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Design and Economic Analysis of 275 kV HTS Cable for UK Transmission Network

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Abstract— **Achieving Net Zero requires a significant increase in electricity demand for transportation, heating, and industrial sectors. However, the increase in demand poses a challenge for heavily congested urban networks. High-Temperature Superconductor (HTS) 275kV cables offer a credible technology solution that can uprate existing cable routes up to five times higher capacity density, utilizing existing 275kV substations and removing the need to uprate circuits to 400kV. This paper presents a detailed technical design and cost-benefit analysis for the cable installation. The technical analysis covers location selection, power system considerations, and standards alignment. A 12.9km long 275kV cable has been designed using cold dielectric and three separate phases. An equivalent circuit model was built using distance and differential protection methods to study the operation during different fault scenarios. A Standard mapping exercise has been performed to understand the gaps between the HTS and conventional cables by covering seven existing standards to identify the further tests to de-risk the technology. The economic analysis by considering the full lifecycle shows HTS is the economic for the chosen location with instances where substation equipment or land expansion costs are dominant.**

***Index Terms*—HTS cable, standards, faults, transmission networks.**

I. INTRODUCTION

THE discovery of high-temperature superconducting materials in 1987 revolutionized superconductors by enabling operation at temperatures above 77 k, expanding their practical applications from magnets to efficient power transmission in compact, lightweight, and cost-effective systems [1]–[5].

Over the past two decades, significant progress has been made in the development and implementation of HTS cable prototypes and projects for power transmission. These endeavors include a successful one-year test of a 100-meter 3-core/66 kV/1 kA_{rms} HTS cable prototype with impressive critical current performance, an ENDESA cable prototype demonstrating the feasibility of load cycle testing, and the Albany project's installation of a 350-meter HTS cable in the Niagara Mohawk power grid [6]–[9]. The Long Island Power Authority grid installed the first long-length cold dielectric HTS cable with a transmission line level voltage of 138 kV with a power capacity 574 MVA, a current capacity of 2.4kA of 0.6 km long cable [10], [11]. The Essen project in 2013 marked a milestone with a 1 km long HTS cable system incorporating a fault current limiter, transforming the city's grid structure and reducing overall costs compared to conventional systems [12]. These developments showcase the promising potential of HTS technology in revolutionizing power transmission systems.

In the transition from 2022 to 2050, the UK's energy landscape is undergoing significant shifts growing three times according to National Grid Energy System Operator (NGESO) [13]. The National grid is responsible for the transmission level network, and the electrification of energy demand emerges as a great challenge. Consequently, exploring the potential of HTS cables for transmission becomes a compelling path to expedite the journey toward achieving net-zero emissions, representing a critical step in the nation's sustainable energy future.

To reach Net Zero within the next 20 years, the UK faces a significant rise in electricity demand from sectors such as transport and industry, straining its dense urban grids. Upgrading the National Grid from 275kV to 400kV is costly, involving larger substations and transmission lines, and more land. Alternatively, employing HTS could increase the capacity of the existing 275kV system, leveraging current infrastructure and minimizing major alterations and land requirements.

This paper explores the potential of HTS cables in the UK's transmission network, analyzing the intersection of cutting-edge technology, economic feasibility, and evolving power transmission in the United Kingdom. In an era of increasing energy demands and sustainability imperatives, this investigation examines how HTS cables can transform the UK's transmission network while remaining economically viable, paving the way for a sustainable energy future.

II. PROJECT BACKGROUND

A. SCADENT project introduction

The SCADENT project, a collaborative effort involving National Grid, the University of Strathclyde, the University of Manchester, Frazer-Nash Consultancy, Western Power Distribution, UK Power Networks, Nexans, and AMSC, aims to assess the feasibility and potential of High-Temperature

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Superconducting technology within dense energy networks. This project is funded by Strategic Innovation Fund from Ofgem in the UK.

B. *Location choice and possible options*

The Mersey Ring circuit, spanning 12.9 km between the Birkenhead and Listerdrive substations shown in Fig. 1, faces the crucial need for a power-carrying capacity upgrade, as its present limit stands at 2000 MVA. The system's infrastructure is prepared for future operation at 400 kV but necessitates additional transformers. Three potential solutions emerge to meet the impending energy demands: the first option involves replacing the cable with a 400 kV XLPE cable, the second option entails replacing the existing 275 kV cable with a new 275 kV cable, and installing a second parallel 275 kV cable along a new route, in conjunction with the existing substation, and the final option entails substituting the existing cable with a superconductor while upgrading the substation to accommodate a cooling system. The choice among these options will significantly impact the network and capability to meet the growing energy requirements.

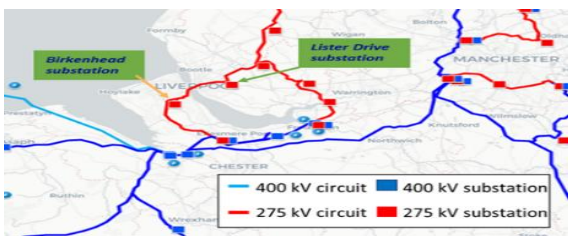

Fig. 1. Site location.

III. CABLE DESIGN AND SPECIFICATIONS

In this setup, a three-phase cable employs three separate single-core HTS cables for each phase, a design choice necessitated by dielectric considerations at the 275 kV voltage levels. Cooling is facilitated by a single cryo-cooler, supplying coolant to all three phases, with the coolant circulating through one phase and returning via the other two phases, as illustrated in Fig. 2. The cable termination, which serves as the crucial connection point between the superconductor operating at cryogenic temperatures, the conventional cable at ambient temperatures, the cryocooler, and the joint in the HTS cable, is visually depicted in Fig. 3.

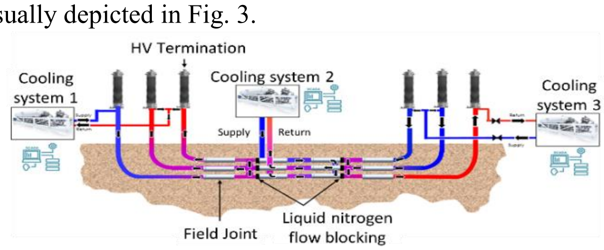

Fig. 2. Schematic view of the HTS cable system provided by Nexans, one of our co-authors.

The critical temperature for the cable is set at Tc=92 K, with a critical current of Ic(T)=2730 A for the HTS phase and 3000 A for the HTS screen. The cable spans a length of 12.9 km and operates at a rated voltage of VL-L(rms)=275 kV. Additionally, the HTS cable's resistance, inductance, and capacitance are 0.0003 Ω/km, 0.06 mH//km, and 0.2 µF//km, respectively. Similarly, conventional cable parameters are 0.0142 Ω/km, 0.51 mH//km, and 0.332 µF//km.

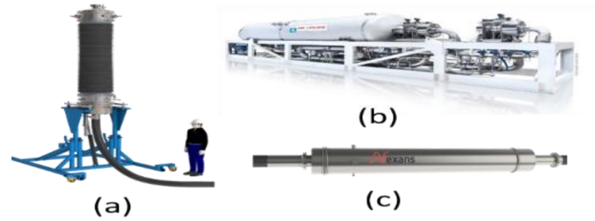

Fig. 3. HTS cable accessories provided by Nexans, one of our co-authors (a) cable termination (b) Colling system, and (c) HTS Joint.

IV. NETWORK STUDY

We developed the power system network which incorporates the distance and differential protection system in MATLAB software shown in Fig. 4. Our study focused on examining the operation of both differential and distance relay protection systems within the 275-kV electrical grid in the UK. We conducted differential relay case studies considering fault level, internal/external fault, fault type, and fault location. Additionally, distance protection case studies were performed, considering fault level, fault type, and fault location. The peak winter and summer minimum fault levels are depicted in Fig.4.

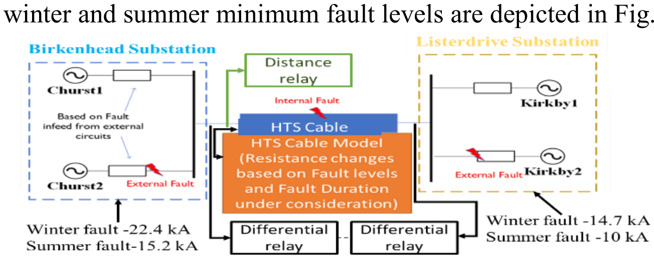

Fig. 4. Schematic view of the network with the protection system.

During the fault, the cable resistance changes due to the inrush of the fault current, this change may impact the protection operation. The sequence impedance under normal operation and resistance evolution during the fault is provided by Nexans for fault duration ≤500 ms and also mentioned the cable was not quenched during these conditions. These data were used in the HTS cable for phase impedance calculation. The change in resistance is small, and the reactance is unchanged. The impact of the changes in the resistance can be managed by adjusting the distance relay settings based on the superconducting impedances and the protection system acts accordingly during the fault. To evaluate the performance of the differential and distance protection on this site, various fault scenarios were tested at different fault currents. The relays successfully operated as intended.

V. COST BENEFIT ANALYSIS

A. *Economic benefit analysis*

A cost-benefit analysis was carried out for three possible upgrade strategies listed in Section IIB. Net present value (NPV) calculations were derived using a discount rate of 3.5% [14] and considering probability distributions for the capital cost (CAPC) and operating cost (OPEC) over 40 years. HTS CAPC includes Cable, Cable containment, Accessories, Cooling System, Project and installation, Protection, and Substation Changes. HTS OPEC focuses on the Cooling System's power and carbon costs, maintenance, and overhaul. Conversely, Conventional CAPC covers Cable XLPE, Cable containment, Cable Sealing Ends, Cable Installation, Protection, and Transformer Changes in Substations. Its OPEC deals with Power Losses in terms of cost and carbon impact.

Capital costs for the HTS cable and cooling system are estimated to be around five times the costs associated with a conventional cable alternative of equivalent power rating. However, once the additional costs of substation expansion/upgrade and cable installation and power losses are included, our analysis indicates that over a 40-year period upgrading to an HTS cable would cost £22 million (GBP 2022) less than installing a second 275 kV cable, and £27 million less than a new 400 kV XLPE cable, as illustrated in Fig. 5.

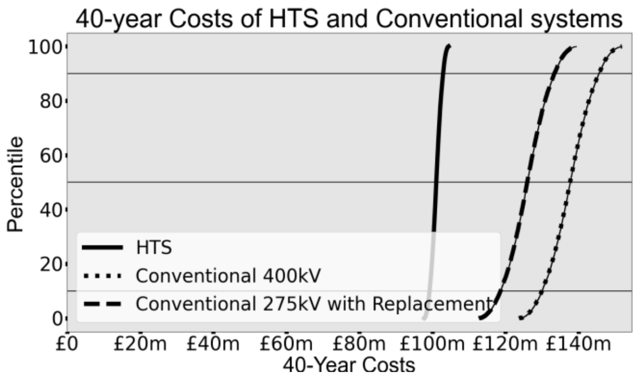

Fig. 5. Cumulative distribution curves for the cost of the HTS and conventional cable system for the upgraded power demand

Table 1: Summary of estimated savings per km from installation of HTS (compared with a conventional equivalent) with varying contingent infrastructure upgrades.

			Existing substation 275kV			Existing substation 400kV					
			Existing cable 275kV						Existing cable 400kV		
	Required substation upgrade	Conventional upgrade voltage	New Tunnel	New Trench	Existing Tunnel	New Tunnel	New Trench	Existing Tunnel	New Tunnel	New Trench	Existing Tunnel
2022 HTS prices	New bay not needed	275kV	£20.3m	No saving	No saving	-	-	-	£20.3m	No saving	-
		400kV	£39.3m	No saving	£10.6m	£25.3m	No saving	No saving	£25.3m	No saving	-
	New bay needed	275kV	£23.8m	£0.7m	No saving	-	-	-	£20.3m	No saving	-
		400kV	£41.1m	£13.3m	£8.8m	£29.2m	£1.5m	No saving	£25.7m	No saving	-
	New bay + expanded site needed	275kV	£30.2m	£7m	No saving	-	-	-	£20.3m	No saving	-
		400kV	£44.3m	£16.5m	£5.7m	£36.2m	£8.4m	No saving	£26.3m	No saving	-
HTS prices fall 50%	New bay not needed	275kV	£23.2m	£0.1m	No saving	-	-	-	£23.2m	£0.1m	-
		400kV	£42.2m	£14.5m	£13.5m	£28.2m	£0.5m	No saving	£28.2m	£0.5m	-
	New bay needed	275kV	£26.8m	£3.6m	No saving	-	-	-	£23.2m	£0.1m	
		400kV	£44m	£16.2m	£11.7m	£32.1m	£4.4m	No saving	£28.6m	£0.8m	
	New bay + expanded site needed	275kV	£33.1m	£9.9m	No saving	-	-	-	£23.2m	£0.1m	
		400kV	£47.2m	£19.4m	£8.6m	£39.1m	£11.3m	£0.5m	£29.2m	£1.5m	

> £40m; £35m - £40m; £30m - £35m; £25m - £30m; £20m - £25m; £15m - £20m; £10m - £15m; £5m - £10m; £0m - £5m; No saving

The analysis for the Merseyside use case was expanded to assess the circumstances in which the contingent system changes associated with a conventional upgrade lead to HTS being the most cost-effective option. The following generic upgrade requirements were considered: the requirement for tunnelling or trenching to accommodate higher voltage or additional conventional lines; the construction of new substation bays; the expansion of the substation footprint; and the upgrade of transformers from 275 kV to 400 kV. Calculations were also performed to consider the impact of future cost reductions for HTS.

Table 1 summarises the results of the analysis. It shows the savings over 40 years for the installation of an HTS cable compared with the specified conventional alternative and different existing substation infrastructure. Results indicate that where significant costs are associated with the installation of a new conventional line – e.g. a tunnel for installation in a high-density urban area; upgrades to transformers; expansion of substation sites – opting for an HTS solution may be significantly less costly over the cable lifetime.

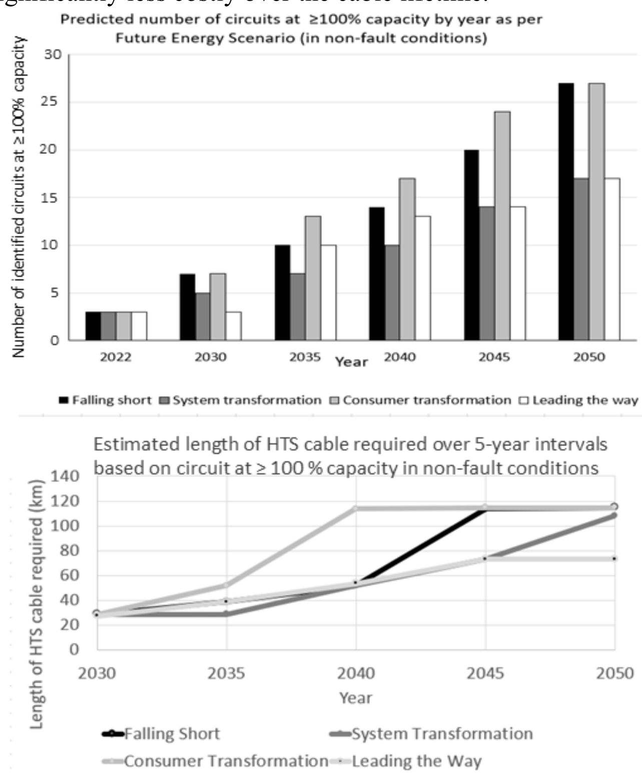

Fig. 6. Estimated numbers of GB circuits and cable lengths that will exceed 100% rated capacity under non-fault conditions for different future energy needs pathways

Future increased capacity need is the key driver for exploring new technologies that can offer cost-effective alternatives to building new circuits. Fig. 6 shows the indicative number of circuits and km of cable within urban areas on the GB network that are predicted to exceed 100% of rated capacity under non-fault conditions for different NGESO Future Energy Scenarios [13] based on data within the NGESO Electricity Ten Year Statement [15]. This analysis indicates that the next 20 to 30 years will bring potentially ongoing and significant requirements within GB urban areas for additional transmission capacity, providing possible opportunities for cost-saving through the deployment of HTS solutions.

VI. STANDARD MAPPING

High voltage testing allows original equipment manufacturers (OEMs) and owners to understand the electrical and mechanical performance of a certain design. Assets are tested in accordance with a range of international standards (IEEE, IEC and ASTM), to understand their performance under a range of stresses (mechanical/electrical/thermal). With regards to cables, testing is mainly performed to understand the insulation performance under normal and load cycle conditions.

As part of the work, an in-depth analysis of current cable standards was performed. The analysis conducted provided insight into how the technology is assessed and stressed in laboratory conditions, and pave the way for the steps and tests required to de-risk the technology for UK-specific environments and network criteria. With the view of certifying and verifying the technology for UK Utilities, the current standards mapping has been done with a key emphasis on the current technical specifications of National Grid and international standards available on high voltage cables and accessories. Caution must be taken in comparing conventional cables against HTS systems, as they are two completely different technologies. However, the standards that have been used in the comparison have many areas of overlap and provide a basis for initial analysis. Due to the constraints of the project, there were limitations to this current study. The present analysis is very much an insight into the electrical testing of the cable system and does not include any mechanical testing.

A. STANDARDS

The standards reviewed as part of this project can be divided into three categories as mentioned in Table 2.

Table 2: Summary of standards review.

Cable Type	Summary	Ref.
HTS Cable Specific Standards	These are standards and technical brochures that are applicable to HTS systems.	[16] [17]
Conventional Cable Standards	A more mature technology, there are a raft of standards that address the testing and qualification regimes of extruded insulation and fluid-filled cables. Whilst there is significant literature, three key references have been looked analysed to provide the basis for comparison against the HTS standards. These two standards cover the voltages at both distribution and transmission levels in the UK.	[18] [19] [20]
UK Technical Specification	Major utilities like the UK's National Grid have their own technical specifications, comprising elements from international standards (e.g., IEC) and adaptations to suit UK conditions. This exercise references two primary National Grid standards that have been reviewed and employed.	[21] [22]

B. Findings from gap analysis

The main limitation of the standard was found to be the lack of a long-term demonstrator. This offline trial using a demonstrator system would be an essential step in qualifying this technology as an option for future network upgrades, especially a requirement for GB networks. As such it was suggested to set up a demonstrator running for at least 12 months to cover all the environmental challenges that the seasons offer.

IEC 63075 highlights that there is no need for prequalification of the HTS cable system, as it concludes that there are no thermomechanical stresses on the insulation system during normal operation, due mainly to the superconductive nature of the operation. The standard suggests the lack of thermal cycling within the system will limit any damage to the insulation system (unlike conventional XLPE cables) and suggests mathematical models estimate HTS cables should have twice the lifetime coefficients of conventional cables. However, the lack of such long-term testing does not allow for the long-term ageing and evaluation of key accessories such as the terminations. These are sensitive and complex assets where the HTS cable (operating at superconducting temperatures) transitions into the overhead line or switchgear operating at ambient temperature. These accessories are unique to HTS cables and a relatively new technology within the UK so long-term testing will allow experience to be gained to better understand the stress these assets undergo and further understand the ageing mechanisms.

The cryogenic systems for the HTS are not considered within the scope of either IEC 63075 or CIGRE TB538. IEC 63075 has an annex that recommends some basic tests to be performed after installation (pressure, flow, temperature tests, etc.), but there is nothing to observe or stress the system under operating conditions. As such it is believed that a demonstrator system would provide invaluable information on the performance throughout all seasons. It would also provide the opportunity to stress the system and understand how robust it is to internal or external conditions. Examples could include artificially varying the ambient temperature around the refrigeration system to mimic hot/cold periods, mimicking pressure loss, coolant leaks, etc.

VI. CONCLUSION

In conclusion, the decision to pursue a 275-kV cable upgrade within the UK's transmission network is supported by rigorous analysis and evaluation. The successful network study has affirmed the feasibility of incorporating this cable into the existing system, albeit with the necessary updates to the differential and distance relay protections. The comprehensive standards mapping exercise has not only identified areas for improvement but also laid the foundation for a robust de-risking strategy for the 275 kV HTS cable system. Crucially, the cost-benefit analysis has demonstrated that opting for HTS technology as a replacement for the current cable, as opposed to alternative solutions such as upgrading to a 400-kV cable or installing a parallel 275 kV line, presents the most favourable economic case over a 40-year operational horizon in circumstances where a conventional alternative requires significant additional infrastructure. Furthermore, the anticipation of increasing electrification in energy usage within the broader network underscores strong and sustainable demand for HTS cables, reinforcing the soundness of this strategic investment choice.

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