DOI : XXXXX/XXXXX

3.1. Superconducting AC Cables for Power Distribution

Author: Peter Abrell (Vision Electric Super Conductors, abrell@vesc-superbar.de)
Wolfgang Reiser (Vision Electric Super Conductors, reiser@vesc-superbar.de)

Last revision: 2024-12-06

Abstract

This paper describes the future challenges faced by Europe's distribution grid in the wake of European decarbonization goals. Superconducting alternating current (AC) cables are introduced as an emerging technology that can eliminate difficulties while also increasing energy efficiency.

Introduction

The EU has committed to lofty decarbonisation goals: becoming carbon neutral by 2050 and reducing carbon emissions by at least 55 % by 2030 [1]. The largest share of emissions generated in Europe stems directly from burning fossil fuels. Reducing these emissions is only possible by switching energy sources from fossil to electric power. Electric cars and heat pumps are replacing gasoline cars and gas heating. Electricity demand is expected to increase across Europe, up to triple by 2050 [2].

Not only power generation and transmission will need to rapidly expand, but also the power distribution inside cities. Alongside this, urbanization is set to increase to 83.7 % in 2050 [3], meaning 83.7% of Europe's population will be living in cities, towns, and suburbs by 2050, an increase of around 4%. With increased energy demand and population density, the power distribution networks will need to be modernized to accommodate additional load. Higher load levels lead to higher currents which leads to higher losses. A fact that is unavoidable for copper and aluminium cables, but not for superconducting cables.

Solution

Superconducting AC cables are a promising solution to modernising the distribution infrastructure, especially in urban areas. Present cables in underground distribution infrastructure partially date back to the 1950s and need replacement. Renewing these sections with conventional cables, while also increasing the capacity of the distribution system would mean digging up large sections of underground cables and installing a larger protective conduit as larger cable cross-sections are needed. This does not have to be the case with superconducting cables. Due to their superior current and power densities, a higher rated power system can be installed in existing conduits. This means that capacity can be upgraded without the need for costly underground construction.

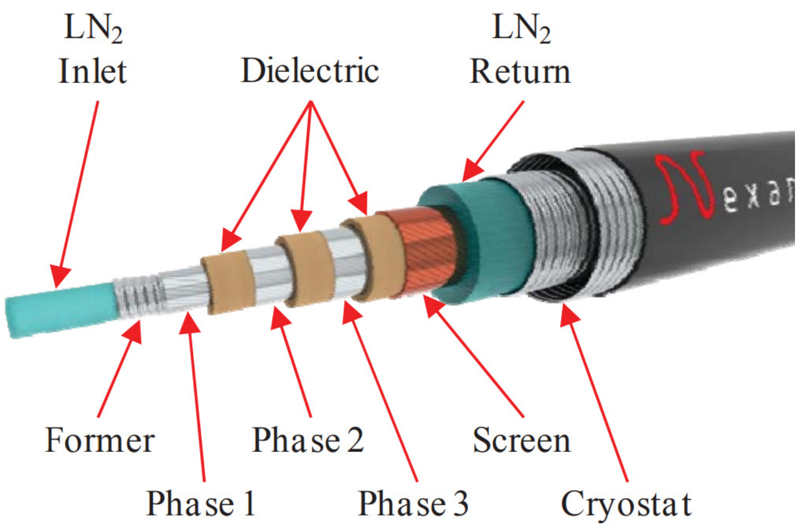

Figure 1: Illustration of a concentric three-phase AC cable used for the AmpaCity project in Essen, Germany [4] (Copyright Nexans).

Compared to a conventional cross-linked polyethylene (XLPE) cable, superconducting cables require additional elements for cooling and thermal insulation as the superconductor needs to be cooled below its critical temperature for operation. For AC cables HTS with a critical temperature well above 77 K are chosen. As Nitrogen liquifies at 77 K it can then be used as a reliable liquid cooling medium just by pumping it through the cable. It is also an excellent electric insulator reducing the need for further insulation.

The main losses in HTS cable systems result from heat entering from outside the system. This heat needs to be transported away by the cryogenic system. To minimise the heat input a cryostat is used. It consists of a pipe with two walls and a vacuum in between them very similar to a thermos flask. The vacuum reduces the heat input by convection. To reduce the heat input by radiation, a multi-layer isolation is used. An advantage exclusive to superconducting cables like the one shown in Figure 1 is reduced electromagnetic interference (EMI). By reducing the EMI, surrounding distribution infrastructure will experience better power quality, performance, and reliability. Due to the negligible electric resistance, HTS cable systems are more efficient. One HTS cable can transport the pow-

DOI : XXXXX/XXXXX

er of two conventional cables while reducing losses by over 40% [5]. At a distance of 1,000 m and voltage of 110 kV, two XLPE cables that each carry 1.5 kA produce losses of around 200 kW. In comparison, one HTS cable will only lose 112 kW including thermal losses and power for cooling machines. The improved current carrying capabilities at lower voltages means existing distribution lines' capacity can be increased. Furthermore, the need for intermittent substations (for example on the 110 kV level) can be avoided, as the same power can be transferred at a lower voltage. Reduced voltage facilities are generally cheaper and require less space and insulation than the higher voltage equipment.

A conventional distribution system will suffer load dependent voltage loss between source and load. Eliminating the resistance between voltage source and load with superconducting cables counteracts this and results in higher voltage stability. Furthermore, other superconductive applications such as fault current limiters can be easily introduced, since cryogenics are already present, to further optimize distribution stability. These characteristics give superconducting cable technology the potential to modernise electrical infrastructure and cities.

Status

There have been several completed HTS AC cable projects in the past as listed in table 2. One of the most applicable to the scenario outlined in this paper is the AmpaCity project in Essen, Germany, in which a superconducting cable was integrated in existing distribution infrastructure and successfully operated for many years. The 10 kV cable replaced a conventional 110 kV cable, demonstrating the application benefits of superconductors.

Table 2 List of completed AC HTS cable projects between 2011 and 2021 [6] (3P: three-phase, 1P: single-phase).

Year	Country	Project/City	Phases	Power (MVA)	Rated Current (kA)	Voltage (kV)	Length (m)
2021	China	Shanghai	3	133	2.2 (3P)	35	1200
2021	USA	Chicago	3	62	3 (3P)	12	200
2021	Japan	Yokohama City	3	51	4.5 (3P)	6,6	200
2019	South Korea	Shingal	3	50	1.26 (3P)	23	1000
2016	South Korea	Jeju	1	346	2.25 (1P)	154	1000
2014	Germany	AmpaCity/Essen	3	40	2.3 (3P)	10	1000
2013	China	Shanghai	1	70	2 (1P)	35	50
2012	Japan	Yokohama	3	200	1.75 (3P)	66	50
2011	Spain	Endesa	3	139	3.2 (3P)	25	30
2011	South Korea	Icheon	3	50	1.25 (3P)	23	500

Several AC cable projects are underway in Europe at the moment. The SuperLink project will develop the technology to link two substations in Munich (DE) across a distance of 12 km, distributing up to 500 MVA at 110 kV [7]. The project HighAmp will develop and test a 20 kV, 100 MVA, 3-phase cable as a first step to a 110 kV cable which will be used in Cologne's (DE) distribution grid.

Challenges

The Ampacity Project in Essen demonstrated that superconducting cables are ready for use [8]. However, there are still challenges to overcome until superconductivity can replace conventional cables as a widespread technology. The high cost of the superconducting cables is a significant deterrent today so that the focus today is on special projects where the specific properties of the cables lead to high cost savings compared to conventional solutions.

It was suggested that a price reduction for superconductive material by a factor of four is needed to make superconductor cables generally competitive with conventional cables [4]. Furthermore, today's production capacity for HTS is still too low to produce commercially relevant length of AC cables. A foreseeable sequence of projects with a significant length would generate the necessary demand to justify the high investments in the necessary expansion of production capacities and subsequently lower the price for HTS. In parallel also the cost of the cryogenics would decrease. To realize these projects, a combined effort of the superconductor industry, distribution net operators and politics is necessary. Once the production capacity is increased, a stable market penetration will be possible, and superconductors will become the high efficiency complement to copper and aluminium.

Raising public awareness of the potential and possibilities of superconducting products is also important. Interest in the topic will ultimately lead to new practical applications and projects. Overcoming these challenges will allow distribution infrastructure to become efficient, require less space, and become more reliable.

DOI : XXXXX/XXXXX

References

[1] European Commission, “Delivering the European Green Deal - On the path to a climate-neutral Europe by 2050.” [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

[2] McKinsey & Company, “Global Energy Perspective 2022,” 2022. [Online]. Available: https://www.mckinsey.com/~/media/McKinsey/Industries/Oil%20and%20Gas/Our%20Insights/Global%20Energy%20Perspective%202022/Global-Energy-Perspective-2022-Executive-Summary.pdf

[3] European Commission, “Urbanisation in Europe.” Accessed: May 29, 2024. [Online]. Available: https://knowledge4policy.ec.europa.eu/foresight/topic/continuing-urbanisation/urbanisation-europe_en

[4] M. Stemmle et al., “Three years operation experience of the AmpaCity system installation in Essen, Germany,” in 13th European Conference on Applied Superconductivity, EUCAS 2017, 2017. [Online]. Available: https://indico.cern.ch/event/659554/contributions/2709480/attachments/1527270/2388461/3LO4-05_Jean-Maxime_Saugrain_Room_1.pdf

[5] D. Kottonau et al., Evaluation of the Use of Superconducting 380 kV Cable. KIT Scientific Publishing, 2020. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000117918

[6] C. Räch, “Untersuchung von Wechselstromverlusten verschiedener hochtemperatursupraleitender Mehrleiterkonzepte für dreiphasige Hochstromanwendungen,” Doctor of Engineering Thesis, Fakultät für Elektrotechnik und Informationstechnik des Karlsruher Instituts für Technologie (KIT), 2023. [Online]. Available: https://publikationen.bibliothek.kit.edu/1000168809/152396802

[7] W. Prusseit and R. Bach, “The Munich SuperLink project,” Transformers Magazine, no. Special Edition: Superconductivity, 2021, [Online]. Available: https://ivsupra.de/wp-content/uploads/2021/05/Transformer-Magazine_SuperLink-140521.pdf

[8] M. Stemmle, F. Merschel, M. Noe, and A. Hobl, “Ampacity project - worldwide first superconducting cable and fault current limiter installation in a German city center,” in 22nd International Conference and Exhibition on Electricity Distribution (CIRED 2013), Institution of Engineering and Technology, 2013, pp. 0742–0742. doi: 10.1049/cp.2013.0905.