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Feasibility of Superconducting DC Railway Traction Substations

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The growing need for efficient and sustainable electrified rail systems drives the development of advanced electric traction substations. Cryogenic and superconducting technologies offer a transformative approach to reduce energy losses and equipment size. This study investigates the feasibility of replacing conventional components in DC traction substations (transformers, diode rectifiers, and cables) with their cryogenic counterparts (superconducting transformers, cryogenic diode rectifiers, and superconducting cables). We discuss our ongoing efforts on developing and testing these components and present preliminary estimations demonstrating their potential to modernize railway electrification systems.

Keywords: Superconductivity, cryogenics, railway systems, superconducting transformer, cryogenic power electronics, superconducting power cables

1. Introduction

The increasing electricity demand of train systems [1], combined with the spatial limitations of adding more DC traction substations in urban rail networks [2], poses significant challenges. A promising solution to this issue is superconducting technology. The use of cryogenic and superconducting components potentially offers three potential key benefits: increased energy density, reduced equipment size and improved overall energy efficiency.

To date, no superconducting DC traction substation exists. However, prototypes and demonstrators of its main components (transformer, rectifier and power cables) have demonstrated both their feasibility and the potential benefits. Beijing Jiaotong University has successfully designed, developed, and tested a 6.6 MVA high-temperature superconducting (HTS) traction transformer for train applications [3]. Meanwhile, the SuperRail project has implemented the world's first superconducting cable in France's railway network [2]. These advancements highlight the growing role of superconducting technology in modern rail systems.

In Sections 2, 3, and 4, we discuss the development status, results and challenges of each component. Finally, in Section 5, we comment on our findings and outline future work necessary to achieve a fully functional superconducting DC traction substation.

2. Superconducting DC Traction Substation Architecture

A conventional DC traction substation consists of a power transformer, a diode rectifier, and power cables connecting the train catenary. We propose replacing these components with cryogenic equivalents: a superconducting transformer, a cryogenic rectifier, and superconducting cables. Figure 1 illustrates a comparison between a conventional DC traction substation and the proposed superconducting architecture.

One major challenge of superconducting systems is the current leads, that are needed to transfer electrical current between cryogenic and room temperatures while minimizing the heat flow. Current leads contribute significant energy losses by heat conduction and require substantial physical space [4]. This poses a major barrier to the adoption of this technology in dense urban environments. The use of a fully superconducting transformer (both the primary and secondary are wound with superconductors and operate at cryogenic temperature) and of a cryogenic diode rectifier would require 5 current leads (3 for the AC side and 2 for the DC side).

By introducing a partially superconducting transformer (the primary is wound with copper operating at room temperature, while the secondary is wound with superconductor operating at cryogenic temperature) and cryogenic diode rectifier, the 3 AC current leads can be eliminated, cutting both cost, space requirement and energy losses. Moreover, as all components operate at cryogenic temperatures (77 K), a single cooling loop and a single refrigeration system are required, streamlining integration.

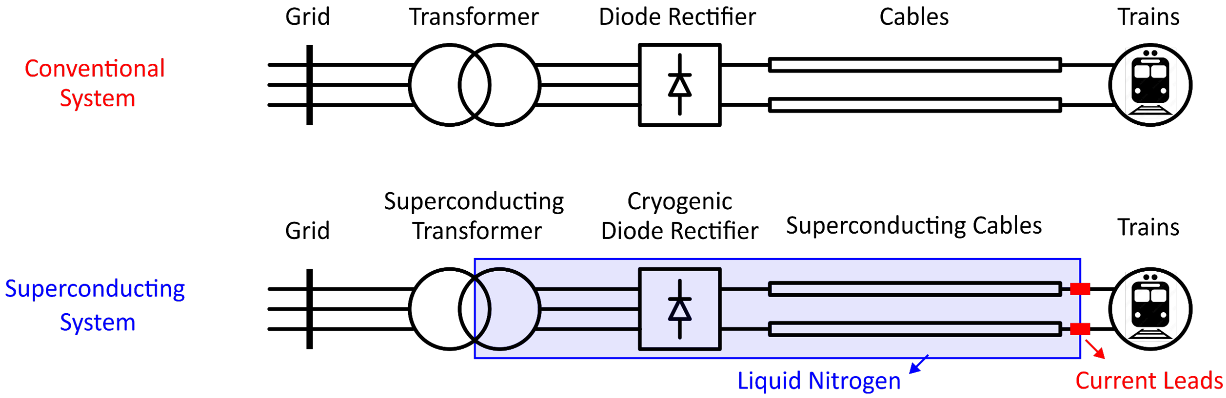


Figure 1: Conventional and superconducting DC traction substation

3. Superconducting Transformer

During history, numerous prototypes of superconducting transformers have been developed and tested. These studies have highlighted significant advantages over conventional transformers, including improved efficiency, reduced size, and enhanced safety due to the elimination of flammable cooling oils. However, it is important to note that the Technology Readiness Level (TRL) of HTS transformers currently ranges from 4 to 6 [5].

To address this issue, we are developing a kVA-scale partially superconducting transformer. This design features a copper primary at room temperature and a high temperature superconducting (HTS, ≥ 30 K) secondary at cryogenic temperature. This makes it possible to transfer power to the cryogenic environment without current leads (Figure 2).

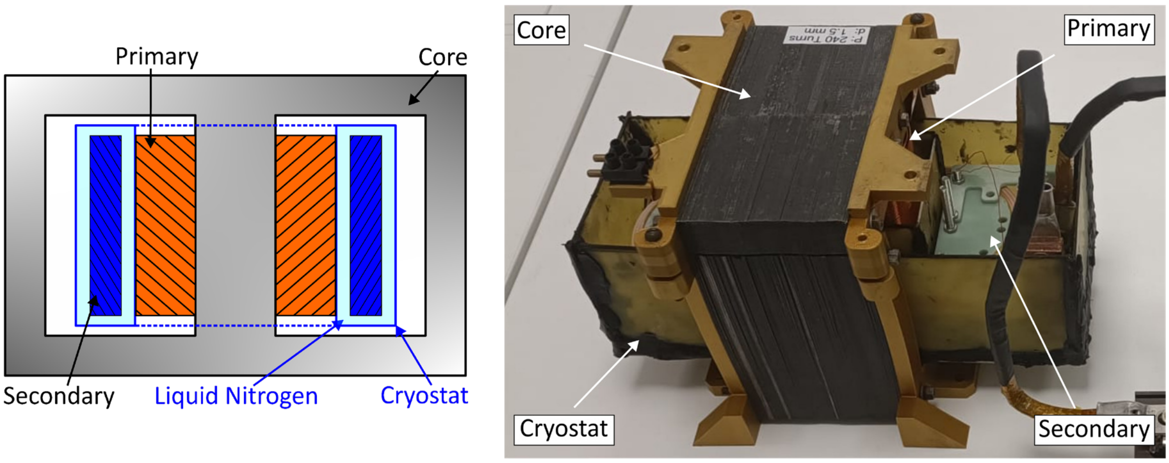
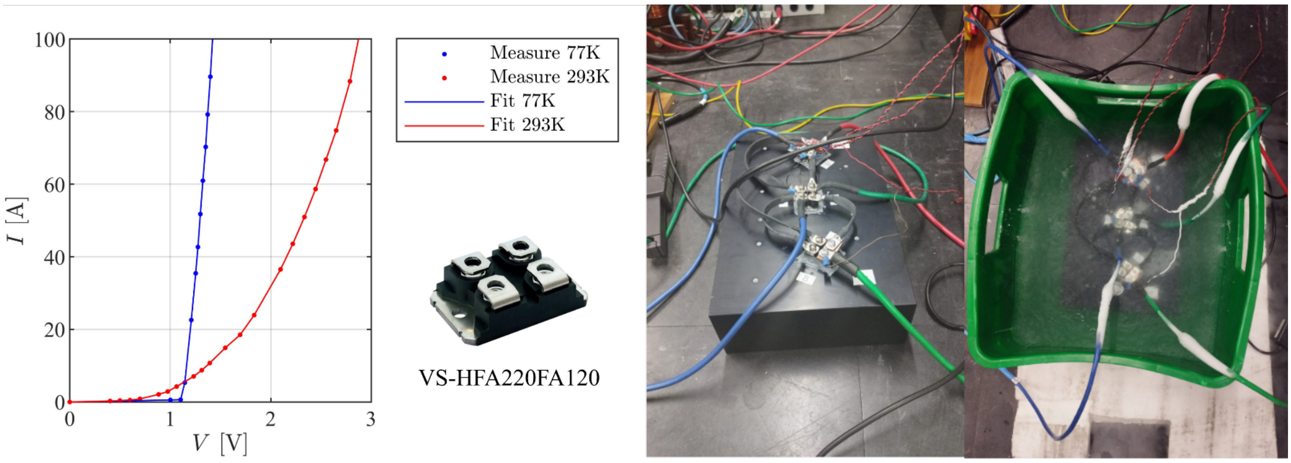


Figure 2: GeePs partially superconducting transformer prototype

4. Cryogenic Diode Rectifier

DC traction substations traditionally use diode rectifiers due to their efficiency and robustness in converting alternating current (AC) to direct current (DC). Recent studies indicate that these rectifiers can operate effectively at cryogenic temperatures compatible with the use of liquid nitrogen (77 K) [6]. It would enable the integration of the superconducting transformers and the superconducting cables in the same cryogenic loop (see Figure 1). Cryogenic operation also provides additional benefits, including a significant reduction in the size of the rectifier's heat sink.

Our current work focuses on measuring the characteristics of commercial diodes at cryogenic temperatures [7]. We have realized several kW-scale diode rectifier prototypes and tested them in a liquid nitrogen bath at 77 K. Figure 3a shows the IV characteristic curve of a diode that exhibits improvements at cryogenic temperatures, while Figure 3b displays the rectifier prototype test developed with the diode VS-HFA220FA120 in liquid nitrogen. We are now scaling up the rectifier nominal power.



a. IV characteristic curve of a diode **b. Prototype test**

Figure 3: GeePs cryogenic diode rectifier prototype [7]

5. Superconducting Power Cables

Among the three main elements of a superconducting DC traction substation, superconducting cables have reached the highest maturity level. A notable example is the SuperRail project, which utilizes two superconducting cables at the Montparnasse train station in Paris to increase the power transfer to the station while addressing the challenge of limited space [2], [8].

Our current work focuses on measuring the characteristics of superconducting power cables [9], [10]. By doing so, we are contributing to the global effort to standardize testing for superconducting cables. In collaboration with laboratories worldwide (Japan, Korea, USA, UK, France, China), we participate in round-robin tests, which aim to establish a unified methodology for measuring the critical current of superconducting cables. This work is crucial for the technology's widespread adoption, and our large current test facility, Gargantua, is a unique piece of equipment in this field.

6. Conclusion

In this study, we introduced the concept of a superconducting DC traction substation and explored its potential. A key point of the proposed architecture is the use of a partially superconducting transformer that allows reducing the number of current leads, addressing one of the primary challenges of superconducting technology.

Through the design and testing of small-scale prototypes of its three main components (the partially superconducting transformer, the cryogenic diode rectifier and the superconducting cable), we demonstrated the feasibility and advantages of cryogenic operation, including reduced system size and simplified integration.

Moving forward, our focus will be on scaling up and integrating these components to validate the practicality of a fully superconducting DC traction substation. By tackling the technical challenges outlined in this work, we aim to pave the way for a new generation of efficient and compact electrification solutions for railway electric grids.

Bibliography

[1] International Energy Agency (IEA), "The future of rail: Opportunities for energy and the environment," Paris, France, 2019. Available at: https://iea.blob.core.windows.net/assets/fb7dc9e4-d5ff-4a22-ac07-ef3ca73ac680/The_Future_of_Rail.pdf (Acessed 2025/01)

[2] A. Allais *et al, "SuperRail – World-first HTS cable to be installed on a commercial railway network in France," IEEE Transactions on Applied Superconductivity, vol. 34, no. 3, pp. 1-7, May. 2024.*

[3] A. Ballarino, "Current leads, links and buses," *Proc CAS-CERN Accel. Sch. Supercond Accel.*, pp. 547–558, 2013.

[4] A. Sadeghi, W. Song, and M. Yazdani-Asrami, "Superconducting transformers for power, energy, and transportation applications: an introduction to superconducting technology for transformer engineer," *Transformers Magazine*, vol. 11, no. SE, Merit Media International, pp. 10–22, May 13, 2024.

[5] X. Zhao *et al.*, "Design, development, and testing of a 6.6 MVA HTS traction transformer for high-speed train applications *Superconductor Science and Technology*, vol. 36, no. 8, p. 085009, Jun. 2023.

[6] L. Ferreira, Y. Baazizi, S. Meunier, T. Phulpin, and L. Quéval, "Feasibility study of a cryogenic diode rectifier," *Symposium on Advanced Technologies in Electrical Systems (SATES)*, Arras, France, Mar. 2023.

[7] Y. Baazizi, L. Ferreira, S. Meunier, T. Phulpin, L. Quéval, "Experimental study of a three-phase diode rectifier operating at cryogenic temperature," *16th European Applied Superconductivity Conference (EUCAS2023)*, id. 3-LO-IS-O4S, Bologna, Italy, Sep. 2023.

[8] S. Aboudrar *et al.*, "Qualification of the SuperRail HTS cable system," *Applied Superconductivity Conference 2024 (ASC 2024)*, id. 2LOr1D-01, Salt Lake City, USA, Sep 2024.

[9] T. Matsushita *et al.*, "International Round-Robin Test of Critical Current of Superconducting Cable Sample," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 7, pp. 1–6, Oct. 2024.

[10] L. Quéval, D. Huchet, F. Trillaud, M. Kiuchi, T. Matsushita, ""Test station for high temperature superconducting power cables," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 3, pp. 1-4, May. 2024..