Superconducting fault current limiters for grid protection

Will SFCL technology soon mature for widespread use?

ABSTRACT

Superconducting fault current limiters are novel equipment for grid engineers. It presents unique features like ultra-fast current limitation, efficient reduction of fault current and very small footprint. It is eco-friendly and non-flammable. The article briefly discusses device basics, available options and recent practical advances in this field. As well, a forward-looking analysis of future SFCL opportunities for application in the electrical grid is presented.

KEYWORDS:

cryogenics, economics, fault currents, fault current limiters, superconductors

1. Introduction

The electrical grid gets more complex in order to respond to electrical consumption growth. If it is the grid of a megacity or a large industrial area, the grid density dramatically increases. An increase of transmitted power, a decrease of distances, cabling of transmission lines, and introduction of distributed generation sources – all this leads to the growth of fault current level. We have a fundamental problem here: by becoming larger, the grid inevitably starts to be much more vulnerable to short circuit events. As a result of the grid growth, the impact of fault currents becomes exponentially more significant and expensive. Although the problem needs proper attention at all voltage levels and at the connection between voltage levels through transformers, it is medium and high voltage levels where the cost of the problem is the largest. And that is exactly the point where many new fault current limiting devices start to be applied to the grid.

Fault current issue is normally addressed by grid sectioning, installing current-limiting devices (inductive reactors, Is-limiters, semiconducting devices) [1], or increasing the rating of switchgears. These approaches have their pros and cons. Grid sectioning is easy and cheap, but it leads to increased losses and a higher probability of blackouts. Using conventional current-limiting devices leads to additional losses, and the number of problems they can solve is limited. For instance, Is-limiters and semiconducting devices are available only for medium voltage range, while inductive reactors have a limited impedance value and produce stray magnetic fields at operation. Increasing the rating of switchgears ultimately leads to rating increases

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for all grid components, including cables, transformers and busbars. Such serious grid renovation is a costly adventure.

The opportunity – and challenge – for superconducting fault current limiter (SFCL) technology lies in solving of fault current limitation task without the aforementioned flaws.

2. How superconductors help

The discovery of high-temperature superconductivity (HTS) in the late 1980s and the emergence of practical HTS tapes in the 2000s brought about a completely new instrument based on the unique physics of these new materials. Although typical HTS materials operate at about -200 °C, the term "high-temperature superconductors" is widely used to differentiate them from low-temperature superconductors, which operate at around -270 °C – in MRI machines and particle accelerators, for example. Due to their odd quantum nature, superconductors happen to "switch" reversibly between superconducting and highly resistive state depending on the level of current passing through. Important for grid: this transition is ultrafast, reliable, and reproducible (Fig. 1). After the fault is cleared, the current-limiting element automatically returns back to the superconducting state. A couple of definitions: the threshold value, above which superconductivity is lost, is called a "critical current" Ic, and the transition property itself is often referred to as a "quench". The current below Ic passes the superconductor with almost no losses. If the current is larger than the designed threshold value, the superconductor turns resistive (as it quenches), and the current level is automatically limited. Superconductor thus serves as a natural "fault current limiter". All you need to do is to keep the superconductor cold and dissipate Joule heat after the fault event.

Very high speed of current limitation, a large reduction of the fault current, and a small footprint are the major technical features that lead to the economic benefit of SFCLs compared to conventional technologies. One may note that the economic benefit can be found today in a limited number of cases, but as the superconducting technology develops and matures, their number will grow. It looks like the grid reliability problems grow in number and impact size while superconducting device cost gradually goes down: it sounds like a perfect scenario for rapid market development.

Engineers offered a variety of ways to make use of the current-limiting property of superconductor [1-3]:

- resistive stand-alone superconducting fault current limiter (r-SFCL),
- inductive stand-alone superconducting fault current limiter (i-SFCL),
- fault current limiting cable,
- fault current limiting transformer,
- superconducting fault current limiting inductive reactor.

The functional principle of these devices is most evident from their very names. The "quenchable" superconductor is placed either in low inductance coils or meanders (resistive SFCL), cable core, or coils (inductive SFCL, superconducting transformer [3] or reactor). Typically, liquid nitrogen serves as a coolant and high voltage insulation at once. All these devices provide ultrafast fault current limitation, as well as not rarely outperform traditional counterparts in other physical characteristics, such as footprint, for example. Further in the text, we will refer to all these different technical approaches collectively as "SFCL" technologies.

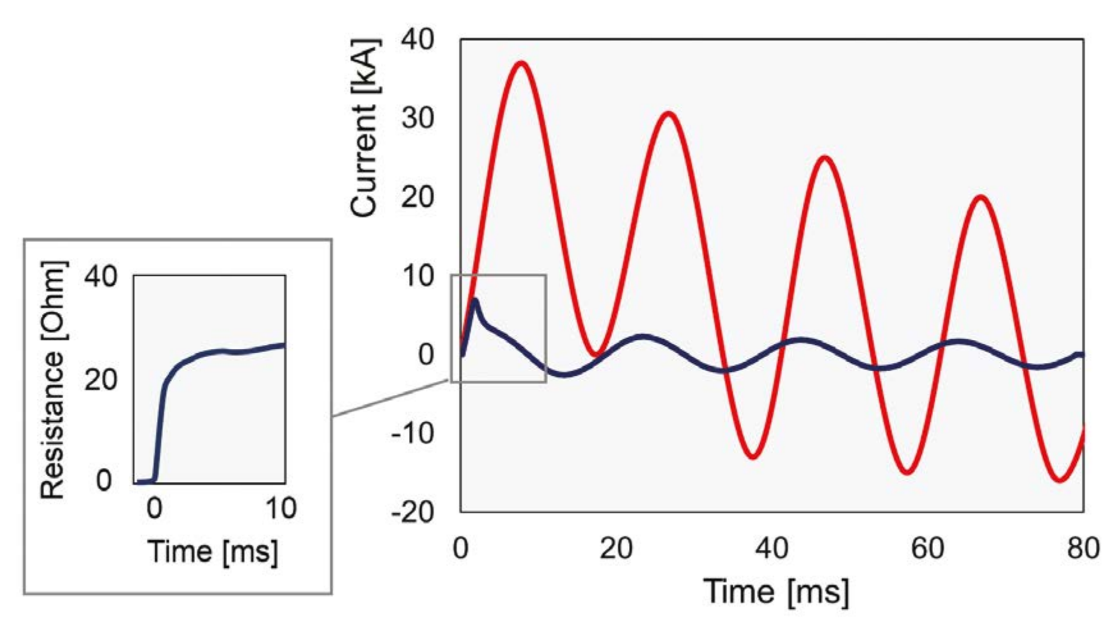

Figure 1. A typical fault current limitation with a superconducting device – ultrafast and extremely effective [10]

3. Wider acceptance and economy of scale will promote each other

To find the way into the real grid, SFCL technologies have to show their viability by winning a cost competition. Superconductors are new materials with a current market price in 150-250 $/kAm range and the perspective to go way down to 50 $/kAm, as a significant production level is reached (Fig. 2). Future engineering is expected to help reduce the amount of HTS tape needed to build SFCLs. The same is true for cryogenics cooling system, which can be expected to become much more affordable, especially if the development of LNG and LH2 production and distribution will progress as planned. The third important constituent of the price is the cost of power testing and corresponding freight costs (Fig. 3). Unlike many other devices, high voltage SFCL needs extraordinarily high power to test its fault current limitation efficiency. For example, SuperOx 220 kV/1,2 kA SFCL was tested with a power of about 2 GW. This type of tests is available only in few test centres worldwide (KEMA Labs in the Netherlands [8] and KERI in South Korea [9] are the most known examples of such centres), making logistics time-consuming and costly. When SFCLs will be serially produced, and international standards in place, producers will benefit from less frequent power tests, thus reducing the selling price for customers. Combined with technology development, the reduction of cost of superconductor and cryogenic equipment, optimization of logistics / tests procedure and scale effect could decrease SFCL price significantly, making it applicable in wider market segments. Today, the price for r-SFCL could be estimated at $50-70 per one kilowatt of nominal power level, while less than one large device is commissioned per year worldwide. It is really a "boutique type" production today. The cost of $20-30 per one kilowatt of nominal power seems to be a reasonable cost for an r-SFCL if the production scale reaches a moderate 10 devices/year target. Until the mass market is reached, r-SFCL will find its application in cases where the problem cannot be cured by cheaper countermeasures. The "good" news is that there are many such cases, and we will continue to see new interesting SFCL projects in nearest future.

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Another mighty driver, which could lead to the rapid acceptance of superconducting fault current limiters is the development of DC technology. Superconductors may greatly help to solve the problem of controlling large DC currents in UVDC and HVDC transmission lines, data centres, electrolysis plants or similar installations. Although there are no grid installations so far, active R&D work has already begun: 160 kV / 1 kA DC r-SFCL is being developed in China [10], EU funds the project to develop 50 kV / 1kA DC r-SFCL [11], and 1.5 kA / 400 mH HTS DC reactor was developed in Korea [12].

Last but not least, SFCL technology is very ecology-friendly and intrinsically fireproof. Liquid nitrogen is a major constituent of the air, and no flammable components are included. The use of solid-state insulated bushings instead of SF6 insulation was shown to be effective for SFCL. This aspect could become very important for future SFCL technology destiny, as these aspects will play a larger role as climate concerns rise.

> **Superconducting fault current limiters are ecology-friendly and intrinsically fireproof**

4. Cases where SFCL already work

Today, superconducting fault current limiting technologies have already started being applied in a real grid. No wonder this penetration takes place in cases with extraordinary costly and urgent problems – in large cities.

Probably, the most famous example is the 12 kV / 2400 A SFCL protecting 10 kV / 40 MVA superconducting cable in Essen, known as the AMPACITY project, developed by Nexans [13] for RWE (now Innogy). Essen is a part of a large urban agglomeration (Ruhr area), which has over 5 million people and is a giant industrial dis-

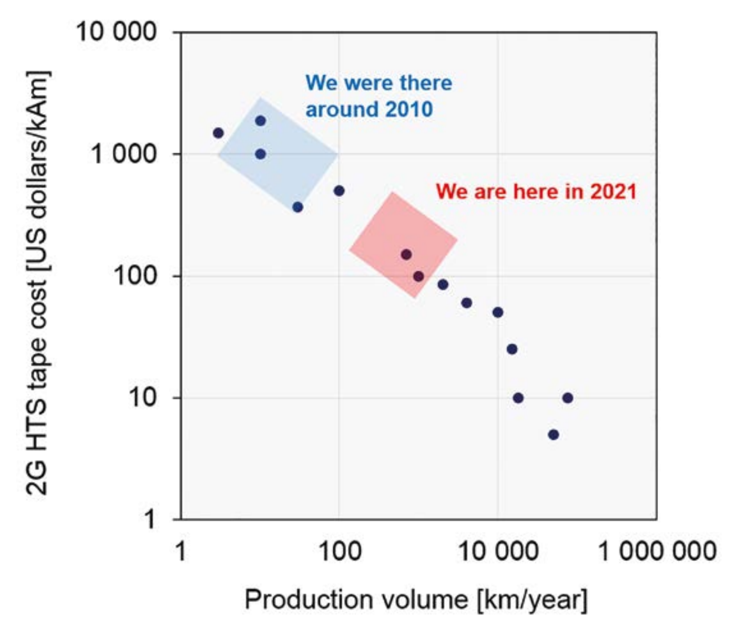

Figure 2. The cost of second-generation high temperature superconductor tape based on various expert opinions [4-7]

Figure 3. One phase of SuperOx 220 kV SFCL in KERI test centre, February 2018

> Today, superconducting fault current limiters help to solve costly and urgent grid problems – in large cities, for example

trict. The AMPACITY SFCL has a 2,4-kA rating that is the highest value for r-SFCLs installed in the grid so far. The device went live in 2014 and has operated smoothly for many years since its commissioning. Another example is the use of SFCL to control fault currents in 220 kV grid of Moscow by UNECO grid company. The Russian capital is a very dense city with more than 12 million people and over 100 TWh yearly consumption of electricity. Due to the need for centralized heating in winter, a significant part of electrical generation is placed inside the city, making generation-consumer distances unusually short. Intensive XLPE cable introduction and simultaneous rapid consumption growth in the 21st century caused fault current level to double in the last 20 years. To address this, 220 kV / 1,2 kA SFCL was designed and built by SuperOx [14]. This SFCL was installed in 2019, and there are high chances that more high voltage SFCL devices will follow in the next 5 years. To date, this is the most powerful HTS device installed in the grid worldwide. In Chicago, IL, ComEd is setting up to install the worlds' first fault current limiting cable in 2021 with the ultimate goal to connect neighbouring substations in the city centre at a distribution level of 14 kV in a "loop". There is no practical way to interconnect such city substations without increasing fault current levels, and the SFCL cable provides a perfect "two-in-one" solution. The project is run by AMSC and is known as REG (resilient electrical grid) [15]. It is important to note that it is the fault-current limiting behaviour of superconductors that ensures this grid resiliency. Such mesh- or circle-like city interconnection is crucial to cope with a threat of potential power outages due to malicious attacks and / or extreme weather influence, which are known to be very costly. Following the Chicago project, it is expected that more US cities will adopt the REG solution.

5. Where future directions will lead us

Practical examples given above prove that SFCL technology has reached enough maturity to start its way in a real grid. As with any perspective high tech, the more you learn, the more work appears to be ahead. Although predicting the future is a tough job, we will try to show directions here, as they are seen from 2021. As it seems, the engineers will spend the decade focusing on one or more of these challenges:

- Reach better device performance: e.g., decrease AC losses in a superconduc-

tor, increase fault withstand time, decrease device cost,

- Develop internationally accepted standards for SFCL equipment and test procedures,
- Create SFCL solutions for yet "untouched" areas with great market potential, such as 220-750 kV AC grids, HVDC and UVDC, 10 + kA busbars, on-board protection systems of railways, ships and aeroplanes, smooth starters for large motors, protection for arc ovens and electrolysis equipment, etc.,
- Develop competitive two-in-one or three-in-one solutions: FCL transformer, FCL cable, SFCL reactor, etc.

If any of these directions will bring results, it will be good for SFCL. The greatest challenge for SFCL, however, is to overcome its present niche-type presence in city grids and become a truly diversified and widespread technology. Only this would provide enough resources for the SFCL market to grow fast.

Conclusion

A high level of fault currents presents a serious threat to the development of electrical grids in densely populated megacities or large industrial areas. Superconducting fault current limiter technology appears to be able to address existing challenges in a number of cases, and this drives first applications in a real grid. As the technology matures, it will benefit from ever-growing electrical grid complexity and more stringent requirements for a stable supply of electricity to customers.

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