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PS1 - Decentralization of T&D Equipment

Results of two-year operation of 220 kV pilot high temperature superconducting fault current limiter (SFCL) in Moscow power grid

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SUMMARY

High temperature superconducting fault current limiters (SFCL) is a modern solution designed for managing increasing fault current levels in power grids. In 2019 pilot SFCL was integrated into a Moscow power grid. This device is first SFCL in Russian grid and currently most powerful in the world.
During operation a number of faults were registered which demonstrated the functionality of the device. Operation of a fault current limiting element of SFCL and auxiliary system (cryogenic cooling system) were analyzed and design characteristics were confirmed.
Also in the course of operation a number of faults in the SFCL subsystems were identified and eliminated. The SFCL remained operational during elimination of these faults and didn't stop energy transmission. Additionally, measures were taken to exclude recurrence of the encountered problems.
The operation of the SFCL confirmed design characteristics including efficacy of short circuit current limiting and reliability of the equipment.

KEYWORDS

Superconductivity – Current Limiter – SFCL - HTS – Operation – Cryogenics

Introduction

Ensuring reliability of power supply to consumers while reducing environmental impact of power facilities is a complex engineering challenge. To address this challenge decentralization of power sources, using, in particular, renewable energy or increasing a number of internal connections in a grid is widely introduced.

However, progress in this direction is often limited by capabilities of existing network equipment. New energy sources or new grid connections increase a level of short-circuit currents in the adjacent network, which can exceed the maximum rating of equipment - breaking capacity of circuit breakers, thermal and dynamic current withstand qualities of disconnectors, cables and transformers.

Traditional measures to limit short-circuit currents include: (1) network division (splitting), (2) installation of current-limiting reactors, (3) large scale modernization of switchgear at substations and even in the whole grid regions. The first solution significantly reduces power grid transmission capacity, reduces number of independent power sources for consumers, and complicates network management, ultimately reducing grid reliability. The second solution, just like grid splitting, complicates transmission of electricity, reduces control over a network and stability of a power system, since there is always a significant reactance in a circuit. The third solution usually requires significant investments, and in some cases is impossible for technical reasons (for example, lack of available space for modernization).

Recent advances in manufacturing process of high-temperature superconductors and the development of various products using superconductivity led to a new solution – high temperature superconducting fault current limiters (SFCL). This solution is the basis of an alternative approach that allows to reduce a level of short-circuit currents without the restrictions imposed by traditional measures, such as network division (grid splitting), installation of current-limiting reactors and large-scale modernization of switchgear. This option opens a possibility to setup a reliable low-loss power supply without complicating network control or increasing cost of upgrades, improving energy usage efficiency and reducing environmental impact.

In Russia, the first city to integrate such a device into its power grid was Moscow. Moscow power grid develops rapidly and, as a result, a significant increase in short circuit current levels is taking place. This is mainly due to: a) increasing electricity consumption, b) short distances from power sources to consumers, and c) intense replacement of overhead lines with underground cables.

To address increasing fault current levels in city grid Moscow government-initiated introduction of SFCL technology/ The first, pilot, SFCL was installed at the 220/20 kV Mnevniki substation (Moscow). Trial operation was completed in 2019, the SFCL was integrated into a 220 kV electrical network and has been in continuous industrial operation ever since [1]. The project received status of a National.

At the moment, the design of a next generation SFCL for Moscow and St. Petersburg power grids is underway. These devices will have a new specification and a type of connection to power grid, different from the pilot SFCL at the 220/20 kV substation "Mnevniki". New SFCLs are to be installed without current-limiting reactors. These projects are part of a general program for the region development, which include installation of 8 SFCLs in Moscow and 7 SFCLs in St. Petersburg.

The article is dedicated to the analysis of the operation of the SFCL in the power grid in a period from December 2019 to December 2021.

Brief description of the pilot project

The design of the SFCL device is extensively depicted in articles [2], [3]. A distinctive feature of SFCL is a non-linear electrical resistance due to the nature of the superconductor, which is the main element of the limiter. The superconductor is placed inside three cylindrical vessels called Phases (Fig. 1) – one per electric phase. Inside these vessels a specific cryogenic environment, required for proper operation of superconductor is provided via auxiliary system, generally called cryogenic cooling system (CCS).

SFCL is designed for voltage class 220 kV. The picture of the device at substation "Mnevniki" is given in Fig. 1. This location was chosen because of high level of short circuit currents in this part of the city power grid – western part of Moscow, not far from the «City» business center. In the past, the Mnevniki substation used a conventional air-core reactor as a current-limiting solution, but now the

SFCL is installed in parallel with the reactor (Fig. 2), which allows direct comparison of traditional and new approaches for fault current management.

Figure 1 - SFCL 220 kV, "Mnevniki" substation

Current limiting is achieved utilizing to a unique property of the superconductor material: when current exceeds a certain value, it almost instantly (less than in 4 milliseconds) transits from a superconducting state with zero resistance to a normal state with a resistance of about 40 Ohm. This ability makes it possible to operate grid without losses during nominal operation, and to limit a current in an event of a short circuit.

On fig. 2 we can see a comparison of a current in a power grid during a short circuit - with and without a SFCL. This current-limiting data was obtained during tests of the phases of the SFCL 220 kV at the KERI test center in South Korea.

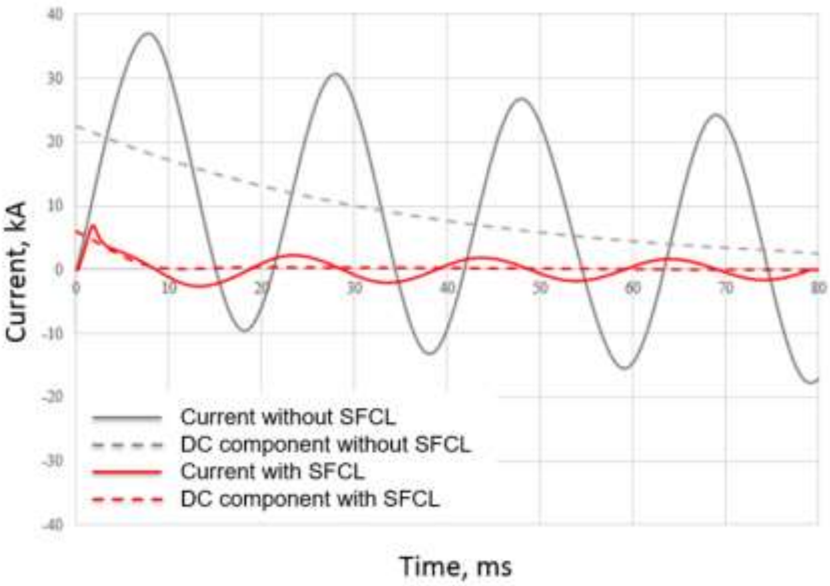

Figure 2 – Current limiting profile of SFCL

Operating experience

From 2019 to the present, the 220 kV SFCL has been operated in continuous mode at the 220/20 kV substation, and constantly being under load, transmitting current to the consumer. Totally, more than 240 million kWh electricity were transferred, providing to more than 0.5 million customers.

To evaluate the effectiveness of the device during operation, two aspects should be considered:

- performance of SFCL key function – fault current limitation;
- operation of auxiliary systems (cryogenic cooling system and other subsystems).

Fault current limitation

During operation, there were several situations that made it possible to demonstrate the main function of the device; during 2019-2021, several short circuits were observed in the network. Data on short circuits for the period of operation of the device are given in Table 1.

Figure 3 compares the city grid short circuit current (left) and the current during device production tests at the KERI test center (right). The behavior of the SFCL in both cases is absolutely identical - as the short circuit current increases, the SFCL first limits the current to 7 kA (peak value), and then reduces the current to about 2 kA (peak value). This confirms SFCL operates in grid exactly as it was designed and tested.

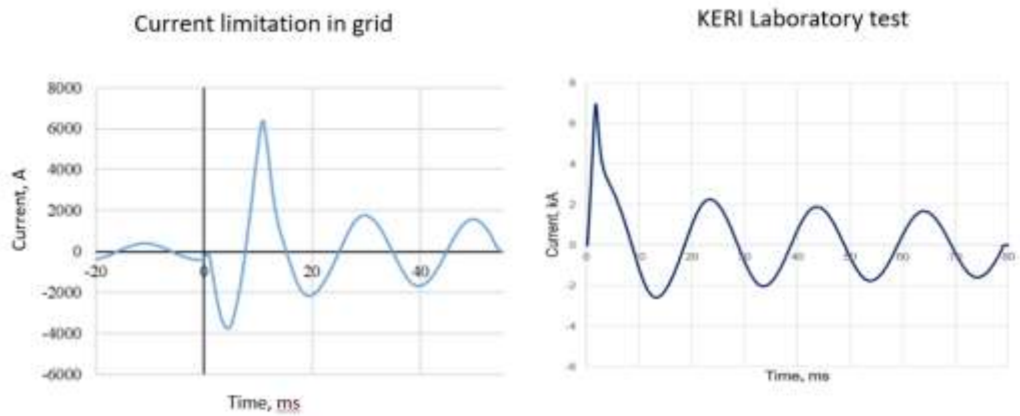

Figure 3 – Comparison of the real short-circuit current of the network (left) and the current during tests at the KERI test center (right)

Table 1 – Functioning of 220 kV SFCL in case of short circuits in the electrical network

Date	**Type of short circuit in relation to SFCL (far, near, internal)**	**The largest effective current value through the SCFL (instantaneous value)**	**Transition to a non-superconducting state - current limiting**	**Evaluation of the operation of Phases (superconductor)**	**Evaluation of the operation of the cryogenic cooling system (CCS)**	**Evaluation of the operation of relay protection systems**
2020-04-16	Far	4.5 кA (6.4 кA)	Yes	Correct: the current through the SFCL exceeded the current of the transition of the SFCL to the non-superconducting state (3.4 kA) – current limitation	Correct: all technological parameters (temperature, pressure, nitrogen level) were within the nominal limits after the recovery time of the SFCL (47 s): ΔT < 2K Δp < 0.1 bar ΔL < 0.01 m	Correct: Relay protection operation (overcurrent protection)
2020-07-14	Far	1.6 kA (2.2 kA)	No	Correct: the current through the SFCL is lower		Correct: Relay protection operation

				than the current of the transition of the HTSC to a non-superconducting state (3.4 kA) - the resistance of the SFCL does not exceed the nominal (0.1 Ohm)		(overcurrent protection)
2020-10-12	Far	1.6 kA (2.2 kA)	No			Correct: Relay protection operation (overcurrent protection)
2020-11-05	Far	2.1 kA (2.9 kA)	No			Correct: Relay protection operation (overcurrent protection)
2021-01-16	Far	1.5 kA (2.1 kA)	No			Correct: Relay protection operation (overcurrent protection)

Operation of auxiliary systems (cryogenic cooling system)

Reliable operation of SFCL auxiliaries (cryogenic cooling system) is crucial for operation of the device as it provides electricity for customers continuously. During the operation of the pilot 220 kV SFCL, several faults in cryogenic cooling system were observed. The list of faults is given in table 2.

Most importantly despite these faults electrical supply was maintained (no disconnection of power line and customer power supply). During the faults and following repairs the SFCL remained fully operational, ensuring stable transmission of electricity (without power line shutdown), even during extended repair periods (in particular, during more than three months of cryogenic cooler repair). Most of the faults occurred in 2020 indicating these are mostly “growth pains”. All faults were successfully eliminated, and will not appear during further operation.

Table 2 – Faults in the cryogenic system of the 220 kV SFCL for the entire period of operation

No	**Date of occurrence**	**Description**	**Cable line disconnection**	**Counter-measures**
1	2019-09-06	Shutdown of cryogenic system due to a voltage drop at substation caused by an external short circuit	No	Control system software update (introduction of auto-restart cryogenic cooling system after power loss)
2	2020-05-06	Cryogenic pipeline damage in pumping system (phase 2), LN2 leak into vacuum chamber	No	Reinforced pipeline designed and installed
3	2020-06-16	Cryocooler power supply (electrical contact plate) failure due to incorrect installation	No	Electrical contact plate replacement. Addiction of installation procedure details into SFCL installation instructions.

4	2020-06-19	Cryogenic coolant (LN2) loss due to cryogenic coolant control system malfunction during power outage	No	Control system software update
5	2020-07-07	Water chiller failure (overload) due to low level of coolant	No	Control system software update (auto-restart). Coolant level inspection included in SFCL maintenance instructions.
6	2020-07-17	Cryogenic pipeline damage in pumping system (phase 3), LN2 leak into vacuum chamber	No	Reinforced pipeline designed and installed
7	2020-09-28	Cryogenic cooler failure (main turbine) due to manufacturers error	No	Replacement of main turbine. During turbine delivery and replacements (3 months) SFCL successfully operated utilizing remaining two 2 cryogenic coolers
8	2020-12-09	Cryogenic pipeline damage in pumping system (phase 1), LN2 leak into vacuum chamber	No	Reinforced pipeline designed and installed
9	2021-07-28	Water chiller failure (condenser leak) due to manufacturers error	No	Condenser repair (leak eliminated)

Conclusions

During the two-year operation in 2019-2021, the SFCL confirmed its technical characteristics. In the event of short circuits in the power system of the city, the device limited the short circuit currents when the current was higher than the pickup current, and remained in a superconducting state when the current did not exceed the designed value. In the course of these emergencies, the auxiliaries – cryogenic cooling system as well as grid relay protection worked in the normal mode without faults.

The faults in SFCL and it’s auxiliaries that occurred during the operational period did not affect the functionality of the device - despite the malfunctions, the power line with SFCL provided continuous transmission of electricity and protection of the network in the event of short circuit currents.

Thus, the device has demonstrated its main purpose - the limitation of short-circuit currents, and has established itself as a reliable technical solution. The operation of the SFCL at the 220/20 kV substation Mnevniki continues; further operating experience and technical solutions applied at the newly designed SFCL facilities will be presented separately.

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