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

Sergey Samoilenkov and SuperOx SFCL Team
Talk Outline

1. Introduction
2. Motivation to use SFCL in Moscow electrical grid
3. One year operation of first 220 kV SFCL at substation
4. Looking further ahead
5. Conclusions
1. Introduction

2. Motivation to use SFCL in Moscow electrical grid

3. One year operation of first 220 kV SFCL at substation

4. Looking further ahead

5. Conclusions
SFCL technology

**Operation principle**

Current: **nominal (≈ 1k A)** → SFCL: **no resistance**

Current: **fault (up to 60+ kA)** → SFCL: **20-50 Ohm**

**Positioning SFCL in electrical grid**

- **Bus-tie SFCL**
- **SFCL in line with cable**

---

*Based on KERI tests of SuperOx SFCL*
SFCL technology enables:

- Increased grid capacity
- Reduced number of sectioning points
- Reduced damage from fault currents
- Reduced cost of grid equipment
- Extended lifetime of grid equipment
- Improved fire safety
- Reduced losses
- Improved quality of power supply
Electrical grid of megapolices

Consumption

Value of Lost Load

Fault currents

SAIDI/SAIFI/Losses
Electrical grid of megapolices – fault currents grow with grid

Consumption

Value of Lost Load

Fault currents

SAIDI/SAIFI/Losses
Electrical grid of megapolices – mitigating FCs via sectioning

Consumption

Value of Lost Load

Fault currents

SAIDI/SAIFI/Losses

Grid sectioning affects the reliability of supply
Consequences of sectioning the grid

Bus bar sectioned:
- power flows in opposite directions

Cables lines sectioned:
- transmission is impossible
Growth of fault currents presents a big and costly problem for large grids.

Fortunately, SFCL can often help.

It’s an opportunity for HTS to penetrate electric power market.
Electrical grid of megapolices (+SFCL)
Talk Outline

1. Introduction
2. Motivation to use SFCL in Moscow electrical grid
3. One year operation of first 220 kV SFCL at substation
4. Looking further ahead
5. Conclusions
Moscow electrical grid is large and grows rapidly
Moscow electrical grid is large and grows rapidly

<table>
<thead>
<tr>
<th>Electrical grid parameters</th>
<th>Russia</th>
<th>Moscow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Installed generation capacity</td>
<td>246 GW</td>
<td>17 GW</td>
</tr>
<tr>
<td>Electricity consumption</td>
<td>1059 TWh / year</td>
<td>108 TWh / year</td>
</tr>
<tr>
<td>Consumption growth rate</td>
<td>+23% / 20 years</td>
<td>+ 59% / 20 years</td>
</tr>
</tbody>
</table>
Moscow electrical grid

Rapid growth of consumption
Generation located inside the city
Short distance transmission
Cables instead of overhead lines

Growth of fault currents
Mitigation of fault currents in the grid

Sectioning the grid  →  Grid redundancy suffers
                    More complicated to operate

Install air core reactors  →  Losses
                        More impedance needed

Install superconducting fault current limiters
Talk Outline

1. Introduction
2. Motivation to use SFCL in Moscow electrical grid
3. One year operation of first 220 kV SFCL at substation
4. Looking further ahead
5. Conclusions
A pilot project – 220 kV SFCL for Mnevnik substation (UNECO)

Installation of 40 Ohm SFCL in parallel to existing 3.0 Ohm ACR

Invited presentation Wk2Lor3E-01 given at the virtual ASC 2020, October 29, 2020.
A pilot project – 220 kV SFCL for Mnevniks substation (UNECO)
Timeline of the 220 kV SFCL project

- Project (first phase)
- State expertise
- Project (second phase)
- Start to build equipment
- Start of civil construction
- Start to install equipment
- Commissioning & tests
- Fully operational
## Specifications of 220 kV SFCL

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>220 kV rms</td>
</tr>
<tr>
<td>Maximum operation voltage</td>
<td>252 kV rms</td>
</tr>
<tr>
<td>BIL test voltage</td>
<td>950 kV</td>
</tr>
<tr>
<td>AC withstand voltage</td>
<td>440 kV rms</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Nominal current</td>
<td>1200 A rms</td>
</tr>
<tr>
<td>Critical current</td>
<td>3400 A peak</td>
</tr>
<tr>
<td>Nominal operational resistance</td>
<td>&lt; 0.01 Ohm</td>
</tr>
<tr>
<td>Fault current limiting resistance</td>
<td>&gt; 40 Ohm</td>
</tr>
<tr>
<td>Transition time</td>
<td>&lt; 2 ms</td>
</tr>
<tr>
<td>Type of placement</td>
<td>Open</td>
</tr>
<tr>
<td>Climate requirements</td>
<td>-45 deg C … +40 deg C</td>
</tr>
<tr>
<td>Size of 1 phase (LxWxH)</td>
<td>5500 x 2850 x 6500 mm</td>
</tr>
<tr>
<td>Weight of 1 phase (dry / with nitrogen)</td>
<td>16/27 ton</td>
</tr>
</tbody>
</table>
Full development cycle – from HTS wire to power system

- Superconductor wire development and production
- High current conductor design and production
- Superconductor module and assembly engineering and production
- Corona rings system HV engineering and production
- Solid state bushings engineering and production
- Closed cycle cryogenic system design and production
- Assembly of SFCL phases, logistics to test sites
- High voltage and power tests
- Logistics of equipment to substation
- Civil engineering work at substation
- Electrical, magnetic, thermophysical, mechanical modelling
- State expertise (price and technical inspection)
- Regulatory paperwork (relay protection, technical regulations, etc.)
Component engineering

Solid state cryogenic bushings (950 kV BIL tested)

Cryostat with two manholes (15 bar tested)

HV coordination (1 min @ 440 kV rms tested)

Superconductor assembly (HV and Power tested)

Composite mechanical support (HV and load tested)
HTS part of SFCL phase

2G HTS wire width: 12.0 mm
2G HTS wire stabilization: Ag/Cu (few micrometers)
Min wire Ic (77K, s.f.): ~ 500 A
Length of 2G HTS wire per phase: ~ 10 km
Resistance @ 77K < 0.01 Ohm
Resistance @ RT ~ 50 Ohm
Component testing

Each component of 220 kV SFCL was rigorously tested in leading world labs
Engineering was refined until all the components passed strict technical requirements
System testing

- Three phases of 220 kV SFCL were tested after IEEE C37.302-2015 guide
- Test program developed jointly by SuperOx and UNECO
- A number of successful tests completed:
  - Acceptance tests of each phase of the device in KERI (Korea)
  - Operational tests at substation (HV, EMI, cooling system, automation)
  - Real time digital simulation (RTDS) tests of relay protection systems
HV and power tests of 220 kV SFCL

Power record of current limiting:

**2000 MW → 300 MW**

<table>
<thead>
<tr>
<th>Name of the test</th>
<th>Value confirmed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lightning impulse</td>
<td>950 kV, 1.5/50 us</td>
</tr>
<tr>
<td>Power frequency overvoltage withstand</td>
<td>440 kV, 1 min</td>
</tr>
<tr>
<td>Partial discharge</td>
<td>Less than 25 pC</td>
</tr>
<tr>
<td>Rated current</td>
<td>1200 A, 1 h</td>
</tr>
<tr>
<td>Short-term overcurrent</td>
<td>2000 A, 400 ms</td>
</tr>
<tr>
<td>Short-circuit current</td>
<td>38 kA → 6.8 kA</td>
</tr>
</tbody>
</table>

220 kV SFCL phase at the test site in KERI (Korea)
HV and power tests of 220 kV SFCL in KERI

950 kV lightning impulse test

High power test

without SFCL

with SFCL
Cryogenic system design

Each SFCL phase is equipped with its cooling sub-system. By-passes between phases provide redundancy to the whole system.
Installation site planning

Closed cycle cryogenic system (indoor)

SFCL Phases (outdoor)
Mathematical model of SFCL for relay protection coordination

System Operator regulation rules have been developed for operation of SFCL in grid

Power grid with SFCL is modelled

SFCL resistance vs time is calculated with a verified mathematical model

Grid operation determined:
- Switchgear capacity verification
- Relay protection setup
- Real time digital simulation
Regulatory paperwork made – to enable commercialization

- High voltage and power SFCL test program based on IEEE C37.302-2015 guide
- SFCL model user manual for relay protection coordination calculations
- Methodology for calculating compatibility of switchgear in the grid with SFCL
- Test program for relay protection devices for RTDS test bench for grids with SFCL
- Methodology for calculating relay protection devices in grids with SFCL
- Instruction manual for substation duty personnel in relation to SFCL
- SFCL user manual
- Program for taking SFCL in grid operation
- General Technical requirements for 220 and 110 kV SFCL at substation
- Draft of national standard for high voltage SFCL
Results of SFCL operation

- SFCL at substation is daily under load since December 2019
- Several cryogenic cooler stops observed – without interrupting power flow through SFCL
- Total electricity transferred by October 2020: 80 million kWh
- SFCL successfully limits faults and continues to operate normally after fault events

<table>
<thead>
<tr>
<th>Date</th>
<th>Fault type</th>
<th>Current limitation</th>
<th>Cooling system operation</th>
<th>Relay protection operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>2020-04-16</td>
<td>single phase</td>
<td>Yes</td>
<td>All nominal (T &lt; 2) K, no (p) and (L) variations</td>
<td>correct</td>
</tr>
<tr>
<td>2020-07-14</td>
<td>two phase</td>
<td>No*</td>
<td></td>
<td>correct</td>
</tr>
<tr>
<td>2020-10-12</td>
<td>three phase</td>
<td>No*</td>
<td></td>
<td>correct</td>
</tr>
</tbody>
</table>

* - fault current was less than switching current (3400 A)
Talk Outline

1. Introduction
2. Motivation to use SFCL in Moscow electrical grid
3. One year operation of first 220 kV SFCL at substation
4. Looking further ahead
5. Conclusions
Opportunities for protection of production plants

5 SFCLs in industrial region – protection of refineries / chemical plants

- Less voltage drop
- No downtime
- Continuous production

SFCL keeps voltage stable at production plant during faults, ensuring no downtime

200-500 MW Consumers

Allowable voltage drop (70% nominal)
Opportunities for protection of generators

**SFCL installed in-line with generator significantly increases generator stability in case of remote faults**

- Transient regime studies of generator stability with and without SFCL
- ETAP-analog software
- Carried out by Russian power sector project institute

**Diagram:**
- Without SFCL
- With SFCL

---

P1 - nominal power
P2 - fault power
Pf - turbine power
$Sy$ - acceleration surface
$S_T$ - deceleration surface
SuperOx is about to start work on next two 220 kV SFCLs

220/20 kV electrical substation
Commissioned in 2014
300 MW transformer capacity
**SuperOx is about to start work on next two 220 kV SFCLs**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value (preliminary)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal voltage</td>
<td>220 kV (Line, RMS)</td>
</tr>
<tr>
<td>Maximum operation voltage</td>
<td>252 kV (Line, RMS)</td>
</tr>
<tr>
<td>BIL test voltage</td>
<td>950 kV Peak</td>
</tr>
<tr>
<td>AC withstand voltage</td>
<td>440 kV RMS</td>
</tr>
<tr>
<td>Nominal frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Nominal current</td>
<td>1200 A RMS</td>
</tr>
<tr>
<td>Critical current</td>
<td>TBD (~ 3000 A peak)</td>
</tr>
<tr>
<td>Nominal operational resistance</td>
<td>&lt; 0,1 Ohm</td>
</tr>
<tr>
<td>Fault current limiting resistance</td>
<td>&gt; 40 Ohm</td>
</tr>
<tr>
<td>Transition time</td>
<td>&lt; 4 ms</td>
</tr>
<tr>
<td>Type of placement</td>
<td>Outdoor</td>
</tr>
<tr>
<td>Climate requirements</td>
<td>-45 deg C … +40 deg C</td>
</tr>
</tbody>
</table>
SuperOx is about to start work on next two 220 kV SFCLs

- SFCL installation without ACRs
- Two SFCLs in two parallel cable lines (~12 km)
- High ability to withstand fault currents:
  - Up to 6 seconds at remote fault
  - Up to 1 second at SFCL bushing fault
- Recovery-under-load capability necessary (no SFCL disconnection during remote fault)
- SFCL resistance sensing relay protection integrated with adjacent grid
Talk Outline

1. Introduction
2. Motivation to use SFCL in Russian electrical grid
3. One year operation of first 220 kV SFCL at substation in Moscow
4. Looking further ahead
5. Conclusions
Conclusions

- SuperOx developed a full scale technology of high voltage SFCL using 2G HTS wire
- 220 kV SFCL was built and extensively tested after IEEE C37.302-2015 guide
- The closed cycle turbo Brayton cryogenic system was developed and used in SFCL project
- Solid-insulation current leads / bushings were developed and used in SFCL project
- First 220 kV SFCL at 220/20 kV substation in Moscow was energized in December 2019
- Engineering stage for 2 SFCLs is about to start with projected delivery of devices in 2022
Acknowledgement to the SuperOx SFCL Team
Thank you!

www.superox.ru/en