Conceptual Study of Superconducting Urban Area Power Systems

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ABSTRACT **- Efficient transmission, distribution and usage of electricity are fundamental requirements for providing citizens, societies and economies with essential energy resources. It will be a major future challenge to integrate more sustainable generation resources, to meet growing electricity demand and to renew electricity networks. Research and development on superconducting equipment and components have an important role to play in addressing these challenges. Up to now, most studies on superconducting applications in power systems have been concentrated on the application of specific devices like for example cables and current limiters. In contrast to this, the main focus of our study is to show the consequence of a large scale integration of superconducting power equipment in distribution level urban power systems. Specific objectives are to summarize the state-of-the-art of superconducting power equipment including cooling systems and to compare the superconducting power system with respect to energy and economic efficiency with conventional solutions. Several scenarios were considered starting from the replacement of an existing distribution level sub-grid up to a full superconducting urban area distribution level power system. One major result is that in the future a full superconducting urban area distribution level power system could be cost competitive with existing solutions. In addition to that, superconducting power systems offer higher energy efficiency as well as a number of technical advantages like lower voltage drops and improved stability.**

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I. INTRODUCTION

The development of High-Temperature Superconducting (HTS) power equipment, like, *e. g.* cables, fault current limiters, rotating machines, transformers and SMES (Superconducting Magnetic Energy Storage), has made a significant progress in recent years. Many successful tests of prototypes and demonstrators underline the superior technical performance of superconducting power equipment. Particularly superconducting cables [1-3] and superconducting fault current limiters [3-7] have already demonstrated their capability to increase the reliability and efficiency of power systems in long term field tests.

Most studies on superconducting applications in power systems have concentrated on the application of one specific device (cable) at a time [8-9], and have not considered the combined effect of, for example, HTS cables and HTS current limiters. Superconducting power equipment is presently implemented in the grid mainly in so-called stand-alone demonstrator applications. This means, for example, that a conventional high-voltage cable is replaced by a superconducting medium-voltage cable or that a single superconducting fault current limiter or a SMES is implemented in a conventional grid. HTS power equipment has reached such a maturity level that a large scale integration of HTS power installations seems possible within 10-20 years, *i.e.*, within the time frame of large-scale system planning. The main focus of this study is to show the consequences of such large scale integration of superconducting power equipment in distribution level urban power systems. This study concentrates on urban area power systems with relatively short distances between connections, because the present state-of-the-art HTS power equipment is not applicable to long length (>100km) bulk power (>1 GW) transmissions. Several scenarios were considered ranging from the replacement of an existing distribution level sub-grid up to a full superconducting urban area distribution level power system. For the different scenarios, the economic aspects and the potential to increase energy efficiency were investigated.

Table 1 summarizes the impact of the main HTS features like low impedance, high current carrying capacity and inherent short-circuit limitation on power systems. In general, the high current-carrying capacity and the low voltage drop of HTS power equipment results in lower total line length, less switchgear and fewer substations. In addition, the short-circuit limitation offers the possibility to dimension lower short-circuit currents and nurtures the vision of a short-circuit free power system. This would mean a power system without impact of high short-circuit currents.

Table 1. Main HTS Characteristics, their Impact on Power Systems and their Dimensioning

Main HTS Characteristic	Consequence for Power System Dimensioning	Consequence for Power systems
Low impedance and low voltage drops	Longer line lengths at voltage level where HTS is inserted Longer line lengths at subordinate voltage levels	Lower total line length Less switchgear Fewer substations
High current carrying capacity	Higher power rating per feeder	Lower total line length Less switchgear
	Reduced number of voltage levels	Omission of one voltage level at generation and transmission level
Short-circuit limitation	Dimensioning to lower short-circuit currents	Short-circuit free power systems

II. HTS IN URBAN AREA POWER SYSTEM

A. HTS Application Scenarios

Three different HTS scenarios were investigated in detail and were compared with a conventional base scenario. A simplified sketch of the different scenarios is shown in Fígure 1. The conventional power system corresponds to the present structure of an urban area

electrical power grid with an extra high-voltage (EHV) transmission level (380 kV in Europe), a high-voltage (HV) transmission and distribution level (220 kV or 110 kV in Europe), a medium-voltage distribution level (10-30 kV in Europe) and a low-voltage distribution level (< 1 kV). In this basic scenario only conventional power equipment is used.
Scenario 1 assumes that the conventional high-voltage distribution level is replaced by an HTS power system at medium-voltage level. The medium-voltage level is now directly fed by the EHV level and consists of two parts, the new HTS medium-voltage part and the conventional part. This scenario is very likely in retrofitting situations, in which old high-voltage cable installations could be replaced by HTS medium-voltage cables.

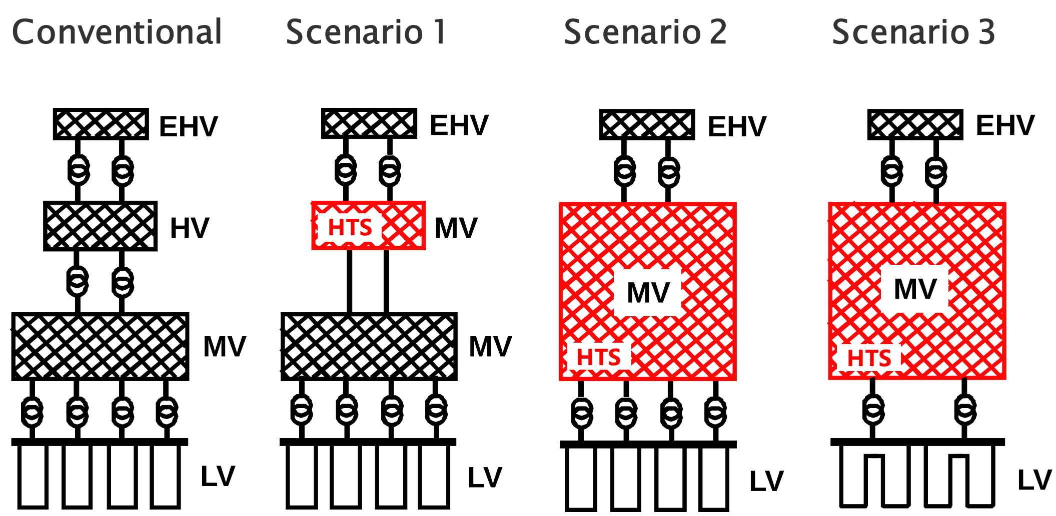

Fig. 1. Simplified sketch of investigated scenarios

In Scenario 2 both the conventional high-voltage (HV) level and the medium-voltage (MV) level are replaced by a HTS power system at medium-voltage level. This scenario is favoured in situations when entire new power systems are planned to supply new load areas. Compared to Scenario 1, the entire medium-voltage grid could profit from higher currents and low voltage drops. The structure of the low-voltage (LV) level remains unchanged.

Scenario 3 differs from Scenario 2 in that the cell size within the low-voltage grid is extended. This is possible by using the HTS benefit of low voltage drops. Nowadays, the voltage at the consumer level may vary within a certain tolerance (*e.g.*, ±10 % at 400 V according to European standard EN 50160) and is usually controlled by tap changers at the HV/MV transformers. Due to the low voltage drop at the HTS medium-voltage level there is more margin for the voltage drop at the low-voltage level. Consequently, the line length, *i.e.*, the cell size at low-voltage level can be increased, which reduces the number of MV/LV transformers. Those can be operated at higher power ratings and the line length at the medium-voltage level can be reduced, too.

B. Assumptions

All calculations were done on a synthetic power system assuming realistic parameters of an urban power supply area of 100 km^2. Calculations for the “base case” were based on 30 kV medium voltage and a load density of 30 MA/km^2. However, within a sensitivity analysis the

load density was varied later between 10 and 90 MW/km^2. In Germany, some downtown areas have already reached about 50 MW/km^2 so that this variation covers the present situation and leaves room for future expectations.
Besides the general structure given in Figure 1, more technical aspects need to be defined. The most important assumptions and boundary conditions for the investigations are:

- The low voltage grid has a ring structure and uses cables only. This means that the n-1 redundancy is fulfilled. This means that one component can fail and the security of supply is still obtained.
- It is common practice of many utilities and assumed for these calculations that there is only one transformer in substations between medium and low voltage. Redundancy in case of maintenance and outage is established via the subordinate low-voltage grid.
- The medium voltage grid is operated as an open ring structure and uses cables only. Even if today some medium-voltage systems in urban areas are operated as a meshed structure, it is reasonable to assume that in future the simplified ring and radial structures will become common practise.
- The high voltage grid is operated in a meshed structure and employs conventional protection schemes. Each high voltage line is equipped with circuit breakers and protection devices at both ends.
- The protection scheme of the low-voltage and the medium-voltage grid is conventional. Fuses are used in all low voltage busbar connections whereas circuit breakers and corresponding protection devices are assumed on the medium-voltage side of all high-voltage to medium-voltage substations.
- The voltage level and the short circuit capacity is kept within permissible boundaries.
- The n-1 criterion was considered for all investigations to guarantee the necessary reliability and redundancy.

To investigate and compare the economic feasibility of the different HTS scenarios, their annual costs were calculated without the effect of inflation. The costs of investment, maintenance, operation and losses were considered. Table 2 summarizes the cost assumptions for the conventional and for the HTS power equipment. No considerable future cost reductions are predicted for the conventional power equipment and, therefore, present average values were considered.

It is difficult to predict the future costs of HTS power equipment today. The values in Table 2 are predictions for a time span of 10-20 years with a considerable production volume assumed. To investigate the impact of the HTS cost assumptions, a sensitivity analysis was performed using twice the values of Table 2 for the HTS power equipment.

The cost of electrical losses was set at 100 €/MWh. This is higher than today, but seems realistic in view of increasing energy costs in the future. The energy loss per year was calculated from the loss at peak load times the number of annual loss hours. Typical values in Germany are 1000 hours (h) at low voltage, 3500 h at medium voltage and 5000 h at high voltage.

Table 2. Cost Assumptions for Conventional and HTS Power Equipment

Power Equipment	Investment	Operation Cost in %/year of Investment
EHV/HV transformer	2.500.000 €	2 %/year
HV/MV transformer 63 MVA	790.000 €	2 %/year
HV cable[1)]	630.000 €/km	0.25 %/year
HV switchgear	800.000 €	1 %/year
MV cable[1)]	220.000 €/km	0.25 %/year
MV switchgear	41.000 €	2 %/year
LV cable[1)]	100.000 €/km	0.25 %/year
LV substation with transformer	50.000 €	1.5 %/year
HTS MV cable 2.5 kA[2)]	1.000.000 €/km	0.25 %/year
HTS MV cable 3.5 kA[2)]	1.150.000 €/km	0.25 %/year
HTS MV fault current limiter	150.000 €	1.0 %/year
HTS switchgear	120.000 €	1.0 %/year

[1)] including installation and terminals
[2)] including cooling, installation and terminals

C. Economic feasibility

The results of the investigation of the economic feasibility are shown in Figure 2, where the annual costs are summarized and compared for the different scenarios. The costs for investment, operation and loss in Figure 2 are calculated for a so-called base case with the following assumptions:

- Load density: 30 MW/km^2
- Medium voltage level: 30 kV

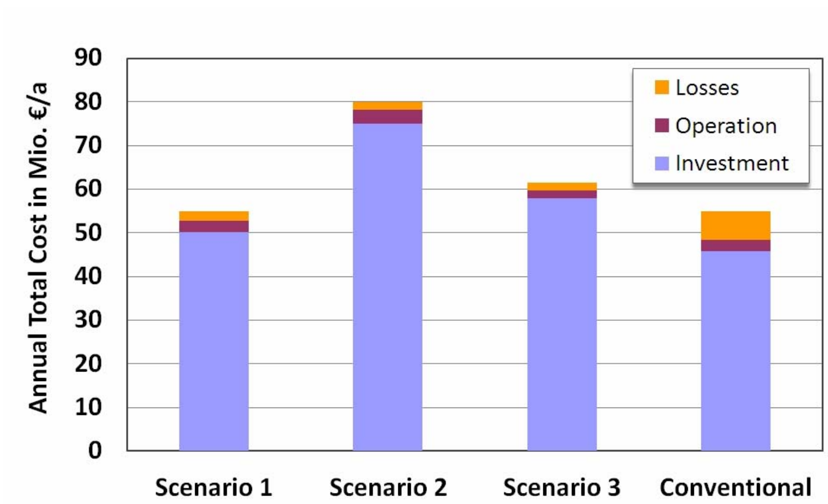

Fig. 2. Annual total cost of the different scenarios

- HTS cable ampacity: 2.5 kA
- All investment and operation costs according to Table 2
- Cost of energy loss: 100 €/MWh.

In these calculations no charges for CO_2 emission or additional costs for CO_2 reduction were considered. If these were included, the cost of losses would presumably double, further increasing the advantage of the HTS option.

The main message of Figure 2 is that there are HTS scenarios (1 and 3) where annual costs are absolutely comparable with a conventional grid. Even if individual HTS components are more expensive than their conventional counterparts, savings on high-voltage equipment are completely balancing this cost disadvantage in Scenario 1, so that costs are practically equal. A similar situation occurs in Scenario 3, where the underlying low-voltage grid takes full advantage of a medium-voltage HTS grid (less voltage drop, higher current density). Costs of the base case in Scenario 3 are just around 10% higher than conventional. It is no surprise that a power system with an HTS medium-voltage level, but conventional low-voltage grid architecture (scenario 2) gives away the HTS benefits and is not competitive. Hence, scenario 2 can be disregarded in the following.

The breakdown of the individual investment costs in Figure 3 relates the costs of the HTS equipment to the conventional parts, and underlines the reasoning above. Even if the medium-voltage HTS equipment in scenario 1 is about double the cost of conventional high-voltage components, the impact is limited due to the small relative share in the total cost. Hence, the investment costs in Scenario 1 are very close to the conventional scenario. In Scenario 2 the conventional medium-voltage grid is completely replaced by HTS power equipment. This leads to much higher investment costs for the medium-voltage system: Scenario 2 is not competitive with the conventional scenario.

Scenario 3 requires much less medium-voltage line length and thus the investment for the HTS part is much lower than in Scenario 2. Another benefit emerges from the reduced number of substations feeding the low-voltage level.

Figure 4 demonstrates that the electrical losses in the HTS scenarios are much lower than in the conventional grid. However, since losses account only for a relatively small fraction of the total cost, reduced losses are only compensating the slightly higher investment costs in

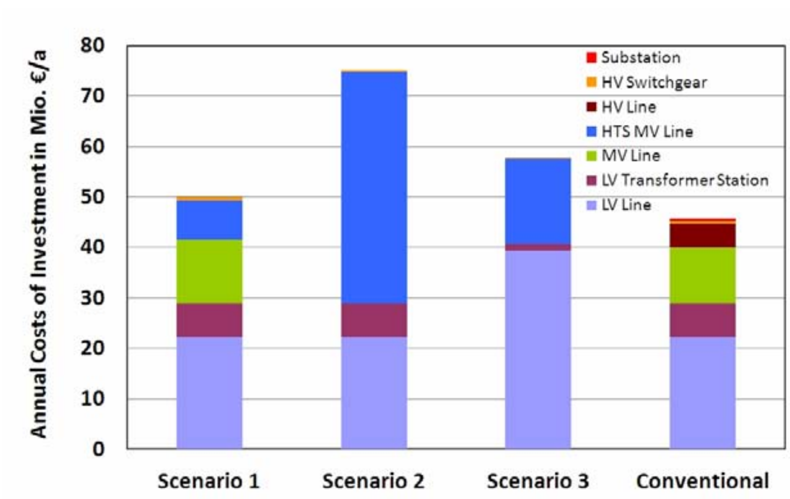

Fig. 3. Annual investment cost for the different scenarios

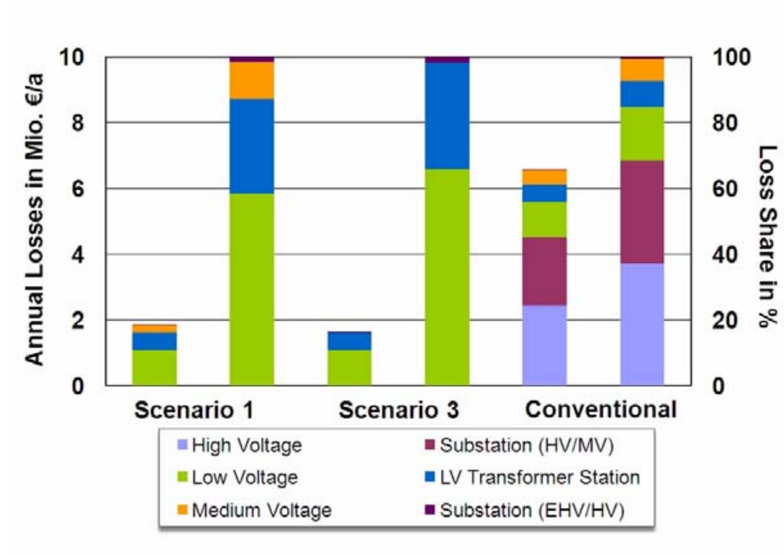

Fig. 4. Annual cost of losses and loss share

Scenario 1. In Scenario 3 they are not sufficient to balance the larger investment in HTS components at the base case load density.

Sensitivity analyses were performed for the HTS Scenarios 1 and 3 to investigate the influence of the load density and the cost of HTS equipment on the economic feasibility. As a result, the higher the load density, the more favourable are the HTS scenarios, due to increased savings in losses. However, the influence of the load density on the total costs is within a few percent.

To check the impact of the HTS cost level, the investment cost for HTS power equipment was doubled, leading to a mere 15% or 25% increase in the total annual cost for HTS Scenarios 1 and 3, respectively. This means that the influence of the cost of the HTS equipment is moderate and the results of this survey are valid even if the extent of the HTS material cost reduction cannot be forecasted precisely.

III. SUMMARY

The impact of an integrated HTS power distribution on the electrical power supply of congested urban areas has been studied. It turned out, that taking advantage of the full systemic added value of HTS, an HTS grid does not only offer technical benefits, such as higher load flexibility, lower voltage drops, higher stability and improved grid safety, but can be more economic and competitive with conventional grid concepts. Replacing metropolitan high voltage distribution lines by medium voltage HTS cables can pave the way for HTS subgrids in well-developed western cities (Scenario 1). In densely populated countries with developing infrastructure or greenfield development of urban areas the EHV transmission level could be favorably connected by a medium-voltage HTS distribution to a low-voltage grid with large mesh size (Scenario 3). As an additional benefit, the HTS option stands out due to its improved energy efficiency and environmental friendliness.

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