Superconductor Busbars—High Benefits for Aluminium Plants

Wolfgang Reiser, Till Reek, Carsten Räch, and Daniel Kreuter

Abstract

Superconductor busbars have reached industrial readiness. Superconductors are conducting direct current with extremely high densities of more than 50 kA/cm^2 with zero losses. Due to their low space requirements, high current carrying capacity, and utmost efficiency, superconductor busbars will find their place in the aluminium industry. The paper introduces the technical basis of superconductors and continues with technical and economic advantages. Five different use cases are illustrated with information about technical limits, energy efficiency, and economic performance. Experiences out of installations are shared. The presented use cases are:

- Main busbars between rectifiers and potroom
- Interconnection busbars between potrooms and to standby rectifiers
- Magnetic field compensation with minimum space and power requirements
- DC connection between potline and power plant or grid connection point
- Superconducting magnetic field shielding—permanent or mobile.

Investment costs are indicated as well as costs for maintenance, operation and total cost of ownership for various timelines. A breakeven can be achieved by case between 1 and below 10 years.

Keywords

Aluminium • Superconductor • Busbar • Efficiency

Superconductors—The Mysterious Material

In the early stages, the industry attracted little attention to superconductivity because the applications were limited and expensive. Nevertheless, many applications became possible after the discovery of high-temperature superconductivity. From then on, existing cooling systems were usable and through research, the superconductor (SC) itself became easy to handle and affordable. Nowadays, high-temperature superconductors (HTS) can transmit high currents with zero losses. In DC operation, the superconductors show no electrical resistance at all. Only the material sets a limit to the current load capacity. For example, a single HTS-Tape with a 12 mm width and 1 mm thickness has a current load capacity of up to 50 kA/cm^2 [1]. The superconductive layer, with a thickness of only 3 µm, is sintered of ceramics materials. A typical setup is shown in Fig. 1, with the arrow indicating the superconducting layer. The remaining layers are used for contacting and stabilization. Compared to conventional conductors, the material need is significantly less, so that existing resources are used more efficiently. Because of its small physical dimensions and versatility, the HTS-technology is space saving and can be installed in restricted rooms. Using individual tapes and arranging them according to their intended purpose, it is possible to manufacture cables for almost every energy transmission. The cooling with liquid nitrogen (LN_2) is established for many years now and contributes to lower operational costs and higher reliability. The entire superconductor busbar system is cooled by standardized refrigeration systems used in many industrial processes and is therefore operationally reliable [2].

W. Reiser
Vision Electric Super Conductors, Kaiserslautern, Germany
e-mail: reiser@vesc-superbar.de

T. Reek (✉)
Consultant, Essen, Germany
e-mail: till.reek@outlook.de

C. Räch · D. Kreuter
University of Applied Sciences, Kaiserslautern, Germany
e-mail: carsten.raech@hs-kl.de

D. Kreuter
e-mail: daniel.kreuter@hs-kl.de

L. Perander (ed.), *Light Metals 2021*, The Minerals, Metals & Materials Series,
https://doi.org/10.1007/978-3-030-65396-5_52

Superconductors Offer Benefits

In many areas of energy intensive industries, high currents are used to produce a wide variety of metals. These high currents are conducted by busbars, cables and overhead transmission lines made of copper or aluminium. However, their low current densities lead to large physical dimensions. Superconducting technology offers decisively smaller solutions. Even after including the refrigeration systems, the operating expense by case is up to 90% lower than the electric losses of conventional busbars. Using HTS, the savings in material compared by masses are between 50 and 90% resulting in a decrease of materials in production and transport [3].

Today's underground cables operating current is limited by the possible heat dissipation to the environment. Superconductive high current systems can transmit multiple times the current and have no thermal effect on their surroundings. In industry plants this saves additional air ventilation cooling or even air conditioning. For grid applications this increases acceptance among the population and preserves the environment.

In the electrical transmission and distribution network, the introduction of superconductive high direct current (DC) systems will enable a new energy efficient distribution. Instead of three-phase overhead lines with extended line widths and corresponding landscape consumption, superconducting high-current systems could transmit the same or higher power on significantly less space and without optical landscape consumption.

Photovoltaic power plants generate direct current that is converted to alternating current (AC) to be accepted by the power grid. Often this AC is converted back to DC to support high-energy processes. Superconductive DC high current transmission offers benefits through possible lower voltage levels and a nearly lossless current transmission [4].

The power requirements in data centres with the increasing importance of Big Data or Industry 4.0 are growing almost exponentially and represent another field of application. The use of superconductors results in economic and ecological advantages.

Like AmpaCity in Essen, Germany [5, 6], or LIPA in Long Island, USA [7, 8], many projects around the world have proven that superconducting transmission lines and cables are feasible, reliable, and ready for general use. However, transmission lines are not the only use case for superconductive systems. There are many successful projects, for example superconducting generator a for a wind power plant (EcoSwing in Thyborøn, Denmark [9, 10]) or superconducting fault current limiter for medium or high

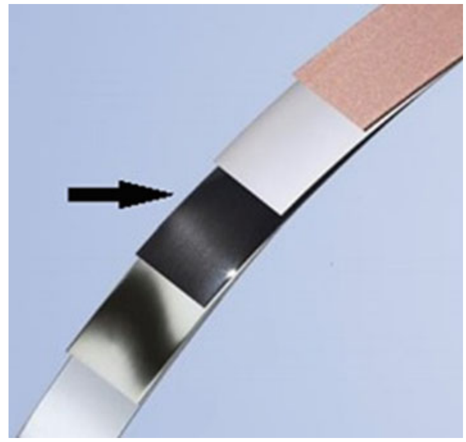

Fig. 1 Superconducting tape consisting of different layers (*Source* [1])

voltage (ASSIST in Augsburg, Germany [11–13]). Also, superconducting industrial applications have been realized. A superconducting busbar system for 20 kA has been installed and tested in a chlorine electrolysis in Germany [14]. In the follow-up project, DEMO200 [15], a 200 kA superconducting busbar system for an aluminium smelter is under development. Deriving from that, the next step could be one of the following five cases.

Five Superconducting Use Cases for Aluminium Industry

Due to the presently used hot electrolysis process, aluminium smelters have an enormous demand for electric energy which is distributed through busbar systems. These busbars cause high material, transport, and installation costs. Also, the space requirements are substantial. In addition, attention must be paid to personal safety and system protection [16].

Superconducting systems offer advantages for several applications in an aluminium smelter. Most of the problems mentioned above can be solved this way. Not only new Projects can benefit from this technology, but superconducting ones can also easily replace many existing busbars. Superconductor technology also offers solutions for reliably magnetic field compensation.

In the following, five use cases for superconducting busbars are shown with short explanations and calculations of investment cost (CAPEX) and operational costs (OPEX). The total cost of ownership (TCO) and payback period are calculated, comparing the superconducting system with a standard aluminium busbar system.

Case 1: Main Busbars Between Rectifiers and Potroom

For connecting several rectifiers with the potroom a busbar system collects the power of the rectifiers and is designed to carry the required current. The smallest busbar current is the operating current of one rectifier. The largest is designed for the operating current of the whole potline. The connections to the cell room are made at the first and the last pot. The busbar lengths range from a few tens to several hundred meters. The operating current easily exceeds 200 kA to be handled by high current busbar systems.

Today the standard material for high current busbar systems is aluminium due to the lower cost ratio compared to copper systems. The crucial disadvantages are large volumes and weight.

A comparable superconducting busbar system carries the high operating current without electrical losses. This property allows the design and construction of highly efficient, ultra-compact, and lightweight busbar systems, as shown in Fig. 2. The main components of a superconducting busbar system are current leads, busbar elements consisting of cryostat and superconductors, efficient tape connectors and a cooling system.

Current leads connect the superconducting system to the standard electrical equipment like rectifiers on ambient temperature. They bridge temperature differences of 250 K and substantially affect both, capital expenditure and operating costs. Optimized current leads for part load are made up of a 3-step cooling system to minimize the thermal input and save up to 45% of the electrical power demand for cooling.

Tape connections are a standard solution for a fast and safe connection of multiple superconducting modules to a variable length system. The contact resistance of the connections is negligible. Therefore, there is almost no thermal load for the cooling system.

The cooling system combines the pump circuit with the cryocooler. The liquid cryogene pump is integrated into the cryogenic circuit, which reduces the heat load on the system. The system is a closed cryocooling circuit with subcooled liquid nitrogen (LN_2) which is steadily cooled down. Thus, no nitrogen will evaporate.

In Table 1 the comparison of an aluminium system and a superconducting busbar system is given for a cell room with operating currents up to 400 kA. The overall length for the main busbar is 415 m, taken from an existing plant.

Currently superconducting busbar systems are technically feasible and an economically reasonable solution. The calculated example indicates that the payback period is below 10 years. After 25 years, a saving of almost 18 million Euro is achieved. These savings overcompensate for the higher initial CAPEX.

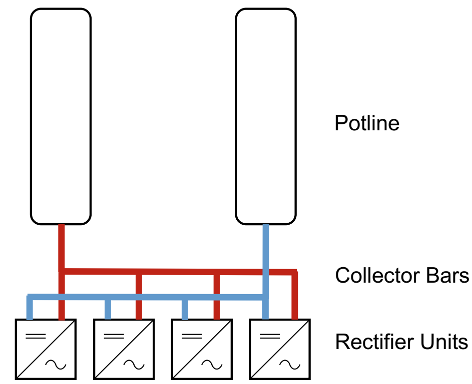

Fig. 2 Collector bars between rectifiers and potline. (Color figure online)

Case 2: Interconnection Busbars Between Potrooms and Standby Rectifiers

Interconnecting busbars are used in aluminium smelters to interconnect potlines or to connect potlines to standby rectifiers. The interconnecting busbars allow compensating currents between the potrooms to achieve an even electrical load of the pots, as shown in Fig. 3. The busbar systems are designed for a fraction of the potline operating current. However, distances up to 500 m may be bridged.

A superconducting busbar system is always smaller, lighter, and more efficient than a conventional system and requires only between 10 and 50% of the material compared to a conventional system. Thus, the environmental impact and the CO_2 footprint are considerably reduced. Additionally, the system requires less space.

With the reduction in weight and volume, even challenging installations can be realized. Some high-current industrial applications require very narrow and flexible routing. Tight bending radii limit the space for installation. In these cases, superconducting busbar systems have significant advantages compared to standard busbar systems and cables. That was impressively demonstrated in the 3S project [14]. Also, due to the system immanent encapsulation of the superconducting busbar system (IP68), personal safety and plant protection are always guaranteed.

In Table 2, a calculation for installation costs and operating cost of an aluminium system and an equivalent superconducting system is shown. The busbar is dimensioned for a nominal current of 50 kA and a length of 500 m with two phases (for an overall length of 1000 m).

After nine years of operation, the superconducting system has reached the payback period. After 25 years a saving of six million Euros is achieved.

Table 1 Comparison of equivalent aluminium and superconducting collector bars

	Al busbar	SC busbar	
Nominal current	400		kA
Conductor current density	0.06	50	kA/cm^2
Conductor cross section	6,667	8.0	cm^2
Conductor mass per meter	1,800	7.0	kg/m
System mass incl. supports & fixation	2,500	60	kg/m
Overall length	415		m
Total mass (incl. LN2 for SC)	1,037,500	24,900	kg
Total electrical resistance	0.022		mΩ
Temperature rise above ambient	40		K
Conductor temperature at nominal current	80/353	−203/70	°C/K
Voltage drop at nominal current	8.9	0.3	V
Busbar power losses	3,557	120	kW
Electrical power for SC cooling machines		820	kW
CAPEX	6,200	17,000	k€
Energy costs	50		€/MWh
Full load hours per year	8,640		h
Operating energy (Losses + machines)	30,700	8,100	MWh/year
OPEX	1,535	405	k€/year
Payback period	Base	9.6	Years
TCO (Total cost of ownership over 10 years)	21,550	21,050	k€
TCO (Total cost of ownership over 25 years)	44,575	27,125	k€
TCO (Total cost of ownership over 40 years)	67,600	33,200	k€

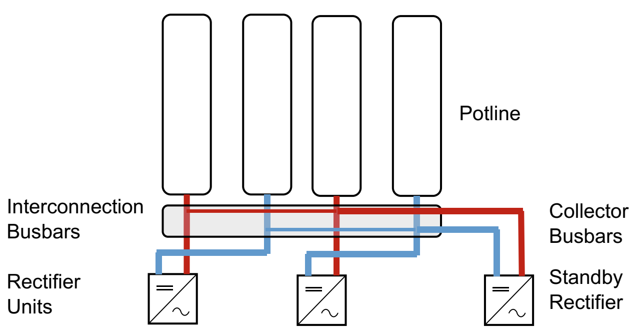

Fig. 3 Interconnection busbars connecting two potrooms as well as an additional standby rectifier. (Color figure online)

Case 3: Magnetic Field Compensation

The production of primary aluminium is one of the most energy-intensive industrial processes worldwide. To increase efficiency and reduce irregular operating conditions, the magnetic field created by the operation current is compensated. Compensation busbars (MFC) are installed around the pots in a hot and tight environment [17].

The superconducting MFC busbar system consists of a transformer-rectifier unit, one current lead with two phases, and the superconducting system, including cryostat, cooling machines, and the liquid nitrogen as shown in Fig. 4. Furthermore, the superconducting MFC system will be designed as a multi-turn loop system. Thus, the rectifier's output current is reduced. Due to the fact that superconductors do not show any resistance the power of the transformer is minimum which results compared to the standard MFC in a smaller, more efficient transformer unit with reduced costs.

Assuming a busbar system for magnetic field compensation in the range of 40 kA, consisting of 5 turns with 8 kA each and a total length of approximately 500 m, a significant reduction of total mass and ohmic losses can be expected. In Table 3 the comparison of these two systems is shown.

A superconducting MFC busbar system requires minimum space and weight because of small conductor and system dimensions. Particularly in narrow industrial buildings, it is a considerable advantage compared to standard MFC systems. This might give the possibility to engineer for an optimized magnetic field compensation. Additionally, the power loss and the thermal emission are reduced, resulting in minimal interference with nearby components.

Table 2 Comparison of equivalent aluminium and superconducting interconnection busbars

	Al busbar	SC busbar	
Nominal current	50		kA
Conductor current density	0.06	50	kA/cm^2
Conductor cross section	833	1.0	cm^2
Conductor mass	225	0.9	kg/m
System mass incl. supports & fixation	320	36	kg/m
Overall length for 2 phases	1,000		m
Total mass (incl. LN2 for SC)	320,000	36,000	kg
Total electrical resistance	0.429		mΩ
Temperature rise above ambient	40		K
Conductor temperature at nominal current	80/353	−203/70	°C/K
Voltage drop at nominal current	21.4	0.3	V
Busbar power losses	1,071	15	kW
Electrical power for SC cooling machines		141	kW
CAPEX	1,920	5,680	k€
Energy costs	50		€/MWh
Full load hours per year	8,640		h
Operating energy (Losses + machines)	9,300	1,300	MWh/year
OPEX	465	65	k€/year
Payback period	Base	9.4	Years
TCO (Total cost of ownership over 10 years)	6,570	6,330	k€
TCO (Total cost of ownership over 25 years)	13,545	7,305	k€
TCO (Total cost of ownership over 40 years)	20,520	8,280	k€

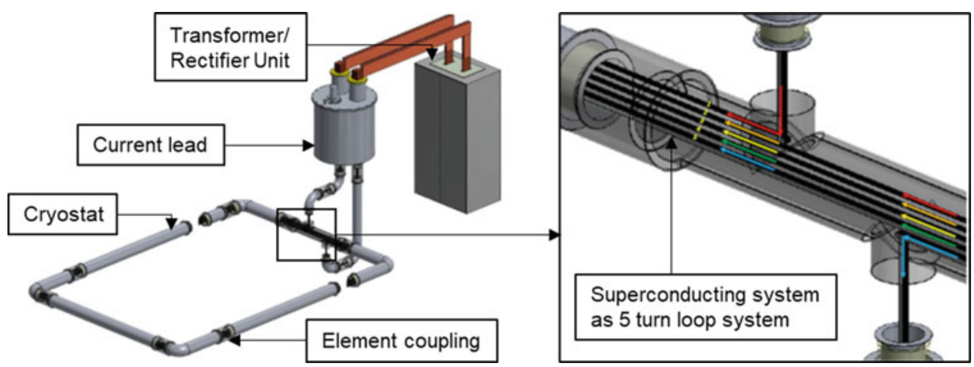

Fig. 4 Exemplary superconducting MFC busbar system as a 5-turn loop system

Case 4: DC Connection Between Potline and Power Plant or Grid Connection Point

The power for an aluminium plant is provided either by a direct connection to the high voltage grid or by a power plant nearby. In the latter case, transmission distances between several hundred meters and some kilometres have to be bridged. Using conventional technology several conversion steps are required to bring the power to the plant with remarkable losses.

On the other hand, a superconducting DC busbar system can provide high power on the same DC voltage level, as shown in Fig. 5, used to run the potline, effectively eliminating transformer power conversion steps. The busbar has no reactive power and no losses in the insulation, leaving only the heat leakage of the cryostat as loss source making the system much less complex with small dimensions.

If the AC/DC transformation is done directly at the power plant or grid connection point, the transportation on the DC side reduces the electrical losses to a minimum.

In Table 4 the comparison of a standard transmission line system is compared to a superconducting busbar system is shown.

In this case a superconducting busbar system can be installed with a payback period of less than 4 years compared to a conventional transmission line. The payback

Table 3 Comparison of equivalent aluminium and superconducting MFC busbar system

	Al busbar	SC busbar	
Nominal current	40		kA
No of turns	1	5	
Conductor current density	0.06	50	kA/cm^2
Conductor cross section	667	0.8	cm^2
Conductor mass	180	0.7	kg/m
System mass incl. supports & fixation	250	20	kg/m
Overall length of the MFC loop	500		m
Total mass (incl. LN2 for SC)	125,000	10,000	kg
Total electrical resistance	0.268		mΩ
Temperature rise above ambient	40		K
Conductor temperature at nominal current	80/353	−203/70	°C/K
Voltage drop at nominal current	10.7	0.2	V
Busbar power losses	429	8	kW
Electrical power for SC cooling machines		43	kW
CAPEX	1,250	2,200	k€
Energy costs	50		€/MWh
Full load hours per year	8,640		h
Operating energy (Losses + machines)	3,700	400	MWh/year
OPEX	185	20	k€/year
Payback period	Base	5.8	Years
TCO (Total cost of ownership over 10 years)	3,100	2,400	k€
TCO (Total cost of ownership over 25 years)	5,875	2,700	k€
TCO (Total cost of ownership over 40 years)	8,650	3,000	k€

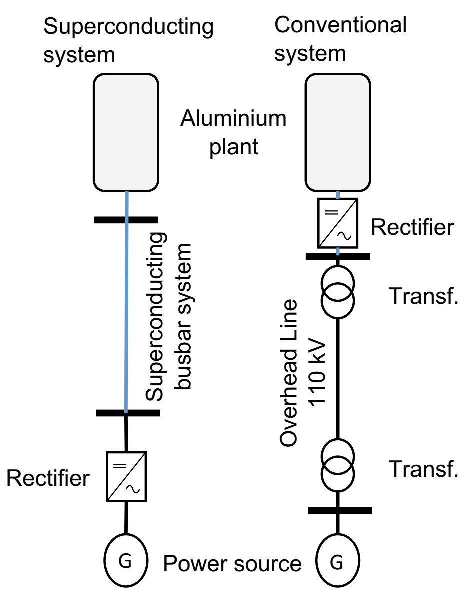

Fig. 5 Superconducting DC/overhead line connection between power source and potline. (Color figure online)

period is strongly depending on the distance between power source and aluminium plant due to the basic invest in two transformers for the overhead line. The installation costs for a superconducting busbar system over a distance of 500 m is even lower than that of the overhead line. In addition OPEX of a superconducting system is much lower compared to the OPEX of the overhead transmission line.

Case 5: Passive Superconducting Magnetic Field Shielding

Permanent

In some aluminium plants the main busbars have to cross roads underground in a covered and often ventilated duct. Driving a car on the road you cannot recognize the difference but only by a traffic sign telling you something about high magnetic fields. If you cross that road for the first time and your car stops you are helpless and do not know why.

Table 4 Comparison of a standard transmission line and a superconducting DC connection

	Overhead Line	SC busbar	
Nominal power	400		MVA
Length of connection	1,500		m
System configuration	Transformer/Overhead Line/Transformer	SC busbar	
Nominal voltage	AC 110	DC 1.25	kV
No of phases	3	2	
Nominal current	2.1	160	kA
Conductor current density	0.1	50	kA/cm^2
Conductor cross section	21.0	3.2	cm^2
Resistance of 1 Phase OH-Line at 80 °C	15.5		mΩ
Power Losses OH-Line, 3 Phases	230		kW
Transformer efficiency	99.6%		
Power losses two transformers	0.8%		
Power losses two transformers	3,200		kW
Voltage drop of SC Busbar		0.3	V
Busbar power losses	3,430	96	kW
Electrical power for SC cooling machines		696	kW
CAPEX	18,000	22,100	k€
Energy costs	50		€/MWh
Full load hours per year	8,640		h
Operating energy (Losses + machines)	29,600	6,800	MWh/year
OPEX	1,480	340	k€/year
Payback period	Base	3.6	Years
TCO (Total cost of ownership over 10 years)	32,800	25,500	k€
TCO (Total cost of ownership over 25 years)	55,000	30,600	k€
TCO (Total cost of ownership over 40 years)	77,200	35,700	k€
Special case at 500 m distance			
CAPEX	14,000	*13,400*	k€
Energy costs	50		€/MWh
Full load hours per year	8,640		h
Operating energy losses	28,200	6,000	MWh/year
OPEX	1,410	300	k€/year
Payback period	Base	*CAPEX LOWER*	

Later you recognize that you should have speeded up your car and run idle over that area. The magnetic field is blocking your car engine.

In a control room where operators work on computer equipment, the screens show strange effects for several hours a day, always at the same time. The monitors show stripes and a very crooked picture of the process. This happens some days more, some days less with lower intensity and is annoying the operators and influencing their performance. The control room is located on the second floor above a transformer and switchgear room. During high power demand the high current generates a magnetic field that exceeds the admissible limit of electronic devices and monitoring equipment. In some cases, this could lead to incorrect information of process values or operator actions without real reason.

In both cases magnetic fields create these effects. Electric field lines begin and end in a positive/negative electric charge. Electric fields can be shielded with a screen connected to earth potential. Magnetic field flux lines have no beginning and no end. Magnets are always bipolar, there is always north and south pole, not a single pole.

The shielding of magnetic flux lines is very difficult and inefficient. Like electric current magnetic flux lines always look for a path with lower resistance (or higher conductivity). High conductivity for magnetic flux lines are ferromagnetic materials like iron or nickel. A magnetic field can be deformed by placing an iron structure around the area where you want to reduce the magnetic flux density. Alternatively, you can create a compensating magnetic field which is generally done at larger aluminium pots and called Magnetic Field Compensation (MFC).

A third method is now available through the use of superconductors having ideal diamagnetic properties which means that the magnetic flux lines cannot penetrate the superconductor up to a critical value. The superconductor is a perfect shielding method for creating a room without any magnetic field. This effect is passive and does not require an external power source. Of course, as mentioned before the superconductor can only work below its critical temperature (namely, 80 K) which is provided by liquefied gases such as nitrogen (<77 K), hydrogen (<20 K), or helium (<4.2 K).

This means that in the case of the underground busbar a flat cryostat may contain one or more layers of superconductors in a liquid nitrogen bath. As explained earlier some thermal energy is penetrating the thermal insulation of the cryostat and is warming up the liquid nitrogen. Either liquid nitrogen is boiled off and needs refill from time to time or the liquid nitrogen is kept on its low temperature by a cooling machine. In both cases the magnetic field on the road is reduced to harmless values, no car engine gets blocked during running over that area.

In the second case of the control room the working principle is the same. A flat cryostat/superconductor installation under the ceiling of the transformer and switchgear room will shield the control room against the magnetic field of the electric power equipment on the first floor. Operators are pleased and perform more efficiently.

Mobile or Temporarily

Electric arc welding is widely used in construction works due to easy handling and high-quality result. Nevertheless, in a high magnetic field, a good quality welding is almost impossible. The magnetic field deflects the electric arc resulting in a "jumping" arc due to the resulting Lorentz[1] force of the magnetic flux field and the electric arc current. The result is a weld seam with many holes and impurities, very often good enough for electric purposes but in some cases not acceptable for mechanical loads.

In aluminium plants a high magnetic field is created by the potline current. A mobile flat, curved, or tube-shaped cryostat with multiple layers of superconductors can shield the welding area against the magnetic field. In this case special forms can be adapted to difficult shielding situations or standard flat devices are used to allow quality arc welding in a strong magnetic field.

Conclusions

Superconductor busbar systems are conducting high currents up to 500 kA and more. On a voltage level of ±1.5 kV this gives a total power of 1500 MW.

Superconductor busbar systems are compact, 500 kA, 1500 MW in cryostats with an outer pipe diameter of 0.5 m filled in most cases with liquid nitrogen.

Superconductor busbar systems are ultra-safe, 500 kA, 1500 MW in a 50 cm cryostat with a protection degree of IP68. Location is not depending on any ambient condition.

Superconductor busbar systems are crossing long distances, 500 kA, 1500 MW in 50 cm, IP68 and a length of up to 5 km and more underground without emitting heat.

Superconductor busbar systems are highly efficient, 500 kA, 1500 MW in 50 cm, IP68 over 5 km with a voltage drop of <0.5 V. This results in an electric power loss of 0.02% or an electric efficiency rate of 99.98%. Compared to conventional systems this saves generating power just for transport losses to an aluminium smelter which finally results in lower operating costs.

Superconductor busbar systems are the answer of today on higher efficiency demands, smaller environmental impacts, lower CO_2 generation, and lower Total Costs of Ownership.

References

1. Bruker HTS GmbH (2020) High temperature superconductors HTS. Datasheet. https://www.bruker.com/fileadmin/user_upload/8-PDF-Docs/BEST/DataSheets/HTS.pdf. Accessed: September 16, 2020

[1]Hendrik Lorentz, Dutch physicist and Nobel prize winner in 1902, derived in 1895 the modern form of the formula for the electromagnetic force which includes the contributions to the total force from both the electric and the magnetic fields.

2. Buckel W, Kleiner R (2013) Supraleitung. Grundlagen und Anwendungen, 7. Aufl. Lehrbuch Physik. Wiley; Wiley-VCH, Hoboken, NJ, Weinheim
3. Rey C (Hrsg) (2015) Superconductors in the power grid. Materials and applications. Woodhead Publishing Series in Energy, Number 65. Woodhead Publishing, Amsterdam Netherlands
4. McConnell BW (2005) Applications of High Temperature Superconductors to Direct Current Electric Power Transmission and Distribution. IEEE Trans. Appl. Supercond. 15(2):2142–2145. https://doi.org/10.1109/tasc.2005.849479
5. RWE Deutschland (2020) AmpaCity – technologische Weltpremiere in Essen. http://www.rwe.com/web/cms/de/1301026/rwe-deutschland/energiewende/intelligente-netze/ampacity/. Accessed: September 08, 2020
6. Stemmle M, Merschel F, Noe M, Hobl A (2013–2013) AmpaCity—Installation of advanced superconducting 10 kV system in city center replaces conventional 110 kV cables 2013 IEEE International Conference on Applied Superconductivity and Electromagnetic Devices. IEEE, S 323–326
7. LIPA Long Island Power Authority (2020) Lipower. https://www.lipower.org/. Accessed: September 8, 2020
8. Maguire JF, Schmidt F, Bratt S, Welsh TE, Yuan J (2009) Installation and Testing Results of Long Island Transmission Level HTS Cable. IEEE Trans. Appl. Supercond. 19(3):1692–1697. https://doi.org/10.1109/tasc.2009.2018221
9. EcoSwing (2020) EcoSwing. https://ecoswing.eu/. Accessed: September 08, 2020
10. Song X, Buhrer C, Molgaard A, Andersen RS, Brutsaert P, Bauer M, Hansen J, Rebsdorf AV, Kellers J, Winkler T, Bergen A, Dhalle M, Wessel S, Brake Mt, Wiezoreck J, Kyling H, Boy H, Seitz E (2020) Commissioning of the World's First Full-Scale MW-Class Superconducting Generator on a Direct Drive Wind Turbine. IEEE Trans. Energy Convers. 35(3):1697–1704. https://doi.org/10.1109/tec.2020.2982897
11. Stadtwerke Augsburg Holding GmbH (2020) ASSiST - Supraleitender Strombegrenzer. https://www.swa-netze.de/service/aktuelle-meldungen/archiv/assist-supraleitender-strombegrenzer/. Accessed: September 08, 2020
12. Janetschek T (2016) ASSiST—Supraleitender Strombegrenzer. Augsburg Stadtwerke Siemens Supraleitender Strombegrenzer, Münschen
13. BRUKER Corporation (2010) Bruker Corporation—Bruker Energy & Supercon Technologies (BEST), Schneider Electric/Alstom Grid and Stadtwerke Augsburg Announce BMWi Grant for iSFCL Joint Demonstration Project. https://ir.bruker.com/press-releases/press-release-details/2010/Bruker-Energy–Supercon-Technologies-BEST-Schneider-ElectricAlstom-Grid-and-Stadtwerke-Augsburg-Announce-BMWi-Grant-for-iSFCL-Joint-Demonstration-Project/default.aspx. Accessed: September 08, 2020
14. Elschner S, Brand J, Goldacker W, Hollik M, Kudymow A, Strauss S, Zermeno V, Hanebeck C, Huwer S, Reiser W, Noe M (2018) 3S–Superconducting DC-Busbar for High Current Applications. IEEE Trans. Appl. Supercond. 28(4):1–5. https://doi.org/10.1109/tasc.2018.2797521
15. DEMO200 (2019) Homepage - demo200. https://demo200.de/?lang=de. Accessed: October 06, 2020
16. Gupta A (2017) Energy Reduction Initiatives to Improve Low Amperage Cell Performance
17. Düssel R (2017) Entwicklung eines Regelungskonzepts für Aluminium-Elektrolysezellen unter Berücksichtigung einer variablen Stromstärke und eines regelbaren Wärmeverlusts. Dissertation, Universitätsbibliothek Wuppertal