

Superconducting Traction Substation

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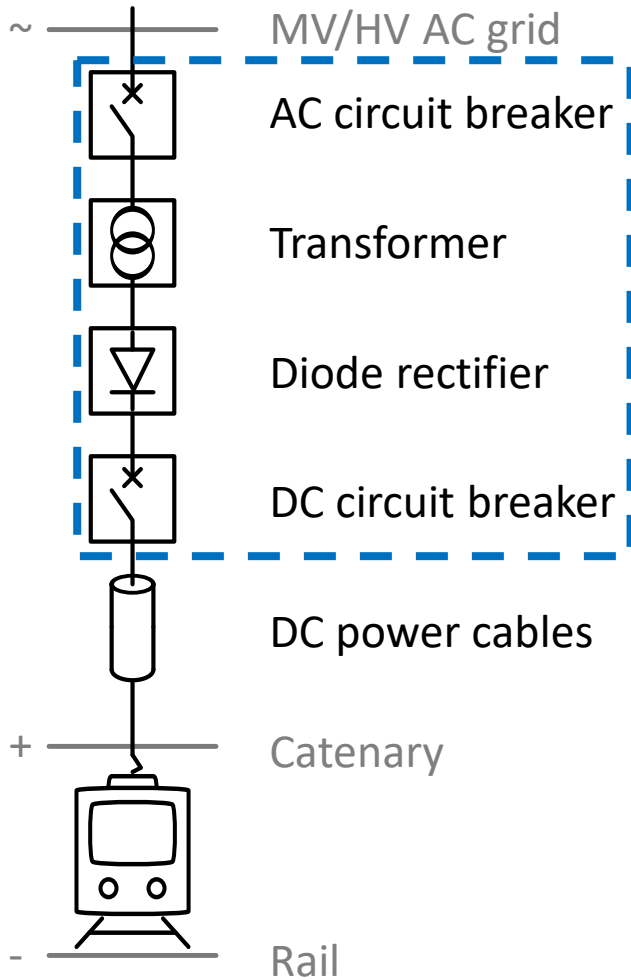
Superconductivity for Railway Applications
UIC HQ, Paris, France

Content

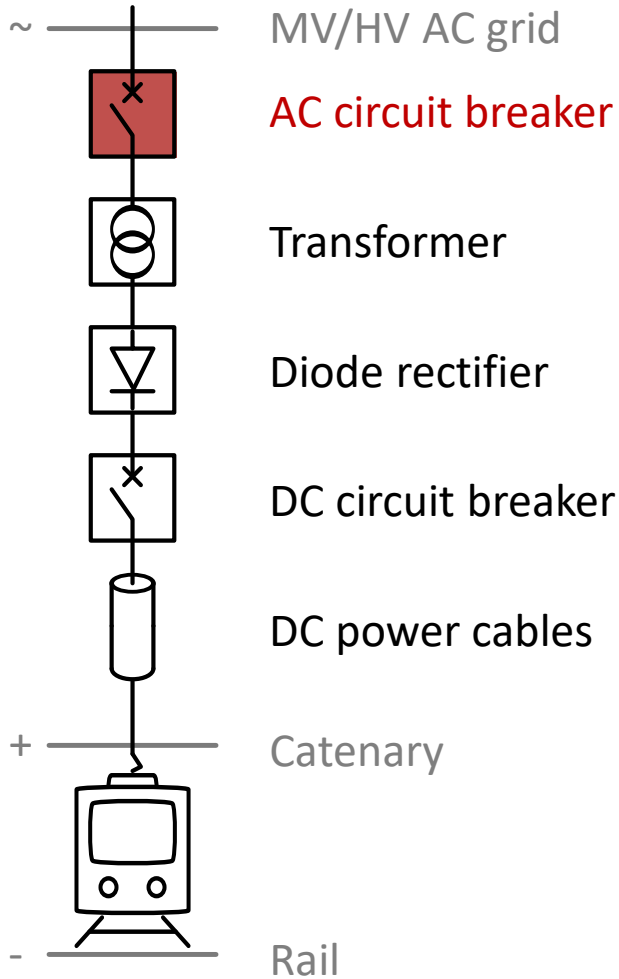
- I. Conventional traction substation
- II. Superconducting traction substation
- III. Conclusion

I. Conventional traction substation

Conventional traction substation

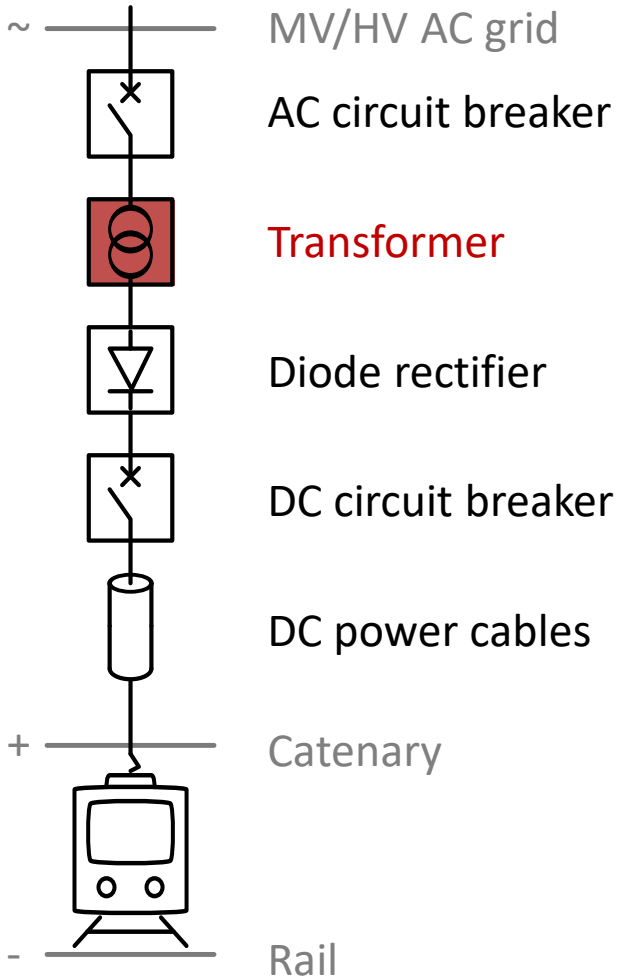


AC circuit breaker



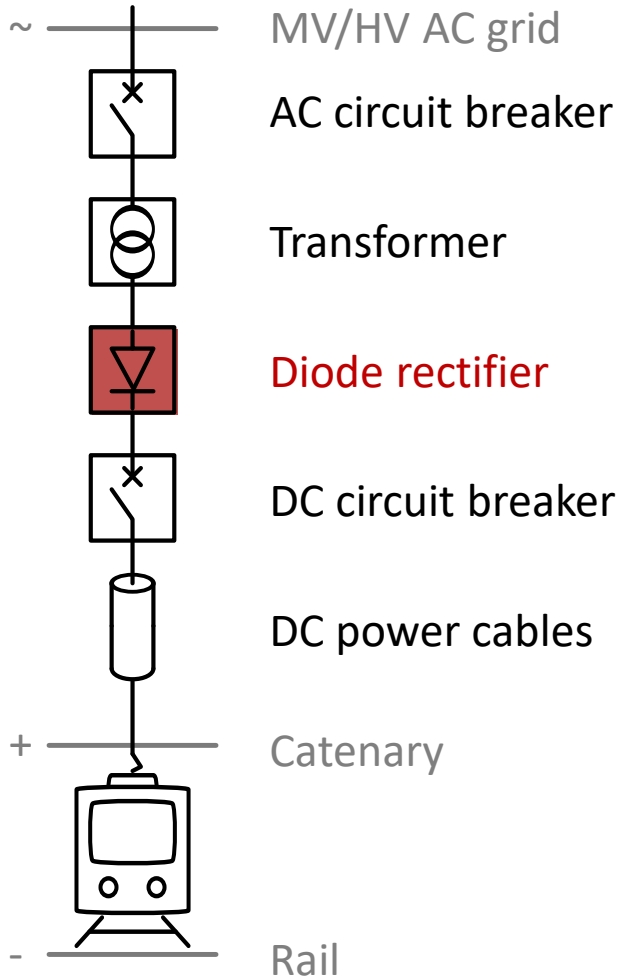
AC circuit breaker
at SNCF Railway Test Agency (AEF)
traction substation

Transformer



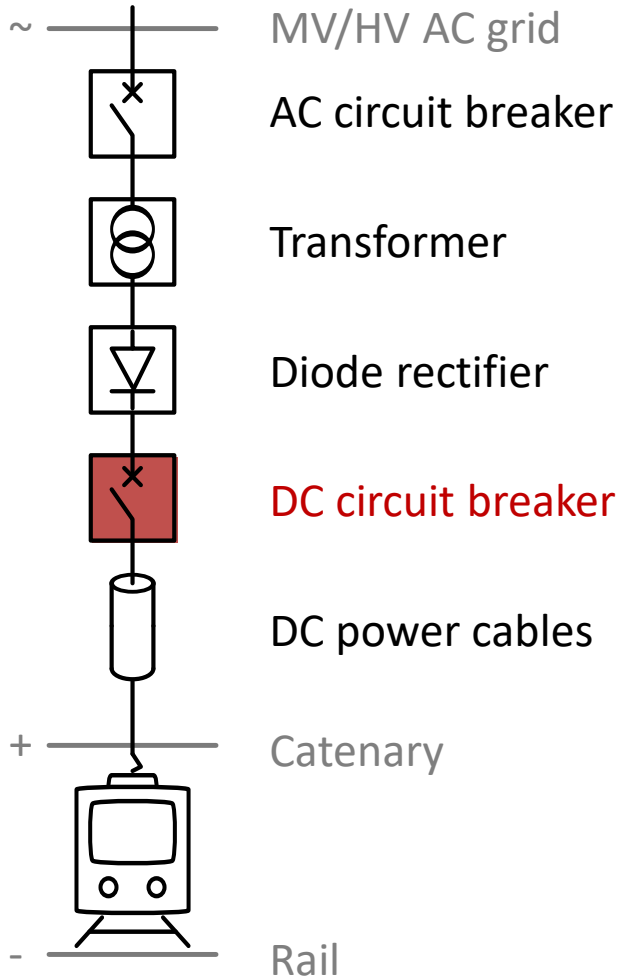
Transformer
at SNCF Railway Test Agency (AEF)
substation

Diode rectifier



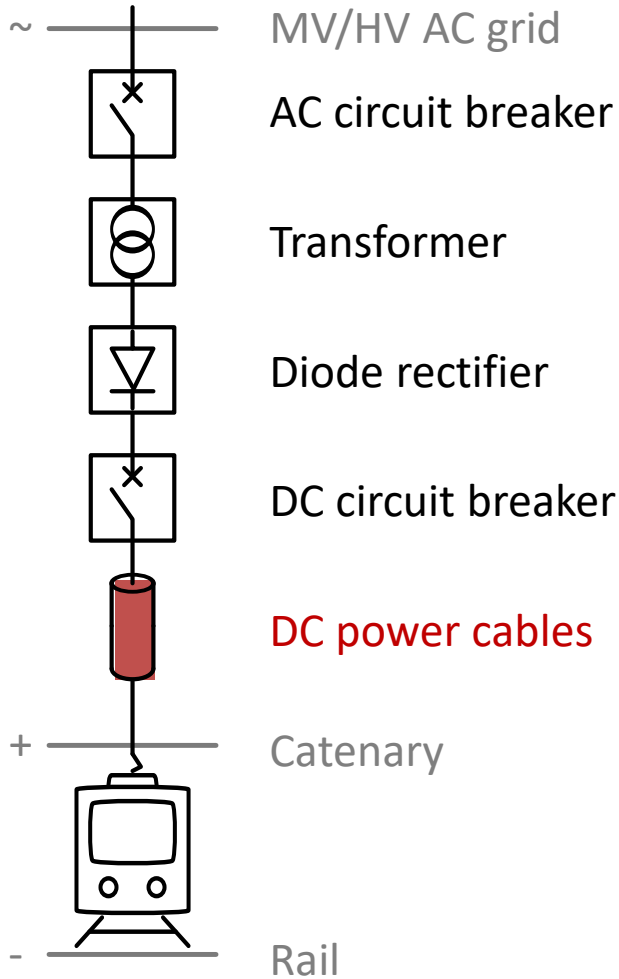
Rectifier C3.P (one half) 6.6 MW
at SNCF Railway Test Agency
(AEF) traction substation

DC circuit breaker



DC circuit breaker
ABB Gerapid high-speed DC air
circuit breaker

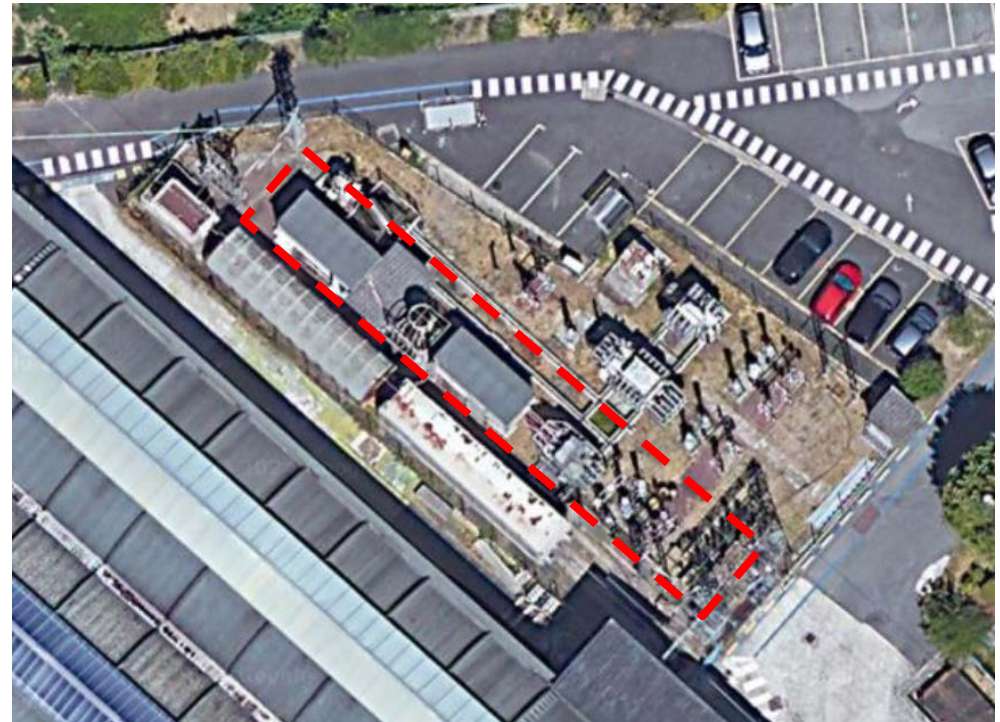
DC power cables



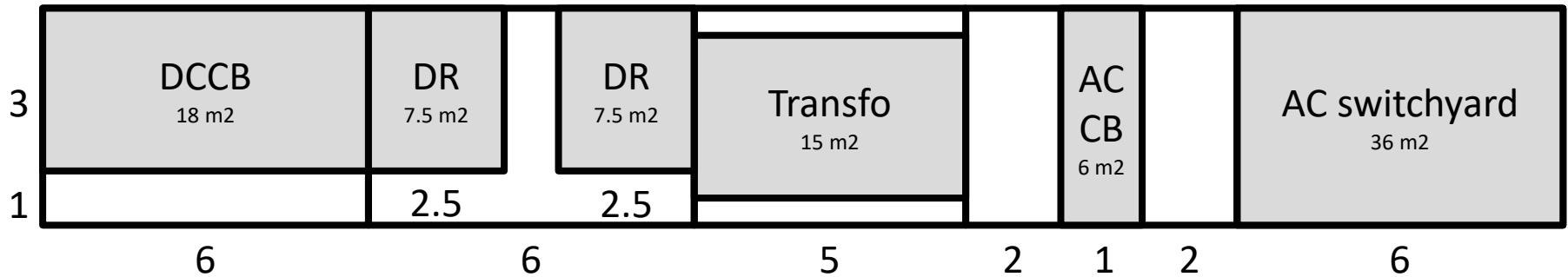
DC power cables
at Montparnasse Vouillé
traction substation

Size reduction

SNCF Railway Test Agency (AEF) traction substation
MVAC / 1500 V DC, 6.6 MW →



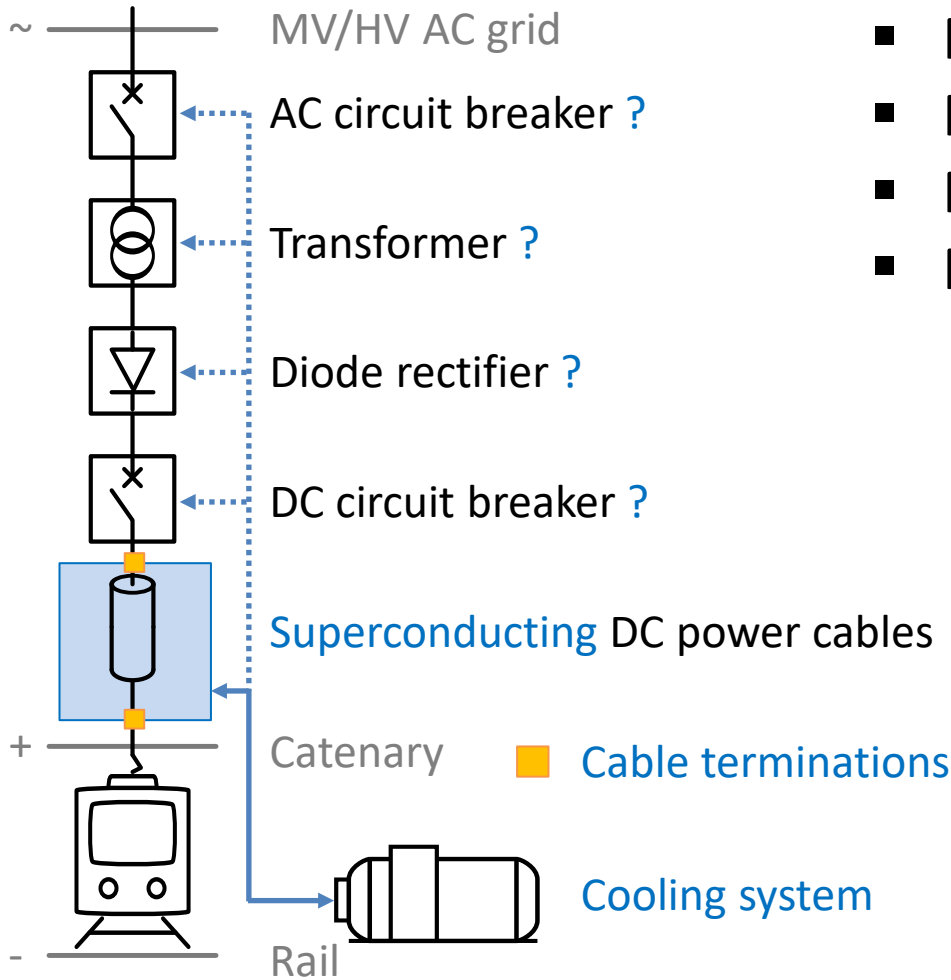
Conventionnel traction substation: 112 m²



II. Superconducting traction substation

Disclaimer: We acknowledge uncertainties in our estimations, and we emphasize that the findings should be interpreted cautiously.

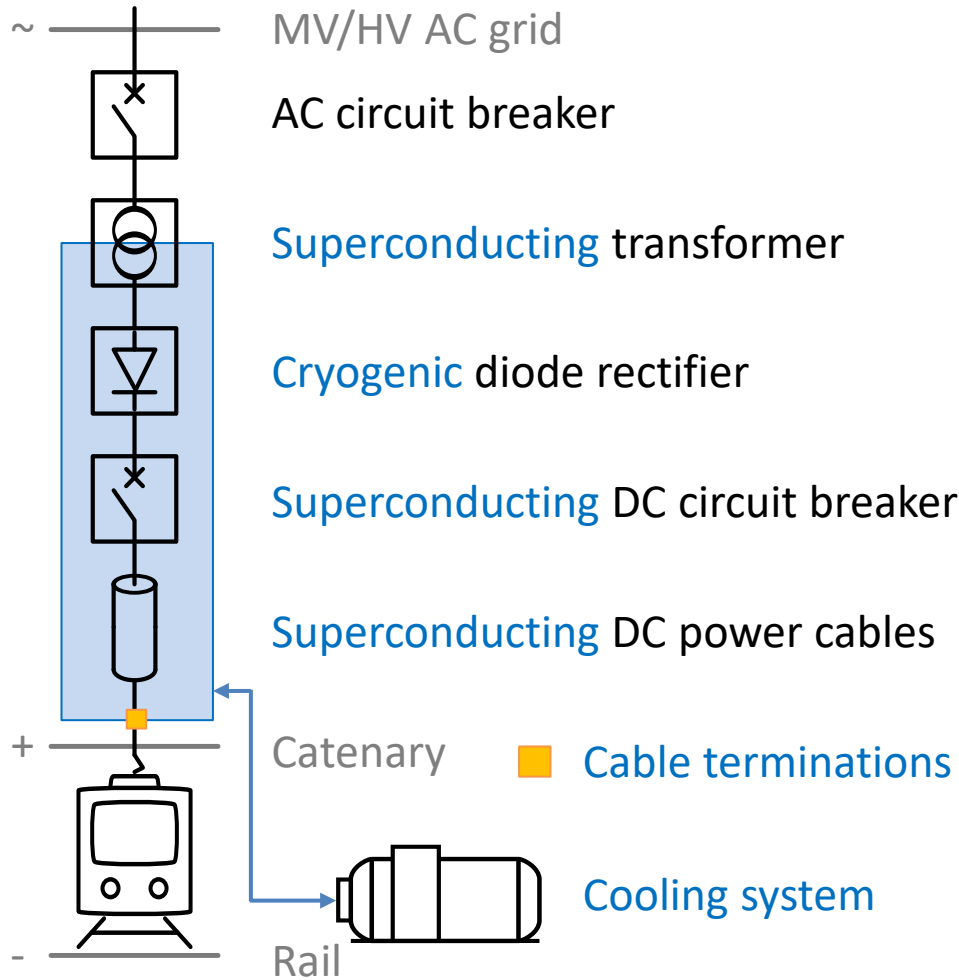
Motivation



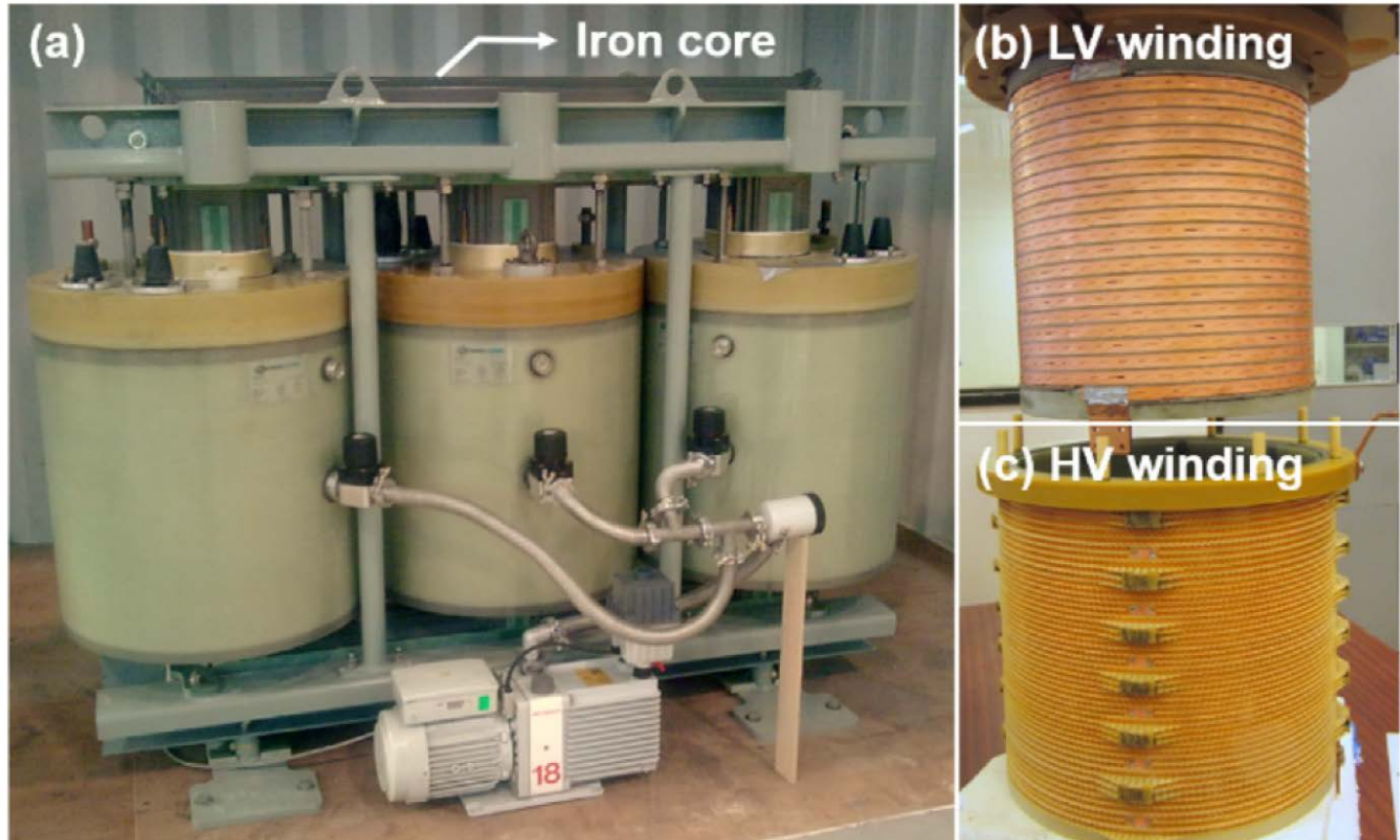
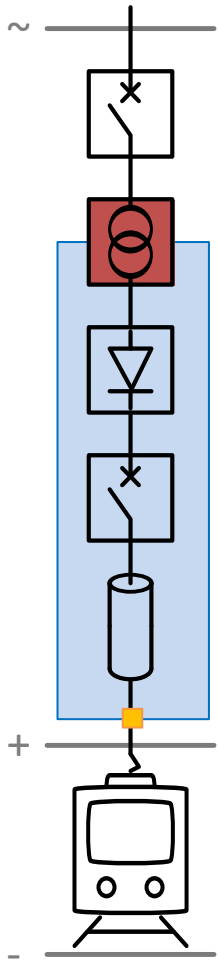
- Mutualize cooling power
- More efficient ?
- More compact ?
- More functionalities ?



Superconducting traction substation



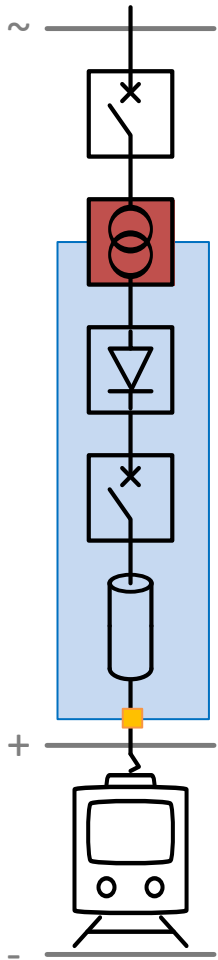
Superconducting transformer



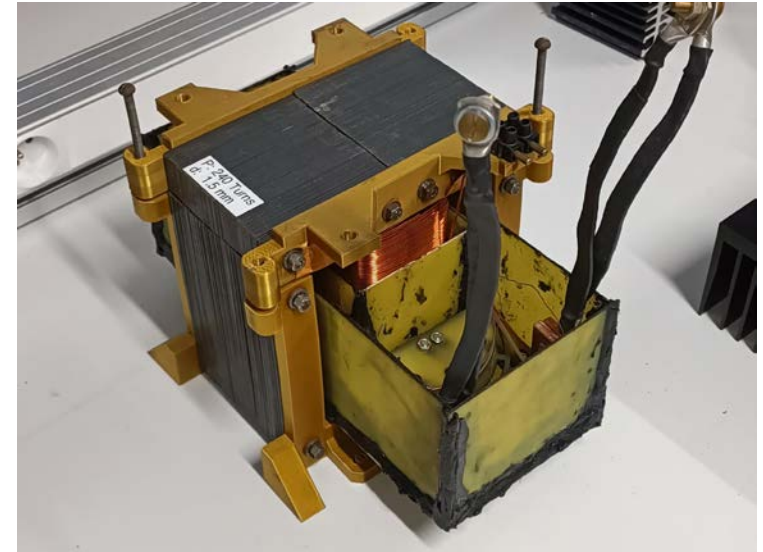
3-ph 1 MVA 11 kV/415 V HTS transformer, by Callaghan Innovation [1]

[1] E. Pardo *et al.*, "AC loss modelling and measurement of superconducting transformers with coated-conductor Roebel-cable in low-voltage winding," *Supercond. Sci. Technol.*, vol. 28, no. 11, p. 114008, 2015.

Partially superconducting transformers @GeePs



Double pancake coil testing @77 K



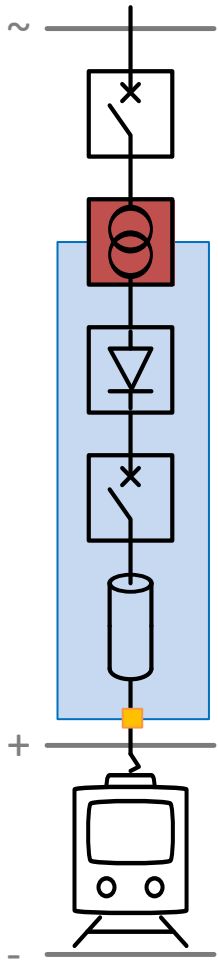
Prototype #4

Lauro FERREIRA
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[1] L. Ferreira, Y. Baazizi, S. Meunier, T. Phulpin, R. Beljio, F. Trillaud, T.-Y. Gong, G. Henn, L. Quéval, "Feasibility study of a cryogenic power supply for superconducting DC devices," International Conference on Magnet Technology (MT28), id. 3PoM10-02, Aix-en-Provence, France, Sep. 2023.

Partially superconducting transformer

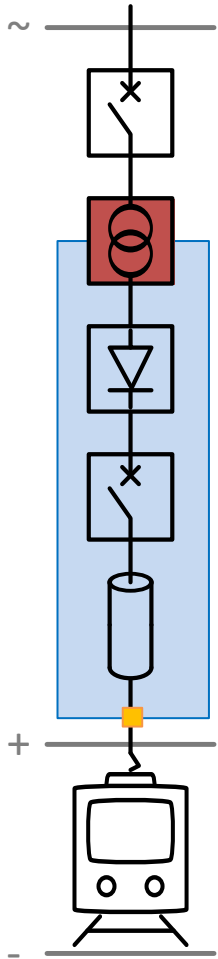


- Operating at 65 K (-208 °C)
- Smaller (50% size) and lighter (50% weight) than conventional transformers [1].
- More efficient (99.9 % including cooling power) than conventional transformers (99.6%) [2].
- Enclosed in a cryostat, operating at constant temperature: environmental isolation, expected to have longer lifetime, unaffected by overloads.

[1] B. Marchionini, S. Eckroad, L. Serri, G. Angeli, H. Ohsaki, D. Mosteller, L. Martini, "High temperature superconductivity application readiness map-energy delivery-transmission, substation and distribution," *IEEE Transactions on Applied Superconductivity*, vol. 33, no. 5, pp.1-5, 2023.

[2] A. Berger, "Entwicklung supraleitender, strombegrenzender Transformatoren," PhD thesis, KIT, Karlsruhe, Germany, Jan. 2011.

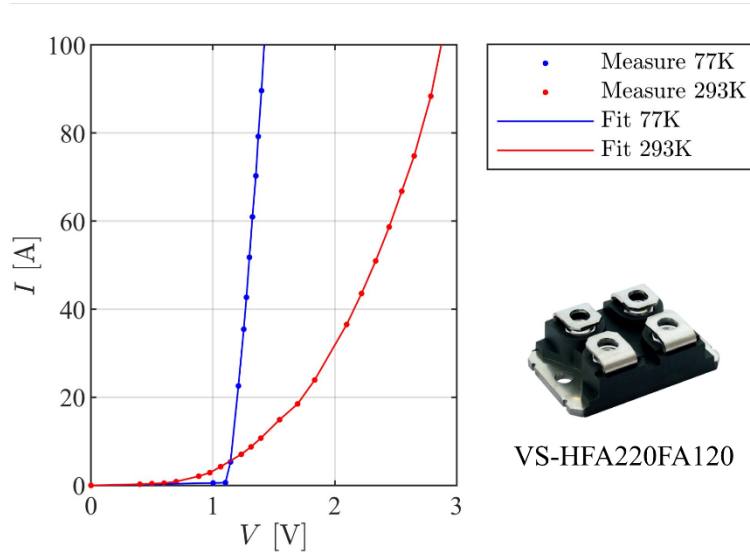
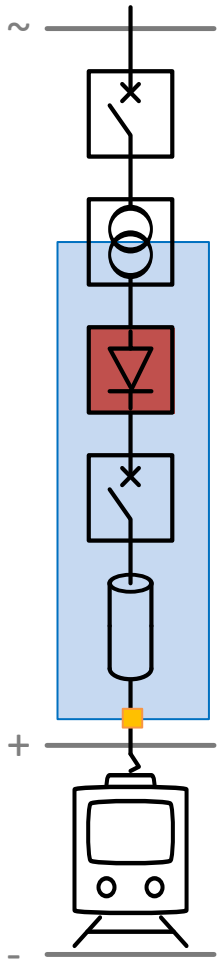
Partially superconducting transformers



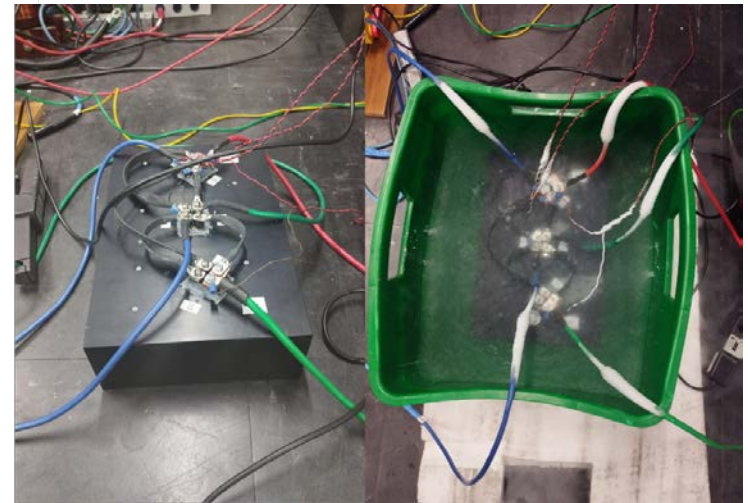
Other advantages:

- Low short circuit impedance, less voltage drops and less reactive power requirements.
- Potentially have intrinsic fault current limiting capability due to winding similarities with superconducting fault current limiters.

Cryogenic diode rectifier @GeePs



VS-HFA220FA120



Selected diode IV characteristic

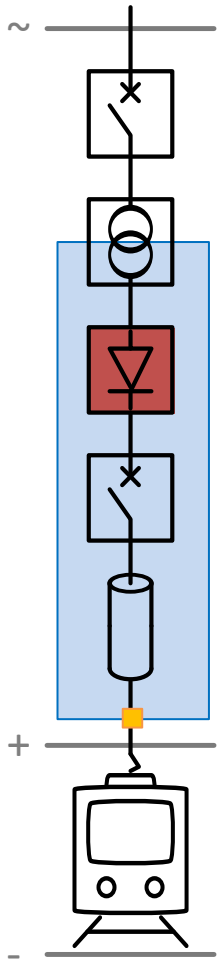
3-ph 3.3 kW diode rectifier @77 K

Yasmine BAAZIZI
3rd year PhD student
at GeePs



[1] Y. Baazizi, L. Ferreira, S. Meunier, T. Phulpin, L. Quéval, "Experimental study of a three-phase diode rectifier operating at cryogenic temperature," *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 3, id. 1101505, pp. 1-5, May. 2024.

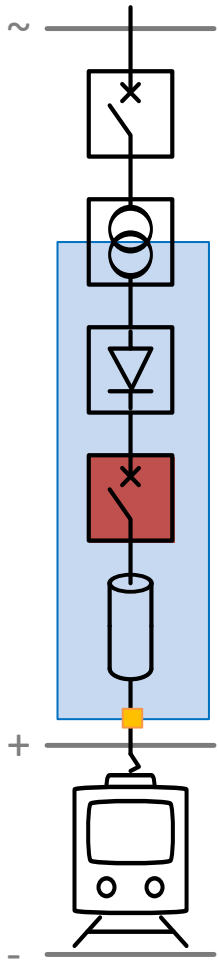
Cryogenic diode rectifier



- Operating at <120 K
- Smaller (20% size) and lighter (20% weight) than conventional rectifiers [1].
- More efficient, with losses $\sim 25-70\%$ of conventional ones [1].
- Losses must be removed from the cryostat by the cooling system. The operation at relatively high temperature reduces the “cooling penalty”.

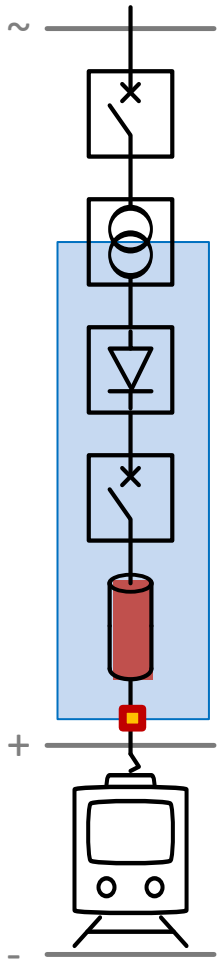
[1] Y. Baazizi, L. Ferreira, S. Meunier, T. Phulpin, L. Quéval, “Experimental study of a three-phase diode rectifier operating at cryogenic temperature,” *IEEE Transactions on Applied Superconductivity*, vol. 34, no. 3, id. 1101505, pp. 1-5, May. 2024.

Superconducting DC circuit breaker



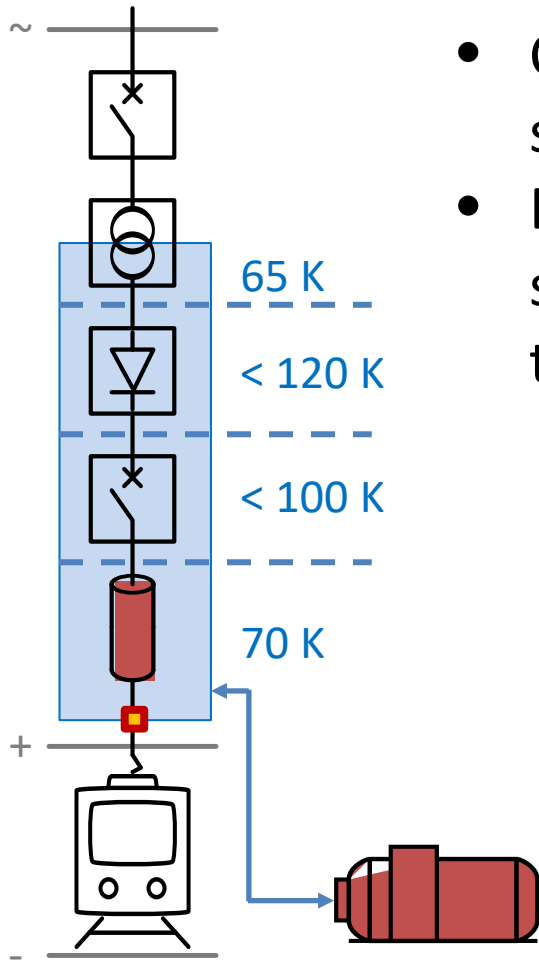
- Probable architecture: superconducting fault current limiter in combination with cryogenic DCCB.
- Smaller (50% size) than conventional DC circuit breaker: no need for large arc-extinguishing chambers found in traditional breakers.
- More efficient, with losses 10% of conventional DC circuit breaker, primarily thanks to the need to interrupt lower fault currents.
- But the necessary cooling system necessary can offset this size and efficiency advantage.

Superconducting DC power cables + terminations



- Smaller (15% cross section) than conventional DC power cables, thanks to the higher current density. Allows increased capacity in retrofits. No ageing.
- More efficient, with losses $\sim 2\%$ of conventional power cables. Mainly due to heat input through the cryostat ($\sim \text{W/m}$).
- Need for terminations, so additional volume (3 m^3) and losses (250 W per termination).
- These losses must be removed from the cryostat by the cooling system.

Cooling system



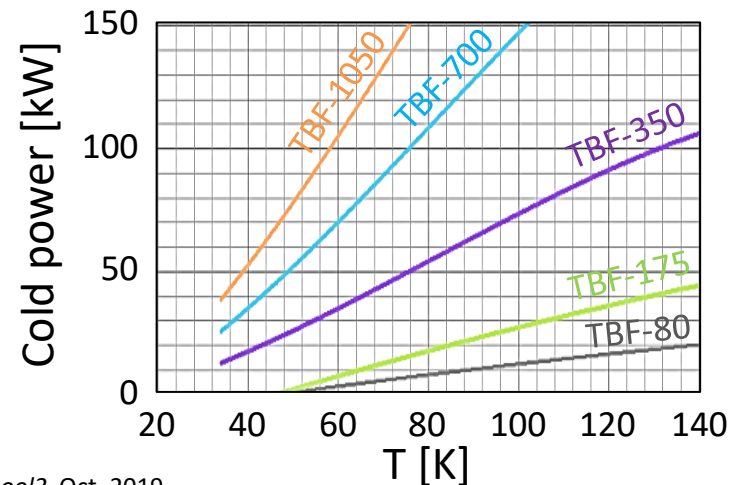
- Cooling power provided by a central cooling system (efficiency & cost effectiveness).
- Each component in the superconducting substation requires cooling, but the optimum temperature for each element is different !

Cooling system

- To ensure reliability and continuous operation, the cooling system is made of 3 units. 2 units can handle the refrigeration load during normal operation, leaving 1 unit offline and available for maintenance.
- Cooling systems with target cooling power already commercially available, with 4+ year maintenance interval: Turbo-Brayton (Air Liquide, Mayekawa, Absolut System ...)



Air Liquide Turbo-Brayton TBF-80



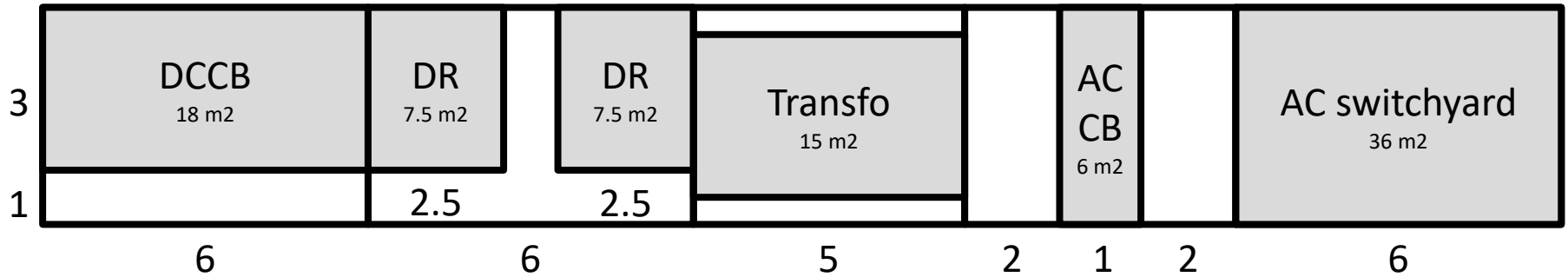
[1] C. Gondrand, "Turbo-Brayton cryogenic systems, An ideal solution for refrigeration," *EASISchool2*, Oct. 2019.

Size reduction

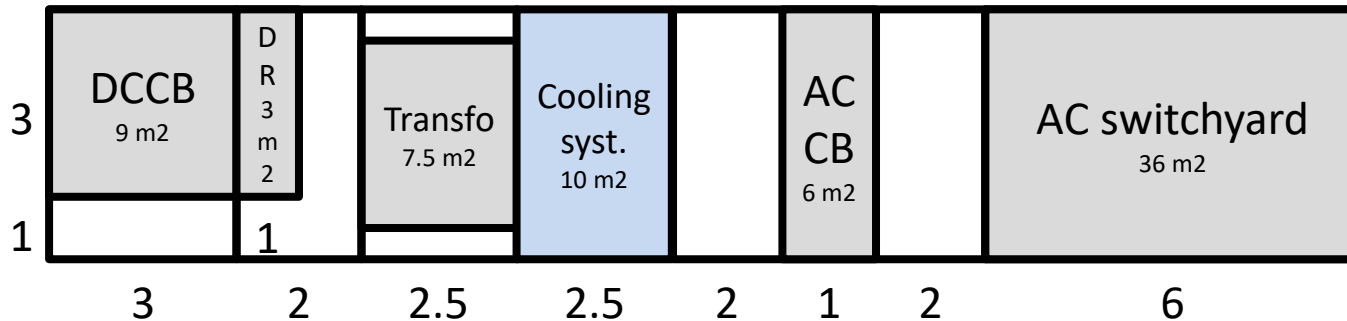


SNCF Railway Test Agency (AEF) traction substation →

Conventionnel traction substation: 112 m²



Superconducting traction substation: 84 m² (25 % reduction)



III. Conclusion

Conclusion

Modern traction substations have a similar design to those from five decades ago. But their components have undergone substantial improvements in efficiency, safety, and performance. To sustain this trajectory, the adoption of new technologies is essential. Superconducting devices, such as transformers and cables, are currently under development and show promise for providing greater reliability and efficiency than traditional components. We explored here the impact of replacing conventional components with superconducting and cryogenic technologies.

Conclusion

The resulting Superconducting Traction Substation:

- Is smaller—has only 75% of the area of a conventional substation, including the cooling system. Alternatively, it could have greater power handling capacity that of a conventional substation of the same area.
- Could be more efficient (or not)—including cooling system. It depends on many factors, including the sizing of the various components, their integration in a single cold loop, the loading profile of the substation, etc.
- Has improved performance—for example intrinsic fault current limiting in the transformers.
- Has potential, but experience is limited, especially at system level. It is therefore too early to assess economic competitiveness.

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