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First Russian 220 kV superconducting fault current limiter (SFCL) for application in city grid

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The superconducting fault current limiter (SFCL) for a nominal voltage of 220 kV and a rated current of 1200 A was developed by SuperOx company to be applied in high voltage substation in Moscow, Russia. The device is a three-phase dead-tank apparatus and is equipped with a closed-cycle cryocooling system. Liquid nitrogen serves simultaneously as a cooling and an insulating media. The device makes use of about 25 km of 12 mm wide high-performance 2G HTS wire with uniform properties along the length. High-voltage tests of the device were performed at Korea Electrotechnology Research Institute (KERI) in accordance with the IEEE C37.302-2015 test guide and Russian national standards for high voltage electrical equipment. The installation of the SFCL at substation in parallel with the existing air core reactors was completed in 2019. Since then, the device is in a daily operation. Over this period, SFCL has fully confirmed its design specifications including transmitting over 80 million kWh to customers and experiencing three fault current events.

High temperature superconductors, superconducting fault current limiter, cryogenic power equipment, electrical grid

I. INTRODUCTION

High level of fault currents is one of the most challenging issues for large power grids [1], which is especially difficult to deal with in large cities. This very costly problem actually gets worse with time due to consumption growth, introduction of new generation including renewables and broader use of cables instead of overhead lines. There are several traditional ways to limit fault current levels in grid:

- *Grid splitting*: disconnecting some of the connections in existing grid [2-4]. This measure is very effective to decrease fault currents and is inexpensive, since no new equipment is needed to split the grid. Grid splitting however increases losses, reduces reliability and grid throughput, hindering power supply for customers and control for grid operator [3]. It is generally referred to as a temporary solution of a problem.
- *Use higher rating of power equipment*. This measure drives the development of switchgears able to disconnect a line at higher currents. For example, typical level of large cities switchgears' ratings in 1990s was about 40 kA, rising to 63 kA in 2000s. In 2013, first substation with 80 kA gas insulated switchgears was commissioned in New Jersey, USA [5]. This path is costly and implies that grid is subject to very high current surges, because switchgears operation time is more than ~ 2 full cycles of AC current. In severe cases, it is impossible to make a switchgear upgrade due to technical restrictions, such as limited space at substation or unavailable switchgear ratings.
- *Use of inductive reactors*. This way is similar to grid splitting by its effect; it reduces power supply and grid control as the impedance of the reactor is permanently present in grid. It increases losses and causes undesirable DC component during fault events. This behavior can lead to saturation of current transformers and consequent problems of relay protection operation.

Neither of the approaches above can provide a long-term solution. The development of fault current limiters (FCL) addresses exactly this challenge – to develop an efficient device, which is able to limit high currents by some sort of smart creation of impedance during the fault, a device, which is free from drawbacks of conventional approaches.

There are many types of FCLs being actively developed today [6,7]. Recent advances in applied superconductivity enabled design of superconducting fault current limiters (SFCLs) [8,9]. Resistive SFCL is a non-linear resistance typically installed in series with power transmission line or between substation busbars (the preferable position is dependent on particular grid structure). At normal operating conditions, current through SFCL is lower than a certain switching current value (critical current of superconductor) and SFCL resistance is close to zero. In this mode, SFCL transmits electrical power almost without losses. In case of fault, current through SFCL surpasses the switching current value and superconducting element quenches. SFCL becomes resistive, providing active resistance to the grid and reducing fault current exactly when this action is required. After a fault clearance is provided by operation of conventional relay protection, SFCL returns to normal operation with low resistance by cooling of quenched superconductor assembly. The transition from low- to high-resistance occurs in less than few milliseconds and it is a unique quality of superconductor material. This quality enables SFCL to become an efficient solution for ultrafast limiting of fault currents in grid, while not affecting grid operation in its normal mode. Interconnecting of grid sections with SFCL results in high throughput grids with reliable power supply and low losses.

Moscow today is a city with 12.7 million inhabitants. Its power consumption grew rapidly by +59 % from 2000 to 2019. It is obvious that reliable electrical power supply is a pre-requisite for city development. The task of mitigation of fault currents in Moscow is emerging not only due to a rapid electricity consumption growth but also because of the short distance between generation and consumer, as many power stations are located inside the city, and massive substitution of high voltage overhead lines by low-impedance underground cables in 2010s.

To provide a comprehensive test of technology in city grid, Moscow-owned electric utility company UNECO decided to install one SFCL at its 220 kV-class substation with high fault current level of above 50 kA. The SFCL is installed in series with 220 kV cable line, which connects west and southwest parts of city grid (Fig.1). Three phase 3.0 Ohm air-core reactor (ACR) was present at substation before the SFCL project and is left connected to the line for the sake of redundancy. The SFCL has been put under daily current load in 2019.

This paper presents the details of SFCL construction, results of SFCL operation throughout the 2019-2020 period and outlines several future prospects of SFCL technology based on authors' view.

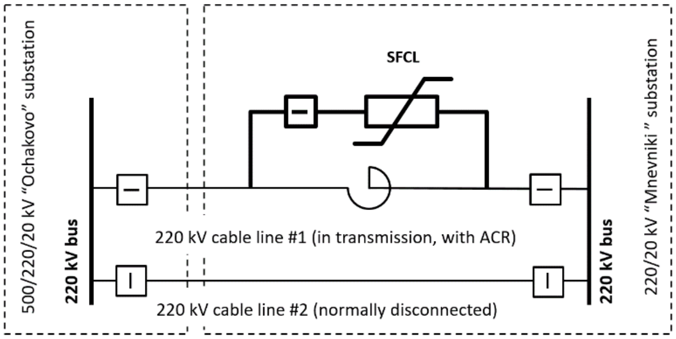

Fig. 1. 220 kV SFCL electrical installation scheme at "Mnevniki" high voltage substation in Moscow.

II. 220 KV SFCL PROJECT AT "MNEVNIKI" SUBSTATION

When this project was about to start, resistive high voltage SFCL devices were at initial stage of their development. AMSC/Siemens one phase of 115 kV device [10] and KEPCO one phase of 154 kV device are to be mentioned here as significant engineering milestones of the time [11].

The task of this project was to design, manufacture, test and install for permanent operation at substation three phases of 220 kV SFCL. In order to make this, full development cycle had to be organized, including but not limited to:

- design and production of second generation high temperature superconductor wire,
- design and production of superconductor assembly,
- design and acquisition of closed cycle cryogenic system,
- design of high voltage insulation,
- mechanical design,
- thermophysical design,
- high voltage and power tests of components,
- high voltage and power tests of SFCL phases,
- civil engineering and construction,
- Russian state expertise of the project,
- paperwork necessary for placing SFCL in grid and go live.

The project started in 2015 and was completed in three main stages: engineering stage was finished in 2016, procurement stage has been completed throughout 2016, 2017 and 2018, finally, construction stage was performed during 2018 and 2019 (Fig.2). The commissioning and final tests of SFCL were finished in September-December 2019 period.

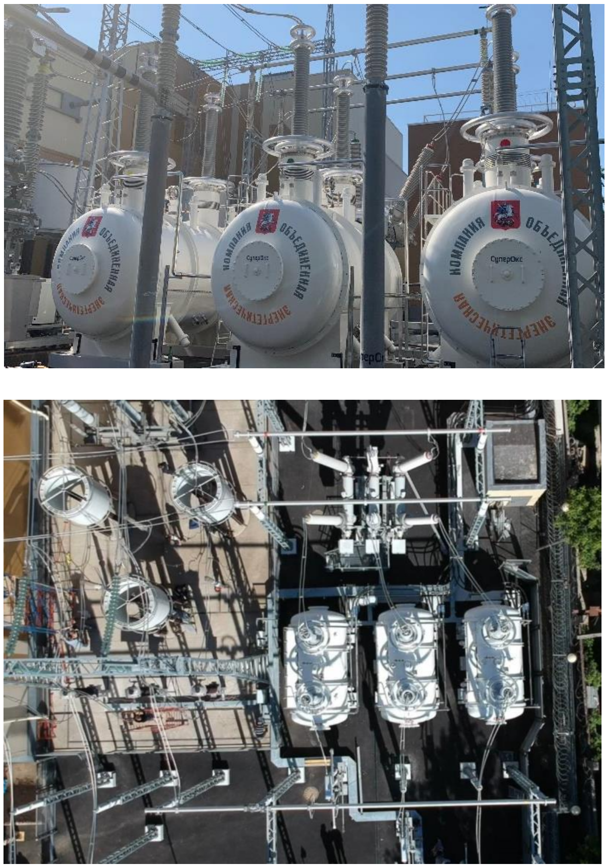

Fig. 2. Front (upper picture) and top view (bottom picture) of the 220 kV SFCL at the substation in Moscow.

TABLE I
220 KV SFCL SPECIFICATIONS

Property	Value
Nominal voltage	220 kV rms
Maximum operation voltage	252 kV rms
BIL test voltage	950 kV
AC withstand voltage	440 kV rms
Nominal frequency	50 Hz
Nominal current	1200 A rms
Switching current	3400 A peak
Resistance in superconducting state	< 0.1 Ohm
Resistance in fault current limiting state	> 40 Ohm
Switching time	< 2 ms
Type of placement	Outdoor
Climate requirements	-45 deg C … +40 deg C
Size of 1 Phase (LxWxH)	5500 x 2850 x 6500 mm
Weight of 1 Phase (dry / with nitrogen)	16/27 ton

III. 220 kV SFCL CONSTRUCTION

220 kV SFCL device consists of three outdoor single phase dead-tank apparatuses (further on referred to as ‘Phases’, Fig.2) and a cooling system, which is placed in a separate 7x14x10 m^3 building. Main specifications of the device are given in Table I.

Each SFCL Phase consists of a cryostat, high-voltage bushings and superconductor assembly (Fig.3). Superconductor assembly is comprised of a set of current-limiting modules combined with high voltage shields (corona rings). Corona rings help to distribute electrical field inside the device uniformly. Superconductor assembly utilizes second generation high temperature superconductor wire (2G HTS wire), serving as a switching resistor.

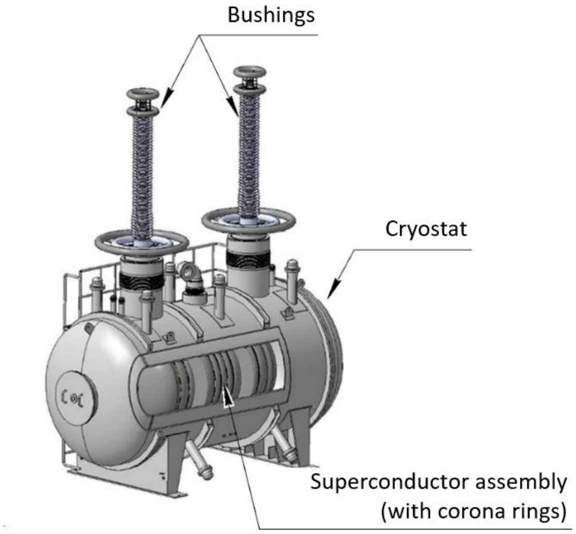

Fig.3. The scheme of 220 kV SFCL Phase.

SFCL performance is critically dependent upon 2G HTS wire quality. Before being used in the device, each wire piece was rigorously tested to comply with specifications listed in Table II. Uniform critical current and room temperature resistivity along HTS wire length were carefully measured to ensure that the material quality is sufficient for the task. Critical current deviation parameter (CCDP) was determined from I_c vs length dependences, which were measured by reel-to-reel TapeStar XL instrument (Theva GmbH). The procedure for CCDP determination is shown in Fig. 4a. Room temperature resistivity deviation parameter (RDP) was measured using a specially built reel-to-reel instrument and calculated as a difference between maximum and minimum values per sample length. The corresponding procedure for RDP determination is given in Fig.4b.

The critical current of superconducting modules measured at 77K and self field conditions was in 2.1-3.0 kA interval. After Ic measurements, each superconducting module was tested by short circuit current in high power laboratory as a part of internal quality control procedure [12] followed by a second I_c(77K, self field) test. Each module had to withstand at least 10 full power fault current tests before being accepted for application in the device. High voltage tests including dielectric breakdown threshold determination, nominal load current tests and critical current tests were routinely performed upon superconducting modules as well.

TABLE II
SPECIFICATIONS OF 2G HTS WIRE USED FOR 220 KV SFCL

Property	Value
2G HTS wire width	12 mm
2G HTS wire single piece length	60 m
Total length of 12 mm wire per Phase	~ 8 km
Total length of 12 mm wire per SFCL	~ 25 km
Stabilizer material	Silver/Copper
Specific resistivity at room temperature	0.21 Ohm/m
Resistivity deviation (RDP) per one piece	< 10 %
Minimal critical current (77 K, s.f.)	> 350 A
Critical current deviation (CCDP) per one piece	< 20 %
Phase resistance @ 77 K	< 0.1 Ohm
Phase resistance at room temperature	> 50 Ohm

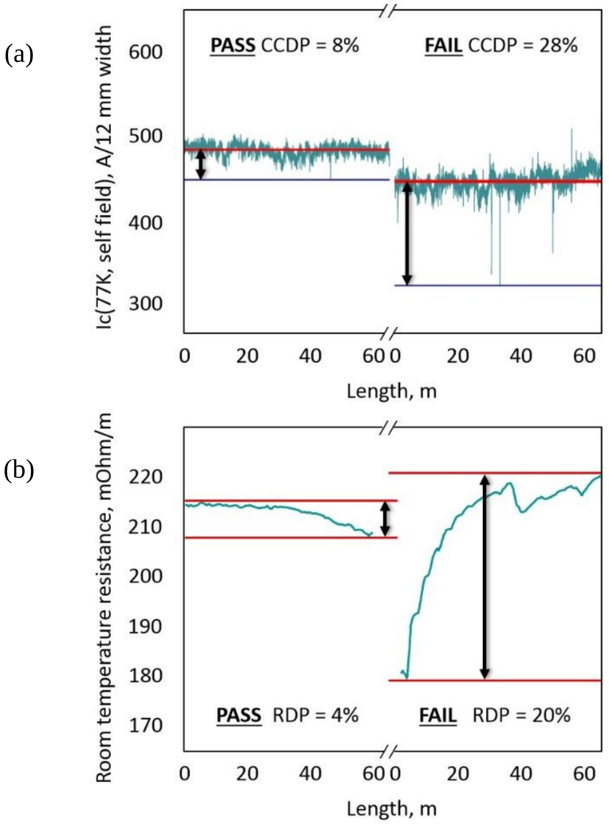

Fig. 4. (a) Critical current vs length for 2G HTS wire and determination of the critical current deviation parameter (CCDP). (b) Wire resistivity vs length for 2G HTS wire and determination of the room temperature resistivity deviation parameter (RDP).

Solid-state cryogenic bushings for the 220 kV SFCL were developed specifically for this project in collaboration with a company “Isolator” (Russia). Before being assembled into SFCL Phases, the bushings underwent a separate set of high voltage tests.

SFCL cryostats were double-walled vacuum-MLI-insulated vessels. The walls were made of stainless steel to withstand inner pressure. Each cryostat was leak-tested with helium with a pressure up to 15 bar. A special feature of these cryostats are two removable manholes from both sides enabling maintenance, connection and disconnection of superconductor assembly from bushings, and other operations. The diameter of manholes was limited to 0.5 m enabling an access inside cryostat, while keeping an engineering challenge reasonable.

Each SFCL Phase was equipped with its cooling sub-system. The cooling sub-system consists of pressure builder, Turbo-Brayton NeoKelvin cryocooler (rated cooling capacity 2 kW at 70K, built by Taiyo Nippon Sanso), circulation pump (Cryozone) and pipes (Nexans) for liquid nitrogen transport. Redundancy is provided by by-passes between separate Phases: even if one subsystem fails, SFCL remains fully operational.

IV. 220 kV SFCL TESTING AND MODELLING

Test program of 220 kV SFCL was based on IEEE C37.302-2015 “Guideline for testing of SFCLs rated above 1000 V AC” document. Among other tests, the program included high voltage tests, load current test, and fault current tests. Each SFCL Phase was tested separately. These tests were performed in KERI test center in Changwon, Korea (Fig.5).

Fig. 5 220 kV SFCL phase at the KERI test center.

Basic insulation level of SFCL was confirmed at 950 kV (Fig.6a), fulfilling the Russian standard for high-voltage equipment for a voltage class of 220 kV. To our knowledge, it’s a record level of test voltage, ever applied to any HTS SFCL. As well, each Phase was successfully tested for AC withstand voltage of 440 kV (RMS value) for 1 minute in dry conditions and 360 kV (RMS value) for 1 minute in wet conditions.

Tests of short-circuit currents of each SFCL phase proved that the device effectively limits the short-circuit current. For instance, with prospective short-circuit current level of 38 kA, inrush current through SFCL did not exceed 7 kA (Fig.6b). Electrical resistance of the SFCL during fault was over 40 Ohm after 50 ms of the fault time.

Grid operation requires quick calculation of short circuit currents for adjustment of a grid regime, grid structure, relay protection schemes, etc. SFCL is a novel device with a unique nonlinear resistive characteristic, which is not typical for any other grid component. Specific software and guidelines for calculation of electrical grid regimes were developed by SuperOx. These instruments enabled Moscow grid operator to predict SFCL behavior and calculate grid regimes and fault current levels within its routine set of operations.

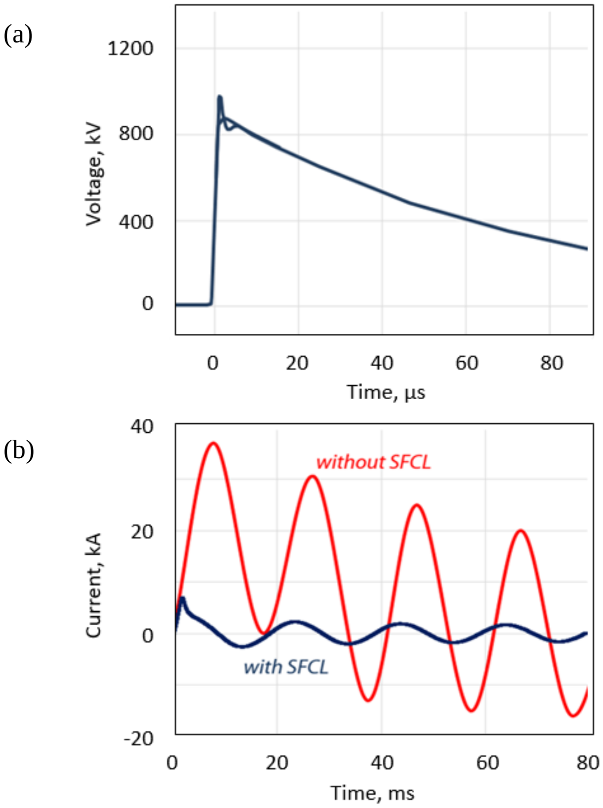

Fig. 6 (a) . 950 kV lightning impulse test of the 220 kV SFCL phase.
(b) Short circuit current test of the 220 kV SFCL phase.

V. IN-GRID SFCL OPERATION EXPERIENCE

At the moment of preparation of this publication, Moscow 220 kV SFCL had over 20 months of operation in subcooled state, more than a year under high voltage and 11 months under daily electrical load. During its operation, the device has repeatedly confirmed its design characteristics including variable electrical load transfer, redundant cooling system performance, and in-grid fault current limitation (see Table III). During grid faults technological values of cryogenic system (e.g., pressure and liquid nitrogen temperature and level) remained within nominal operation intervals. After fault clearance, SFCL successfully returned to normal operation.

In spite of several cryocooler stops during in-grid operation, SFCL remained fully functional due to redundant design of cooling system and continued power supply even during cryocooler maintenance. By now, the device has transmitted over 80 million kW*h, daily providing power to roughly 500 thousands of consumers.

The long-term operation experience allowed to determine existing engineering bottlenecks and improve them. It is expected that future cooling systems will be even more redundant and fail-safe.

TABLE III

IN GRID FAULT CURRENT EVENTS DURING 220 KV SFCL OPERATION

Date	Fault type	Switching (transition to non-superconducting state)	Cooling system operation	Relay protection operation
2020-04-16	single phase	Yes	Nominal: $\Delta T < 2$ K $\Delta p < 0.1$ bar $\Delta L < 0.01$ m	correct
2020-07-14	two phase	No*		correct
2020-10-12	three phase	No*		correct

* - fault current was less than a switching current value (3400 A peak)

VI. PERSPECTIVES OF SFCL TECHNOLOGY

Moscow 220 kV SFCL is a first device of its kind with positive operation experience in a real grid. Further potential areas of application can be indicated. Apart from demonstrated application of this technology in megacities, protection of 100s MW-class power plant generators and continuous production plants is of a great practical importance and economical value. We present below some results of our analysis of these applications. The scope of this paper allows to present only a short summary, while more detailed results will be published elsewhere.

First application concerns power plant generator protection. We have performed transient regime simulations of generator stability with and without high voltage SFCL using data for our 220 kV device. Fig.7 provides results of a calculation of nominal generator power (red line) and fault generator power (blue line) vs. power angle in same conditions (same generator, same load, same grid regime, etc.) with and without SFCL. According to this study, a generator with SFCL sustains its stability as indicated by comparison of acceleration and deceleration areas. Our conclusion on the positive effect of SFCL on the generator stability is in good correspondence with observations made by several other groups earlier [15-17]. The technology can be very useful in grids with high reactive loads, long distance lines and/or direct current sources, which are known to reduce generator stability.

Another promising application is a protection of continuity of production at oil refineries or chemical plants. Remote faults outside of plants' grid cause drops of the voltage level at busbars of sensitive plant equipment (pumps etc.), since a power tends to flow to the faulted section. Voltage decreases rapidly during a fault and at the moment of circuit breaker operation (which happens after 50 ms after the fault detection) busbar voltage could be already well below 70% of the nominal value. Such low voltage often leads to plant cycle malfunction, product loss or stop of production with massive costs for repairs and production restart. SFCL's ultrafast operation helps to keep voltage at production plant grid stable. Fig.8 depicts results of voltage drop simulation for oil refinery and chemical plant cluster in central Russia. The application of SFCL enables elimination of severe voltage sags at five high voltage substations ensuring reliable power supply to oil processing and refinery complexes.

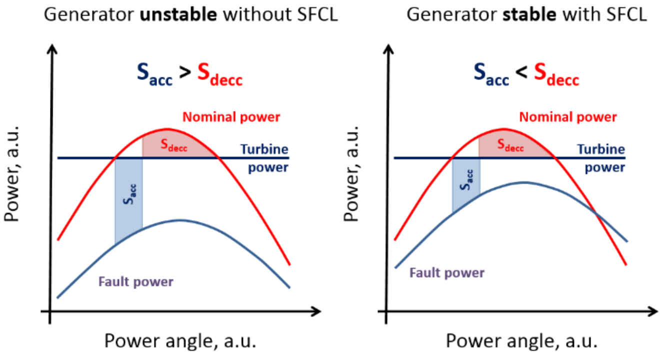

Fig.7. SFCL effect on generator stability (simulations results using data for 220 kV SFCL built in this project).

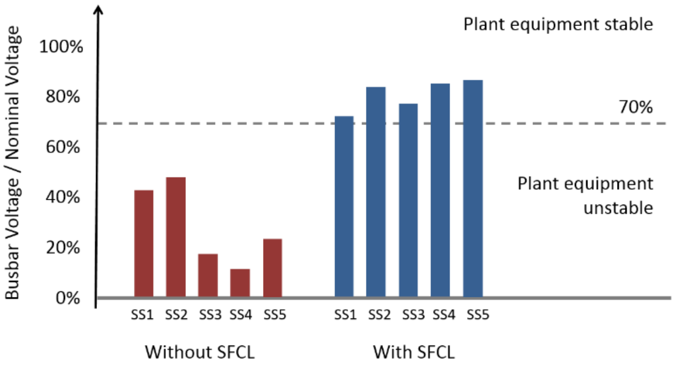

Fig.8. SFCL effect on stability of voltage (50 ms after the onset of fault current) at busbars of five high voltage substations (denoted as SS1…SS5) during remote faults. The minimum voltage criterion for plants' equipment stability is 70%. Simulations were made using data for 220 kV SFCL built in this project.

Following its successful pilot project, UNECO grid company is planning to continue developing protection of Moscow 220 kV grid with the SFCL technology. Recently the company placed the order for two additional 220 kV SFCLs. These devices are planned for installation in series with two cable lines in eastern part of Moscow (Fig.9). The engineering stage is scheduled to be complete in 2021, while construction is expected to take another year.

Specific requirements for this new installation are very challenging:

- SFCLs are to be installed in two parallel cable lines;
- SFCL is to be installed without parallel ACRs;
- SFCLs must have high fault current withstand stability: up to 6 seconds at remote fault and up to 1 second at SFCL bushing fault;
- SFCLs must have full recovery-under-load capability;
- Novel SFCL resistance-sensing relay protection system is to be developed in the project.

This new 220 kV SFCL project is aimed to increase capacity of highly loaded urban network in the southeast region of Moscow city. Further plan foresees installation of up to six 220 kV SFCLs in Moscow.

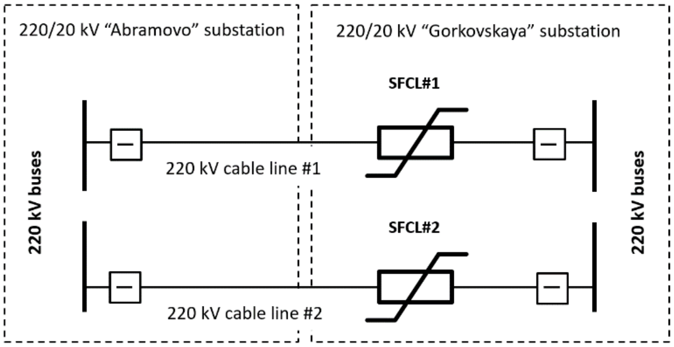

Fig.9. Electrical scheme for two new 220 kV SFCLs for Moscow grid.

VII. CONCLUSIONS

SuperOx company has developed 220 kV SFCL for grid application. The three phase high voltage device was built and extensively tested following recommendation of the IEEE C37.302-2015 test guide. SFCL was installed at the 220/20 kV "Mnevniki" substation in Moscow in parallel with the existing air core reactor and went live in 2019. Months of grid operation fully confirmed SFCL design specifications, including in-grid fault current experience. Further development of high voltage SFCL technology should find its way for efficient protection of megacities, large generators and continuous operation plants.

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