A Novel Configuration for Resistive SFCL with bifilar 2G tapes

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Abstract. Electrical faults on medium voltage electric power distribution systems can damage transformers. This fact motivated an R&D project in Brazil to study Fault Current Limiters for a utility. In this context, innovative design with a bifilar winding was developed for the present work, aiming to reduce self-inductance and to improve cooling rate. Long length second-generation superconducting tapes were used to build the prototype, which was constructed on a fiber-glass base. The prototype module has been tested at low voltage levels. The nominal operation, fault current limitation and recovery time have been examined for prospective currents of 2700 A and reduction of about 90% in the current level. Due to fast recovery time and good heat exchange, the proposed topology has potential to be applied in a full-scale prototype.

1. Introduction

Some Brazilian utilities have a large occurrence of power transformers damage due to short circuit occurrences in medium voltage distribution lines. One of the possible reasons for this problem is related to the actuation of automatic circuit reclosers during the occurrence of permanent short circuits. The automatic circuit reclosers are configured by the utility to try to reclose the circuit 3 times after a fault opening. If the short circuit was not extinguished, this process causes high currents that stress the power transformers and reduce their lives. This problem motivated the development of an R&D project between the Brazilian utility Light S.A.E. and the Fluminense Federal University to study fault current limiters (FCL). Four FCLs bench prototypes using different technologies were designed and constructed: series impedance bypassed by a solid-state switch, series LC resonant circuit, resistive superconducting FCL (R-SFCL) and hybrid power-electronic R-SFCL. In this paper, details and some preliminary experimental results of an R-SFCL prototype will be presented. In terms of R-SFCLs, the literature presents several papers about this technology. Some of them are mature and pre-commercial devices, which are summarized in Table 1.
Table 1. Resume of R-SFCL prototypes.

| Country          | Publication year | Paper Title                                                                 |
|------------------|------------------|-----------------------------------------------------------------------------|
| South Korea      | 2005             | 6.6 kV Resistive Superconducting Fault Current Limiter Based on YBCO Films[1]|
| Japan            | 2009             | Design and Experimental Results of Three-Phase Superconducting Fault Current Limiter Using Highly-Resistive YBCO Tapes [2] |
| South Korea      | 2009             | Study on a Series Resistive SFCL to Improve Power System Transient Stability: Modeling, Simulation, and Experimental Verification [3] |
| Germany          | 2011             | ENSYSTROB - Resistive Fault Current Limiter Based on Coated Conductors for Medium Voltage Application [4] |
| China            | 2012             | The Development and Performance Test of a 10 kV Resistive Type Superconducting Fault Current Limiter [5] |
| Spain/Slovakia   | 2013             | Design and Production of the ECCOFLOW Resistive Fault Current Limiter [6]    |
| Germany          | 2014             | AmpaCity - Advanced Superconducting Medium Voltage System for Urban Area Power Supply [7] |
| Italy            | 2016             | Status of Superconducting Fault Current Limiter in Italy: Final Results From the In-Field Testing Activity and Design of the 9 kV/15.6 MVA Device [8] |
| Poland           | 2017             | Experimental Results of a 15 kV, 140 A Superconducting Fault Current Limiter [9] |
| China            | 2018             | Design and Test of 10 kV/400 A Flux-Coupling-Type Superconducting Fault Current Limiting Module [10] |
| China            | 2019             | Development and test of a 220 kV/1.5 kA resistive type superconducting fault current limiter [11] |

The R-SFCL prototypes described in Table 1 were manufactured with RE-Ba-Cu-O second-generation (2G) tapes, and they have a different configuration. In general, an R-SFCL is designed to cancel or minimize the self-inductance, and in most of the works, a bifilar spiral topology is adopted. Here a novel planar bifilar serpentine shape configuration is proposed for a modular R-SFCL in contrast with the previous works, as presented in Figure 1. In the author’s knowledge, this is the first time this design is proposed in the literature. The goal of this work is to present the experimental results of the first prototype of this new FCL design to evaluate its behavior under fault conditions. As a result, the proposed technology showed potential for the future development of full-scale equipment.
Figure 1. Schematic of the bifilar arrangement used in the R-SFCL module prototype.

2. The R-SFCL prototype

2.1. The bifilar R-SFCL module

The idea of the designed bifilar configuration is to minimize the self-inductance of each unity by two opposite currents passing through the tapes separated by a thin insulating layer. The schematic of the R-SFCL prototype was presented in Figure 1, in which blue and red colors were used to illustrate the direction of the current. These lines in the schematic can represent one 2G tape or multiple parallel superconductors if a higher critical current is needed. In the case of the constructed prototype, presented in Figure 2, only one superconductor tape was used. G10 fiberglass plates were used to build the module that has 3.6 m of Sunam tape with 12 mm width, model SAN12500 manufactured in 2014.

Figure 2. Picture of the final R-SFCL module.

2.2. The prototype and modules assembled

A cryostat was designed to assemble several modules together that can be connected in series or parallel depending on the needed level of voltage and current of the system to be protected. A draw of the cryostat schematic is presented in Figure 3. A cold-head is positioned in the top of the cryostat to remove the heat from the liquid nitrogen, also reducing its temperature, increasing the superconductor critical current, and avoiding bubbles formation. The system is still under development in the time of this manuscript writing. Some pieces of cryostat used in the tests of this work are presented in Figure 4, like the cryostat cover and the LN2 container.
3. Experimental procedures

This section describes the experimental procedure during the tests using the constructed R-SFCL module. The experimental rig is composed of an AC controlled voltage source that is connected to the primary of an electrical transformer. Firstly, the secondary winding of this transformer was short-circuited, and its current was measured by a current sensor, as illustrated in Figure 5.a. The objective of this test is to evaluate the behavior of the prospective current when different voltage profiles are applied in the primary winding of the transformer. After that, the R-SFCL was connected between the two terminals of the secondary winding, as illustrated in Figure 5.b, and the same voltage profiles were applied in the primary. The limited secondary current was measured and compared with the prospective current. The voltage on the secondary winding of the transformer was also analyzed.

The voltage profile applied in the primary winding during the tests has three stages: the first stage results in a 60 Hz sinusoidal current of 200 A RMS in the secondary winding, representing the steady-state condition. The second stage emulates the short-circuit condition for different levels of prospective current: 500 A, 1000 A, 2000 A, and 2700 A. The third stage is similar to the first one and shows the system behavior after the fault extinguish.
4. Results

This section presents the experimental results evaluated in the constructed R-SFCL module. Figure 6 shows the family of prospective currents used for comparison with the limited one, where the legend indicates the approximate RMS value of the current in the short-circuit condition. The limited current itself is presented in Figure 7, where the legend indicates the correspondent prospective current of each test. One should note that the current maximum value is decreasing in each cycle during the fault since the Joule effect makes the superconductor temperature increases. Along with the temperature, the R-SFCL resistance also increases.

Figure 6. Family of prospective currents.

Figure 7. Family of limited currents.

During the tests, the fault was cleared after 6 cycles and the voltage returned to the same level measured immediately before the fault. The SFCL was submitted to a current in the normal state and had to recover under operation. In this case, the current is smaller than the pre-fault level, but it is possible to see that it rises slowly after 0.13 s. Figure 8 presents the voltage on the R-SFCL during the
experiments, indicating that the tape had the same voltage drop in all tests after fault clearing. If the R-SFCL were not under load after the fault, the recovery time would be about 0.5 s, indicating that the proposed configuration has a good heat exchange and can recover very fast.

Figure 8. The voltage on the R-SFCL during the tests.

The recovery time in this prototype was estimated by examining the voltage drop at the R-SFCL. Figure 9 presents the voltage and current results. An initial peak current of 122 A was passing in the R-SFCL, and a fault was applied after five cycles (prospective of 2700 A$_{\text{rms}}$). After the fault, which takes five cycles, the R-SFCL was submitted again to a peak current of 122 A. It took 322 ms to the prototype to come back to the superconducting state. It indicates its capability to become superconductor again, even under load. The recovery time is slightly higher than 322 ms. The recovery time is how long it takes to the R-SFCL comeback to its operational point (77 K in this case). As the temperature was not measured in this experiment, the recovery time cannot be precisely informed. It was noted that if the current after fault is higher than 122 A$_{\text{peak}}$, the R-SFCL was not able to recover, and the 2G tape probably would be damaged if it continues connected during several cycles. The literature reports recovery time for prototypes from 0.88 s to 1.6 s [12-15].

Figure 9. The voltage on the R-SFCL and its limited current during the tests for a prospective current of 2700 A.
Figure 10 presents a summary of the limitation percentual values at each peak of the six first cycles of short-circuiting. The limitation percentual (LP) was computed as follow

\[ LP = 1 - \frac{Max_{\text{limited}}}{Max_{\text{pros}}} \]

where,
- \(Max_{\text{pros}}\) are the maximum values in the prospective test.
- \(Max_{\text{limited}}\) are the maximum values in the limited test.

![Graph showing the summary of limitation percentual values at each peak of the six first cycles of short-circuiting.](image)

**Figure 10.** Summary of the limitation percentual values at each peak of the six first cycles of short-circuiting.

In Figure 10, it was possible to see that the limitation capability increases with the short-circuit current values. Despite the saturation behavior presented in Figure 10, the maximum values of current and voltage supported by the R-SFCL module tested in this work still need to be evaluated by testing it at higher power/voltages.

5. Conclusions

The short-circuit affects the equipment of the substation, principally the electrical transformer and the circuit breakers, they are equipment that suffers more from this problem. Brazil’s electrical companies have been finding this problem in many of their substations.

This paper, a new R-SFCL topology was proposed in order to mitigate the problems about the short-circuited occurred in a Brazilian electrical energy company's substations. Analysing the results obtained, this new R-SFCL configuration can be a technical solution to protect the substation’s equipment decreasing the short-circuit level to an acceptable level.

Therefore, using this new topology of the superconductor fault current limiter, it is possible to mitigate the short-circuit and increase the lifespan of the equipment affected by this problem.

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References

[1] O.-B.Hyun, H.-R.Kim, J. Sim, Y.-H.Jung, K.-B.Park, J.-S.Kang, B. Lee, and I.-S. Oh, “6.6 kV resistive superconducting fault current limiter based on YBCO films,” IEEE Transactions on Applied Superconductivity, vol. 15, pp. 2027–2030, jun 2005.

[2] T. Yazawa, K. Koyanagi, M. Takahashi, M. Ono, M. Sakai, K. Toba, H. Takigami, M. Urate, Y. Iijima, T. Saitoh, N. Amemiya, and Y. Shiohara, “Design and experimental results of three-phase superconducting fault current limiter using highly-resistive YBCO tapes,” IEEE Transactions on Applied Superconductivity, vol. 19, pp. 1956–1959, jun 2009.

[3] B. C. Sung, D. K. Park, J.-W. Park, and T. K. Ko, “Study on a series resistive SFCL to improve power system transient stability: Modeling, simulation, and experimental verification,” IEEE Transactions on Industrial Electronics, vol. 56, pp. 2412–2419, jul 2009.

[4] S. Elschner, A. Kudymow, S. Fink, W. Goldacker, F. Grilli, C. Schacherer, A. Hobl, J. Bock, and M. Noe, “Resistive fault current limiter based on coated conductors for medium voltage application,” IEEE Transactions on Applied Superconductivity, vol. 21, pp. 1209–1212, jun 2011.

[5] Z. Hong, J. Sheng, J. Zhang, B. Lin, L. Ying, Y. Li, and Z. Jin, “The development and performance test of a 10 kV resistive type superconducting fault current limiter,” IEEE Transactions on Applied Superconductivity, vol. 22, pp. 5600504–5600504, jun 2012.

[6] A. Hobl, W. Goldacker, B. Dutoit, L. Martini, A. Petermann, and P. Tixador, “Design and production of the ECCOFLOW resistive fault current limiter,” IEEE Transactions on Applied Superconductivity, vol. 23, pp. 5601804–5601804, jun 2013.

[7] M. Stemmle, F. Merschel, M. Noe, and A. Hobl, “AmpaCity®#x2014 advanced superconducting medium voltage system for urban area power supply,” in 2014 IEEE PES T&D Conference and Exposition, IEEE, apr 2014.

[8] G. Angeli et al., “Status of Superconducting Fault Current Limiter in Italy: Final Results From the In-Field Testing Activity and Design of the 9 kV/15.6 MVA Device,” in IEEE Transactions on Applied Superconductivity, vol. 26, no. 3, pp. 1-5, April 2016, Art no. 5600705.doi: 10.1109/TASC.2016.2524534.

[9] J. Kozak, M. Majka and S. Kozak, "Experimental Results of a 15 kV, 140 A Superconducting Fault Current Limiter," in IEEE Transactions on Applied Superconductivity, vol. 27, no. 4, pp. 1-6, April 2017, Art no. 5601806.doi: 10.1109/TASC.2017.2651120.

[10] C. Maeda, S. Yanai, Y. Shirai, M. Shiotsu, G. Honda and S. Isojima, "Recovery Characteristics of GdBCO Tape in a Pressurized Liquid Nitrogen for a Resistive SFCL," in IEEE Transactions on Applied Superconductivity, vol. 29, no. 5, pp. 1-5, Aug. 2019, Art no. 5602505. doi: 10.1109/TASC.2019.2901894

[11] M. C. Ahn et al., "Recovery Characteristics of Resistive SFCL Wound With YBCO Coated Conductor in a Power System," in IEEE Transactions on Applied Superconductivity, vol. 17, no. 2, pp. 1859-1862, June 2007. doi: 10.1109/TASC.2007.898128

[12] Z. Hong, J. Sheng, L. Yao, J. Gu and Z. Jin, "The Structure, Performance and Recovery Time of a 10 kV Resistive Type Superconducting Fault Current Limiter," in IEEE Transactions on Applied Superconductivity, vol. 23, no. 3, pp. 5601304-5601304, June 2013, Art no. 5601304. doi: 10.1109/TASC.2012.2231899

[13] S. Kar, "Temperature and Resistance Profile on HTS Tape During Fault and Recovery in Modular SFCL unit," in IEEE Transactions on Applied Superconductivity. Early access. 2020. doi: 10.1109/TASC.2020.2978421