distribution level, the cabling is heterogeneous being undergrounded or overhead according to the cost and the regulations. In dense cities, regulations imposes the use of undergrounded lines due to the reduced space available for the general servicing although the major cost of the cable, the civil work required and their maintenance. Due the low cost of energy, which does not include the cost of environmental impact and energy wasting, overhead lines are preferred when regulations allow it.

Origin of losses in conventional cables is based in dielectric polarization of the isolation, Joule losses in the conductor and AC effects, being the dominant the well known Joule contribution. The Joule contribution to losses depends on the conductor, copper or aluminium, its section and the current flowing through. Cost considerations impose the minimization of the conductor section with the constrain of the maximum working temperature that the materials can achieve. In undergrounded cables the maximum temperature, $\Theta$, is limited by the isolation, typically 90\^C in the XLPE isolated systems. According to the temperature of the soil and the thermal conductivity of the isolation, each conductor section defines a maximum current intensity which is a main parameter for the selection of the cable. Once the cable is selected, losses power, $P$, can be easily expressed (Eq. 1) as a function on the load factor, $C$, which is the ratio between the actual current intensity and the maximum allowable.

$$P = Const \times C^2$$  \hspace{1cm} (1)

(Const is a coefficient depending on the thermal environment of the cable and some correction taking in account AC concerns. In a typical undergrounded cable, in Spain, Const is 47.67 kW/km and does
not depend on the cable. Cable constrains are included in the load factor in terms of the maximum allowable current. For 3-phases cable it will be just three times higher, 143 kW/km. Details can be easily found in references [1, 3].

3. Losses in HTS cables
Losses in superconducting cables have a different origin than those of conventional cables. In order to get a better understanding of the grid impact, we can divide them in two groups according their effects. One group is related with the electrical conduction, the losses which can be detected by impedance measurements, and other group corresponds to the losses with no impact in the impendance, they are related with external sources of energy exchange.
Isolation losses, induction losses and magnetic losses on both, the conductor and the shielding, are in the first group, and the other group contain the losses due to thermal isolation, pumping and power required by the cryogenic system.
Losses strongly depend on the design of the cable, depending on the radius of the helix of the stranded tapes, the number of tapes and the compactness of the superconducting layer, the number of layers and on the manufacture and width of the tapes. The effect on the resulting losses is very important and a research effort is being done in order to diminish them [4, 5, 6] but in the actual status is not possible to give a universal law for determine them as a function on the current or the load factor. However, it is possible to approach an estimate of the value with the specific purpose of comparing the efficiency with the conventional conductor based cables. We consider an existing cable with similar performances of our one, and scale it in order to achieve the comparing conditions. In order to have a model, we have used the existing data of the LIPA cable [3, 7] of similar structure of that being built for the “Supercable” project. Scaling the published data corresponding to the LIPA cable, to 3200 A, 18/30 kV, we obtain the estimate of Table 1.

| Energy concept                              | 2000 A | 3200 A |
|---------------------------------------------|--------|--------|
| Conductor AC losses                        | 1.10   | 3.64   |
| Shield AC losses                           | 0.24   | 0.81   |
| Stabiliser - former                        | 0.04   | 0.24   |
| Dielectric losses                          | 0.02   | 0.02   |
| Cryostat losses (energy is not powered by the grid) | 1.3    | 1.3    |
| Pumping losses                             | 0.15   | 0.15   |
| Cryogenic system consumption (COP=11)      | 30.9   | 65.1   |
| Pumping Power                              | 0.2    | 0.2    |
| **Total**                                  | 32.95  | 72.67  |

The scaling performed should be considered as one approach, losses in the superconductor could be underestimated but they match acceptable with the reported values of the power of cryogenics in existing installations [3,7]. Experimental data will be available when ending the first phase of “Supercable” project.
In Table 1, all the concepts in rows over that of “Cryogenic system consumption”, introduce heat to be removed by the cryogenic machine. All the energy is also consumed from the grid with the exception of cryostat losses that are considered only in the cryogenic system consumption. Pumping losses depend very much on the design, they have been estimated in 0.15 kW/km taken in account the pressure drop and the mass flow required [3]. Schematics of the losses sources is reported in figure 1. The 3-phases HTS circuit considered could have two configurations. Three separate cables or three cables in only one cryostat, the values of the voltage allow both configurations. In the first case, the overall losses should be three times the losses of one cable and, in case of only one cryostat, the losses
Figure 1. Schematics of the losses in a HTS cable system. Energies supplied are: heat generated by the carried current and external power supply. Heat from external sources is not supplied by the grid neither the system (coolant flow losses are provided by pumping which is considered in the external power supply term).

are in the range of three times higher with the exception of those corresponding to the cryostat that have considered only one time but slightly increased considering the larger diameter of the cryostat. More details will be found in the next section.

4. Application examples

4.1. 25kV link

In the first application example, we consider a 3-phases 25kV link of 1km length that should be upgraded to achieve an ampacity of 3200 A (138 MVA). According to the typical values allowable for aluminium XLPE cables, the conductor section for this ampacity is excessively large for the working conditions we are considering. A way to avoid this large section is to consider the use of several circuits of typical aluminium-XLPE cables of 240mm² allowing so a better refrigeration of the cables and less conductor section. In order to achieve this ampacity the upgrading should be performed by 8 circuits. Although this way can surprise the reader, it can correspond to actual situations where the link can be made by several routes or by steps. In this way, the load factor could be considered the same for each circuit and the same for the whole system due to the fact that the temperature constrains change according to the great increasing of the heat exchange surface. So, the losses of the system are 8 times the losses of one of the circuits at the same load factor.

In order to perform the 3-phases link, we consider two options, the 3-phases in one cryostat option and separated 3-phases. Due to the shielding, there is no mutual influence between the phases thus the only difference is the increasing of size of the cryostat and a heat load of 1.4 kW/km has been considered in the single cryostat option, meanwhile the losses in the three phase system are just three times larger than those considered in section 3. In figure 2 are represented the results for both cases.

It is clear that for load factors below 0.3 has no efficacy the substitution of the conventional system by the superconducting one on a basis of a improvement of efficiency, only other considerations, as saturation of the soil, could justify the hard increasing of investment corresponding to the superconducting solution but with a mean load factor of 0.7 or 0.8 it is very clear the difference (see figure 2).

The savings of energy at a load factor of 0.75 in case of a three cryostats system is in the range of 514 kW/km (4.51GWh/year km and 1800 Ton CO₂/year km considering an emission factor of nearly a 0.4 kgCO₂/kWh [1]) meanwhile the only one cryostat solution produces energy savings at a rate of 542 kW/km (4.75 GWh/year km and 1900 tCO₂ /year km). Considering the price of energy
(0.065€/kWh) and the rights for the emission excess, in the Emissions Exchange [1], that has achieved 20 €/CO$_2$t, the savings could be estimated to 329 k€/year km and 346 k€/year km.

**Figure 2.** Losses in the conventional, three separated phases and 3 phases in one cryostat options

### 4.2. HTS 25kV link versus a 220kV conventional

From the results of subsection 4.1, it seems clear that the conventional proposal is not adequate to transport the amount of power required at medium voltage level. The conventional solution is just to use high voltage in order to improve the efficiency with cables of shorter section. A reasonable situation is just the linking of two substations (substation 1 and substation 2) with a 220kV circuit. To transport 138 MVA at this level in a 3-phases system, the rms-current should be of 364A. For this ampacity the adequate section of aluminium XLPE cable is just the higher limit of a 240mm$^2$ cable system.

**Figure 3.** Electrical sketch of the link between Substations 1 and 2

with a load factor of 1.07 which can diminish depending on the manufacturer. So, in these conditions, the cable is easy to be provided and the losses correspond to that obtained in section 2: 143 kW/km at a load factor of 1. The medium voltage link with HTS cable produces losses of 218 kW/km or 190.5 kW/km, depending on whether 3 separated phases or only one cryostat, clearly higher than those
produced by the conventional cable. In figure 4, it is shown the clear benefit of using conventional high voltage cables.

![Figure 4](image)

**Figure 4.** Comparation between losses in the HTS link (“separated phases” and “one cryostat” options) and the high voltage conventional link (HV conventional).

The simplified analysis provided, however, is far away of the actual situation: Transformers should be included in the energy path. The situation becomes clearer when dispersed generation in the distribution medium voltage grid is considered. From the circuit of substation 1, energy should use two transformers to arrive the distribution grid of substation 2 (see figure 3). At the power level, we are considering efficiency of the transformers that depends on the manufacturer and the utility rules. For this work we have used the data corresponding to an existing transformer, working in the feeding of an actual substation. Efficiency at power factor 0.9 moves from 99.68% at 37.5% load factor to 99.57% at 80% load factor or 99.49% at a load factor of 100%. We can estimate then losses by taking in account the whole circuit. Results are shown in figure 5.

![Figure 5](image)

**Figure 5.** Losses in the three proposed cases (see text) considering transformers contribution in the high voltage link (AT link).
In the scope of these results we can observe that a benefit of a medium voltage link introduces a benefit that can achieve about 821.6 kW/km (849 kWh/km for the “one cryostat”), equivalent to energy savings of 7.2 GWh/year and 2879 CO₂t/year (7.44 GWh/year and 2975 CO₂t/year for the “one cryostat” system). The benefit, in the conditions of the market, of 525 or 543 keuro/year km.

5. Conclusions
Although losses in the terminations, which diminish when the length of the cable increases, have not been considered, and according to the analysis performed of links at medium voltage between substations, efficiency considerations could justify the use of HTS when a large payback time is considered and the load factor is maintained to a medium high value during time, due to the high price of the investment at the nowadays status. Considerations concerning rights cost or saturation, safety or special circumstances can justify, from the economical point of view, the use of HTS link. However, when comparing HTS cables with links including transformers, the situation could be not so clear. The high cost and inefficiency of the transformers could diminish the payback time of the installation to a reasonable period.

The efficiency in both cases is clearly higher for the superconducting option if the load factor is higher than 0.3 and the installations are running habitually. In both cases we considered, the energy cost and emissions rights contribute in 0.3-0.5 M€/year km at an equivalent 0.75 load factor.

The development of more efficient cooling systems and better thermal isolations, diminishing of the tape losses, simplifications of the cable system and the expected diminishing of the price of the HTS tapes could help to increase the efficiency of our power grid leading to a better perspective of the evolution of our environment.

The existence of lower cost installations would be a good tool contributing to improve efficiency of the power system.

6. Acknowledgments
The authors would like to thank the financial support from ENDESA-NOVARE price 2007 also they would like to thank the support MICINN (MAT2008-01022, NAN2004-09133-CO3-01, Consolider NANOSELECT and FPU), Generalitat de Catalunya (Catalan Pla de Recerca 2009-SGR-770 and XaRMAE), and EU (HIPERCHEM, NESPA and EFECTS).

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