IEEE CSC & ESAS SUPERCONDUCTIVITY NEWS FORUM (global edition), No. 49, March 2021.
Invited presentation Wk2LOr3E-01 given at the virtual ASC 2020, October 29, 2020.

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

Sergey Samoilenkov and SuperOx SFCL Team

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Talk Outline

SuperOx

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

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SFCL technology

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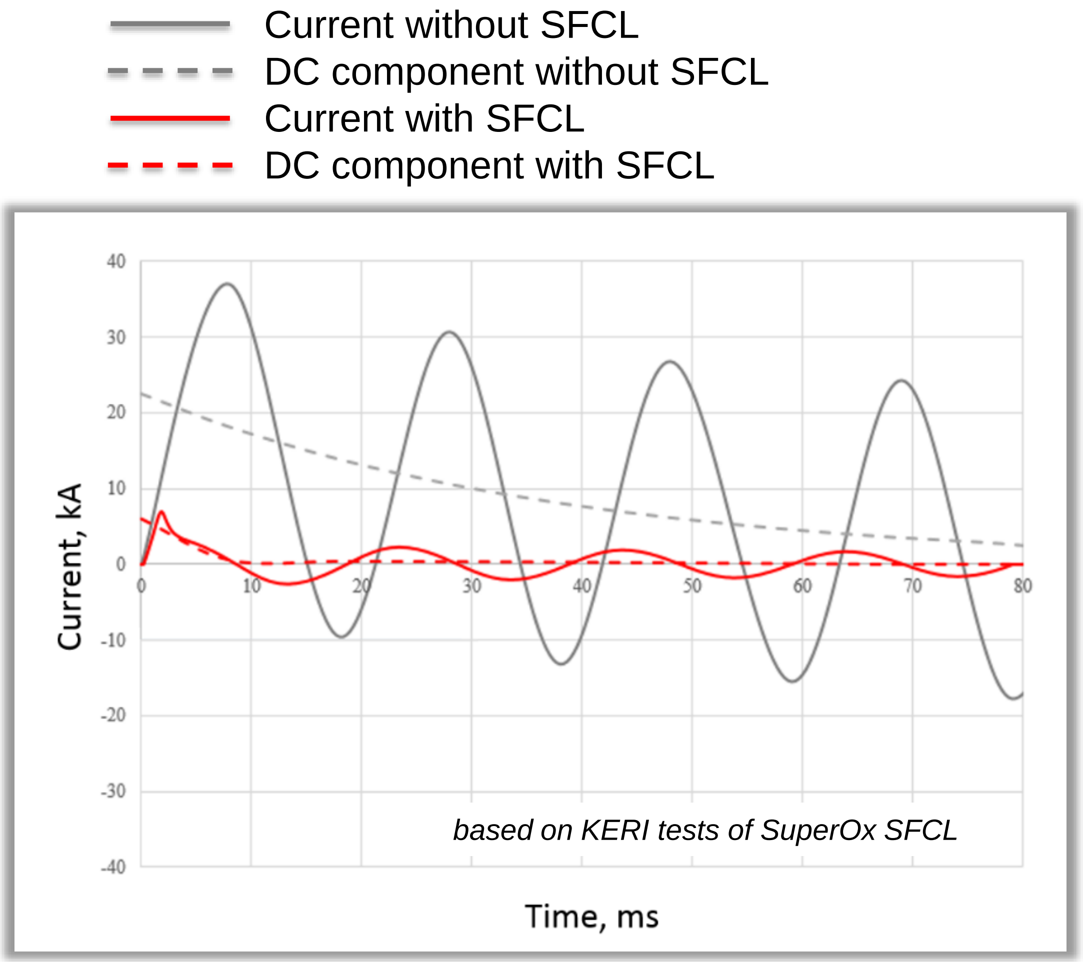
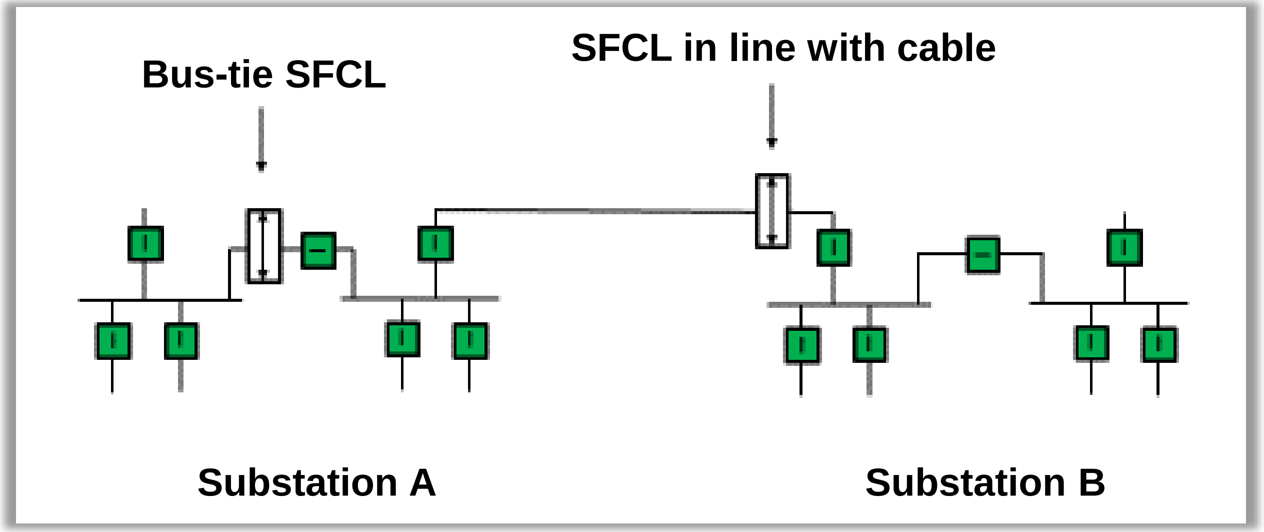
Operation principle

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

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



Positioning SFCL in electrical grid



SFCL technology

SuperOx

- **City grid protection**
  - **Fault current reduction**
  - **Protection of grid equipment (switchgears etc)**
- **Production plant protection**
  - **Voltage drop reduction**
  - **No downtime of production equipment**

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

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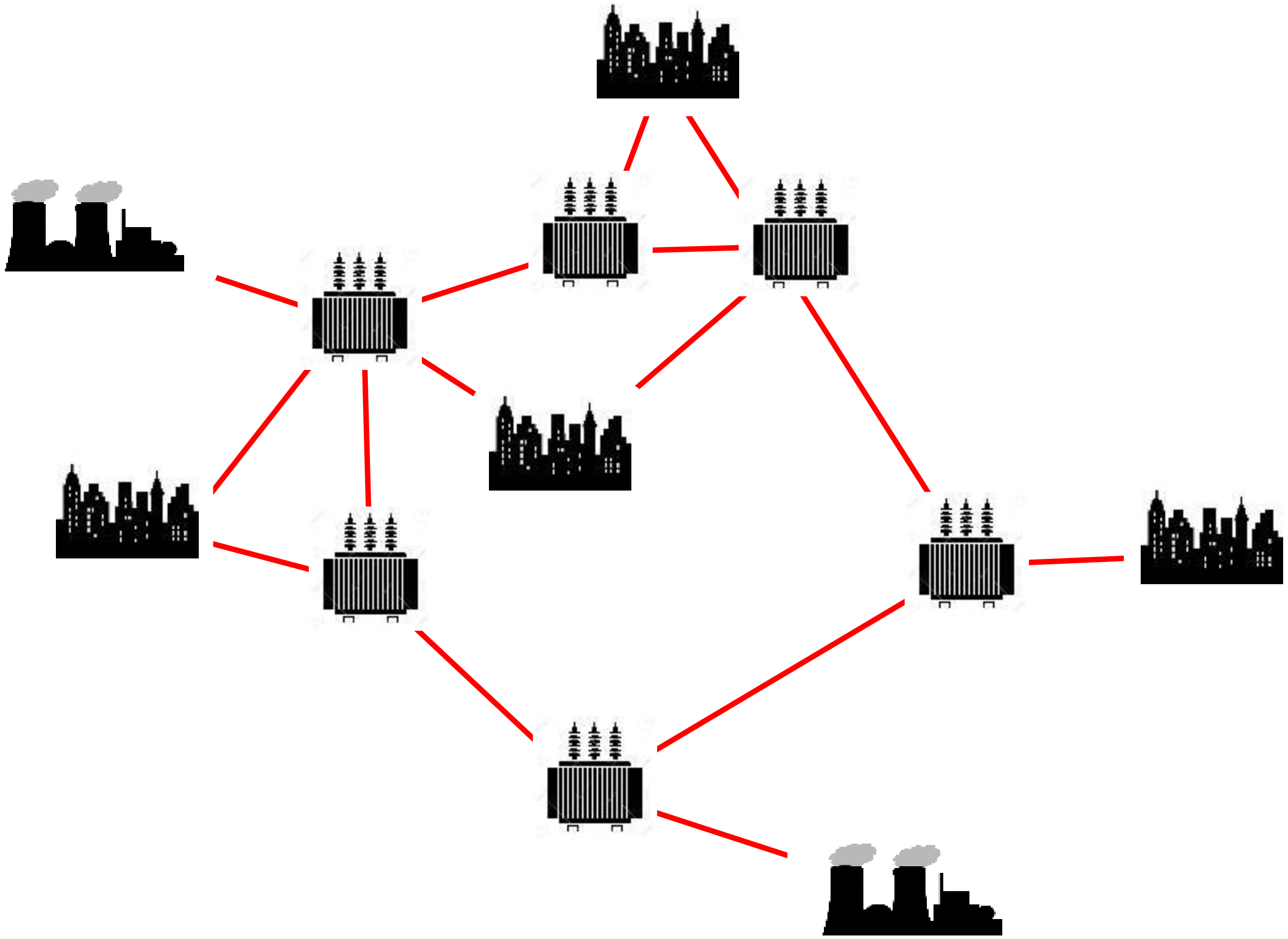
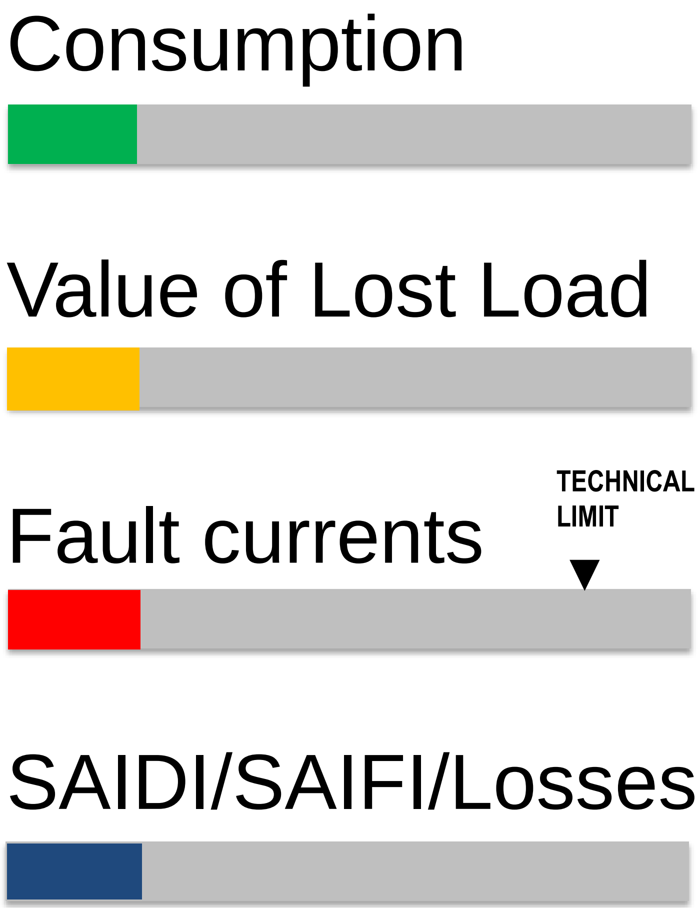
Electrical grid of megapolices





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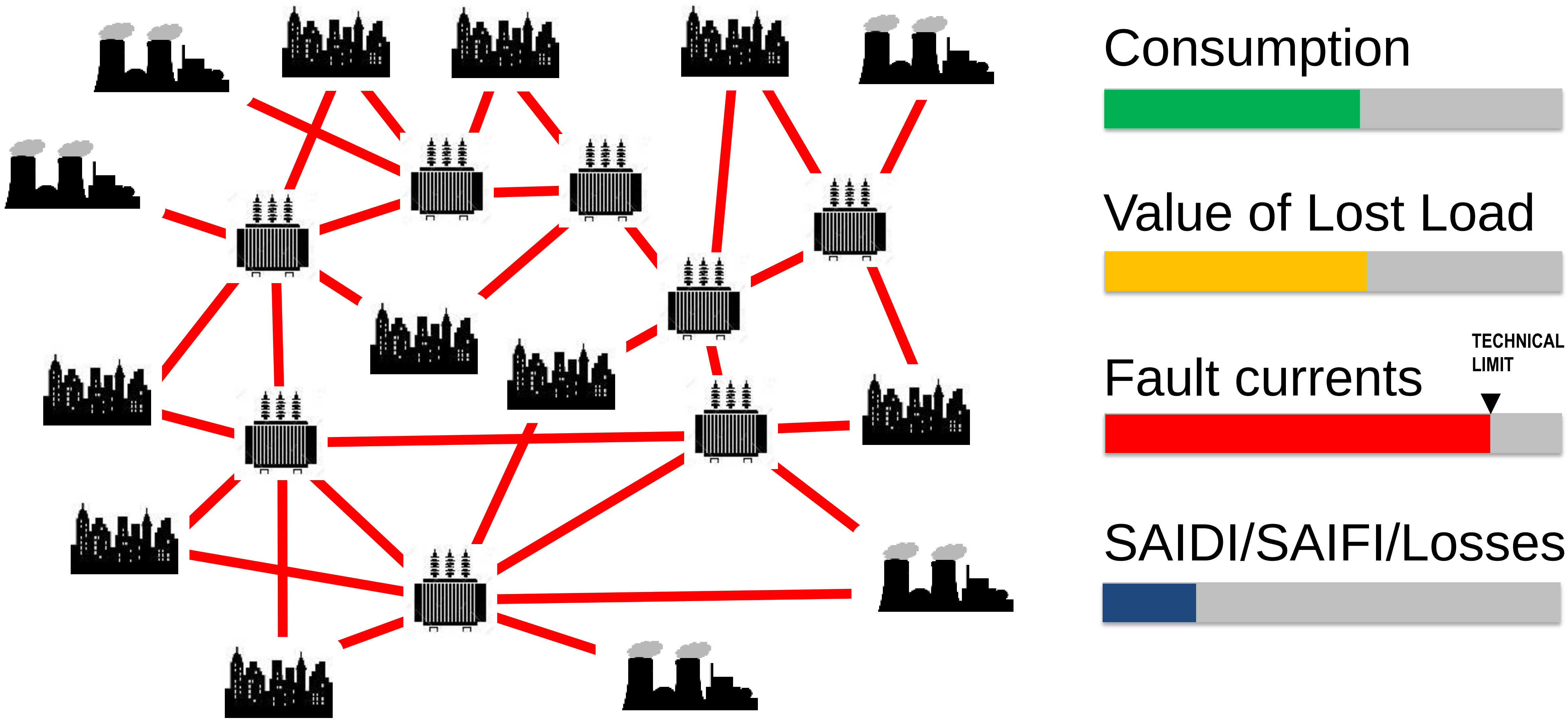
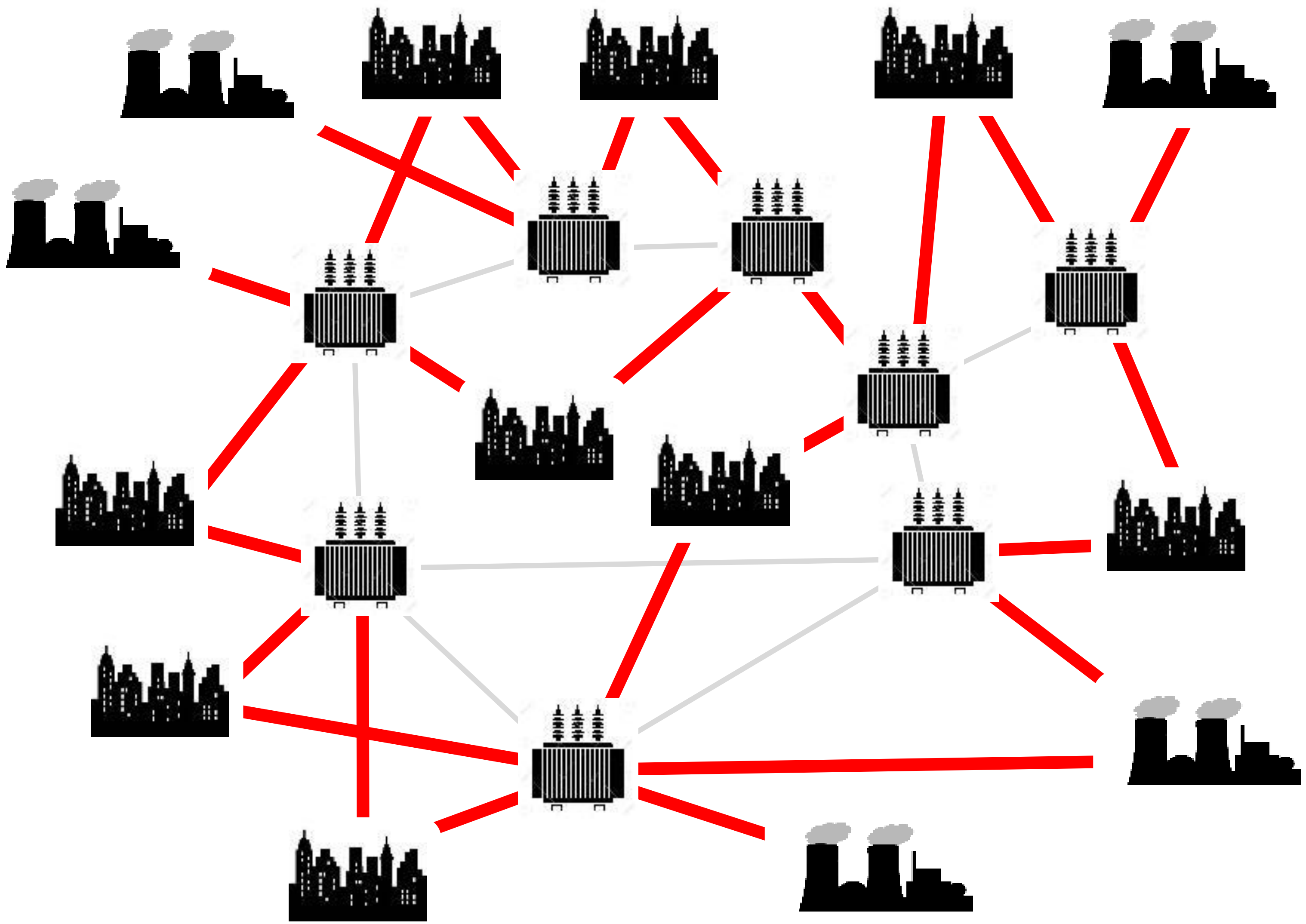
Electrical grid of megapolices – fault currents grow with grid

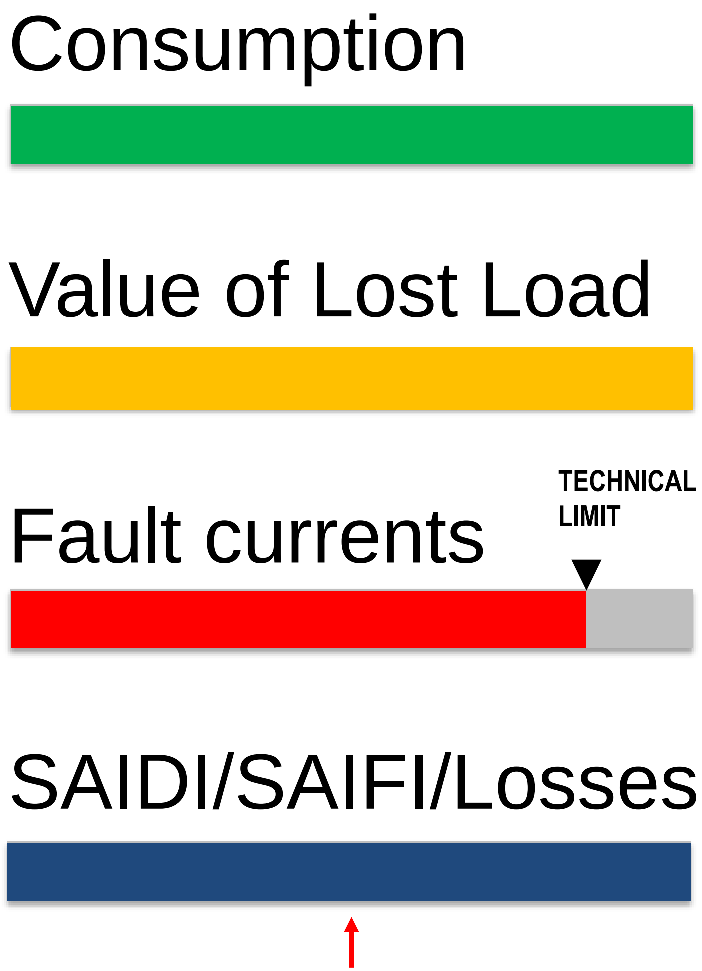
SuperOx



Electrical grid of megapolices – mitigating FCs via sectioning

SuperOx

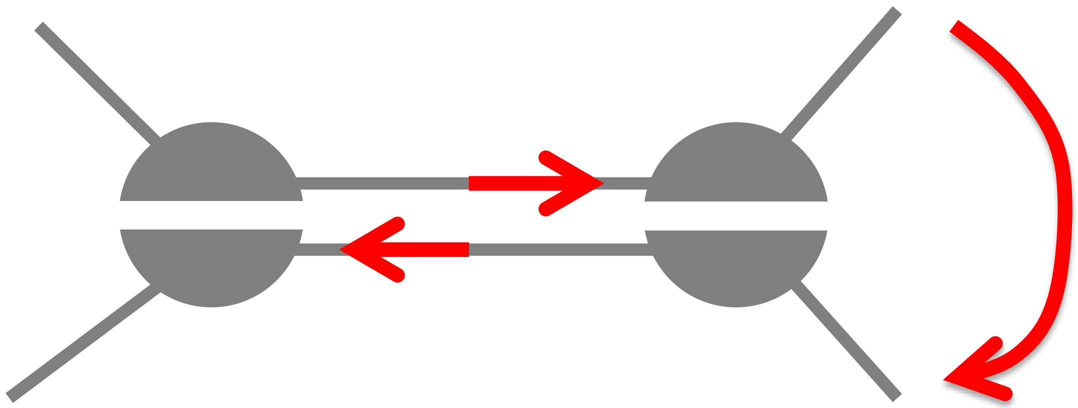




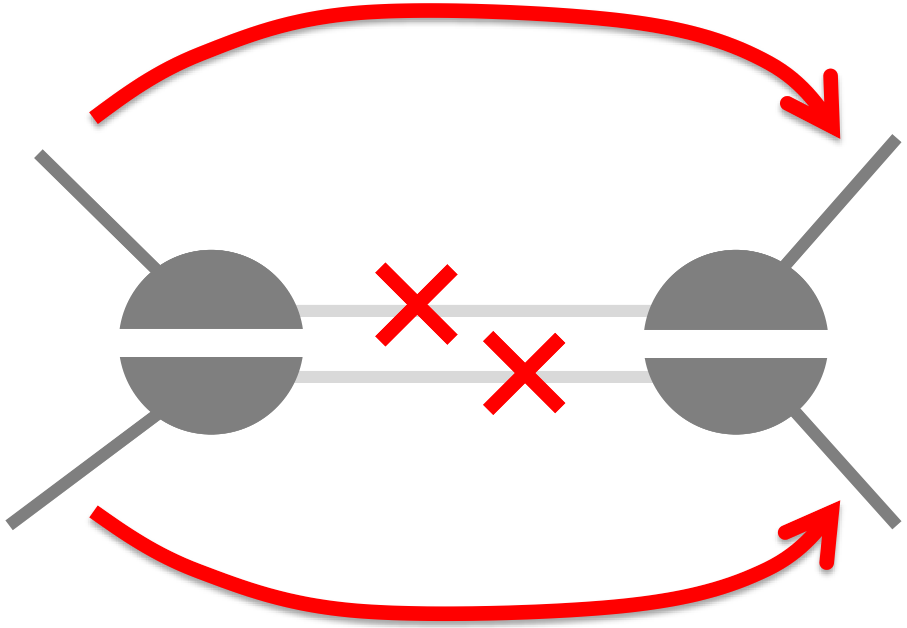
Grid sectioning affects the reliability of supply

Consequences of sectioning the grid

SuperOx



Bus bar sectioned:
power flows in opposite directions



Cables lines sectioned:
transmission is impossible

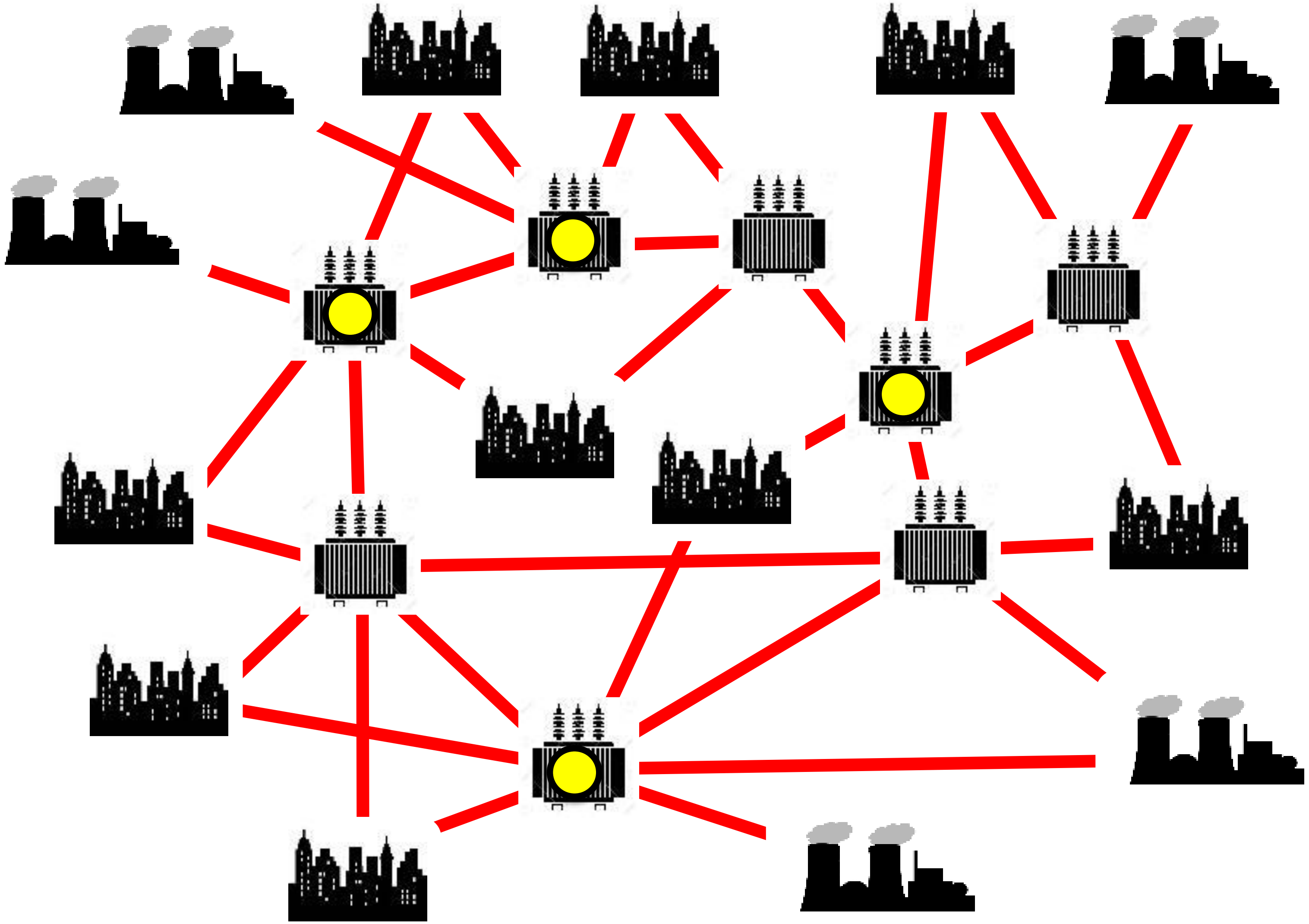
Growth of fault currents presents a big and costly problem for large grids.

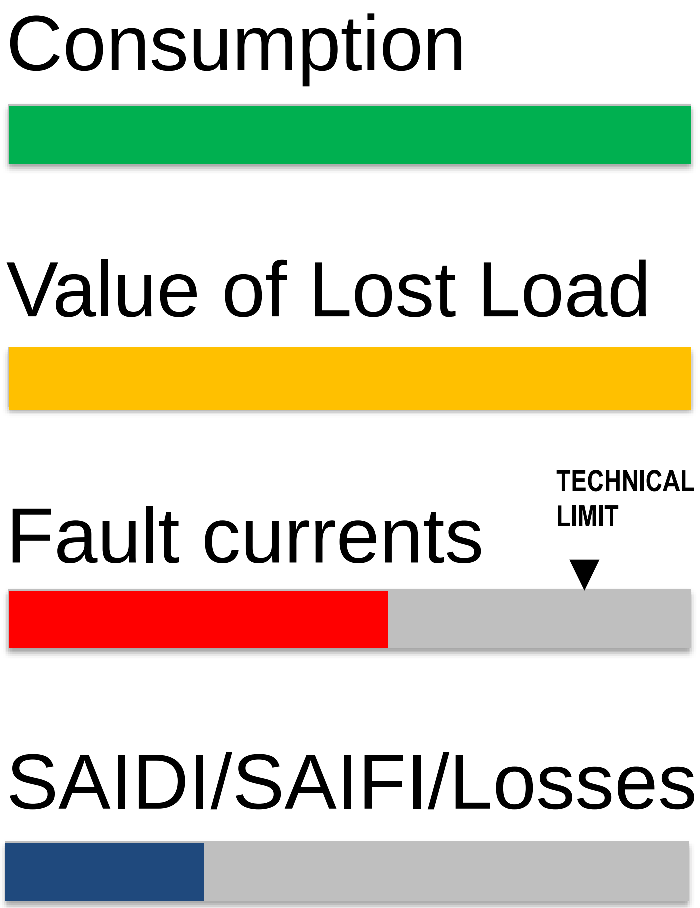
Fortunately, SFCL can often help.

It's an opportunity for HTS to penetrate electric power market.

Electrical grid of megapolices (+SFCL ●)

SuperOx





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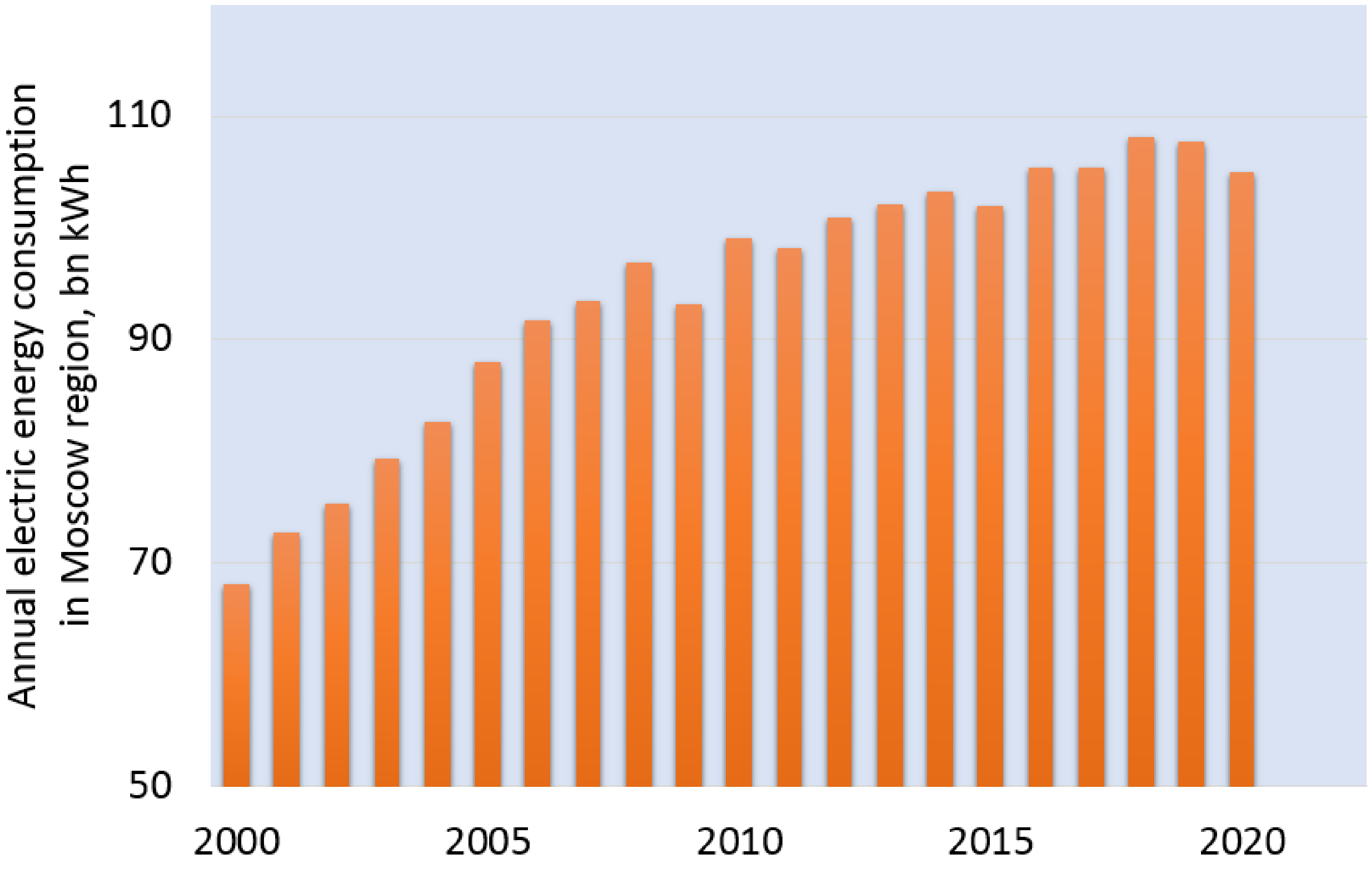
Moscow electrical grid is large and grows rapidly

SuperOx



Moscow electrical grid is large and grows rapidly

SuperOx

Electrical grid parameters	Russia	Moscow
Installed generation capacity	246 GW	**17 GW**
Electricity consumption	1059 TWh / year	**108 TWh / year**
Consumption growth rate	+23% / 20 years	**+ 59% / 20 years**

Moscow electrical grid

SuperOx

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

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Sectioning the grid → Grid redundancy suffers

More complicated to operate

Install air core reactors → Losses

More impedance needed

Install superconducting fault current limiters

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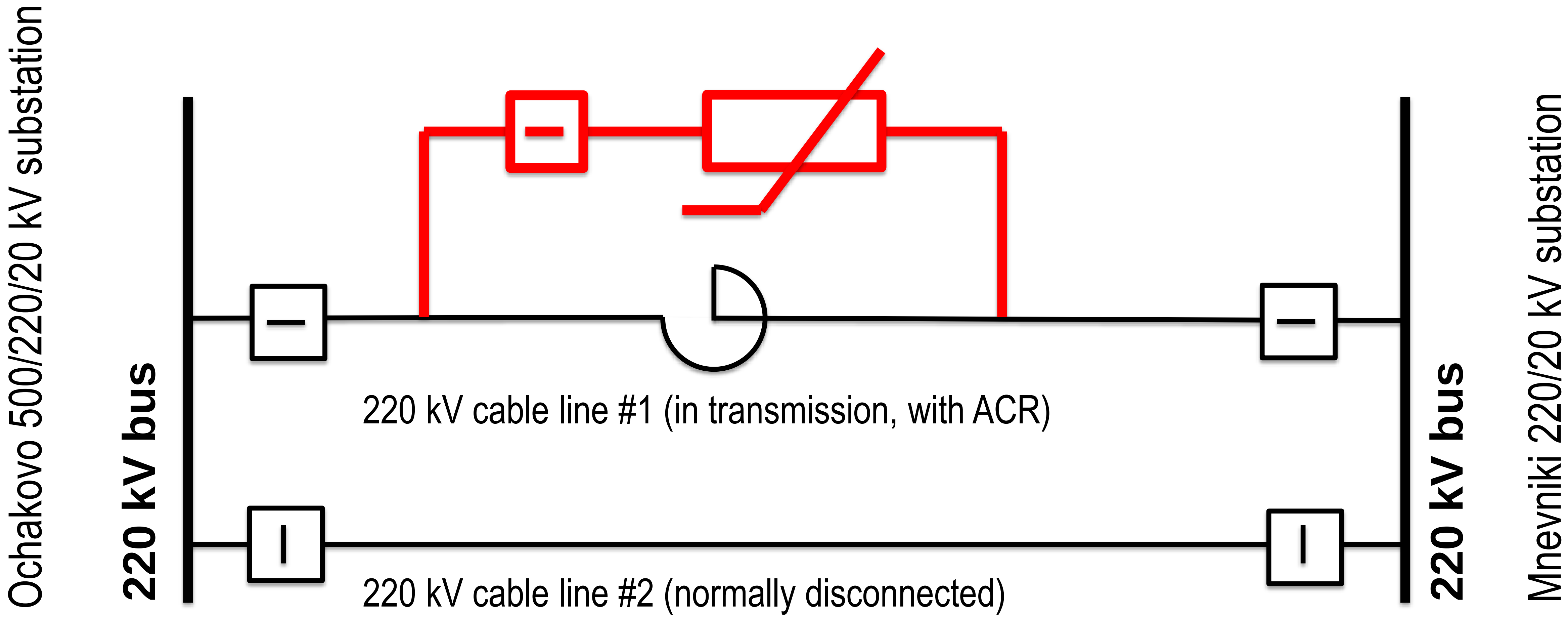
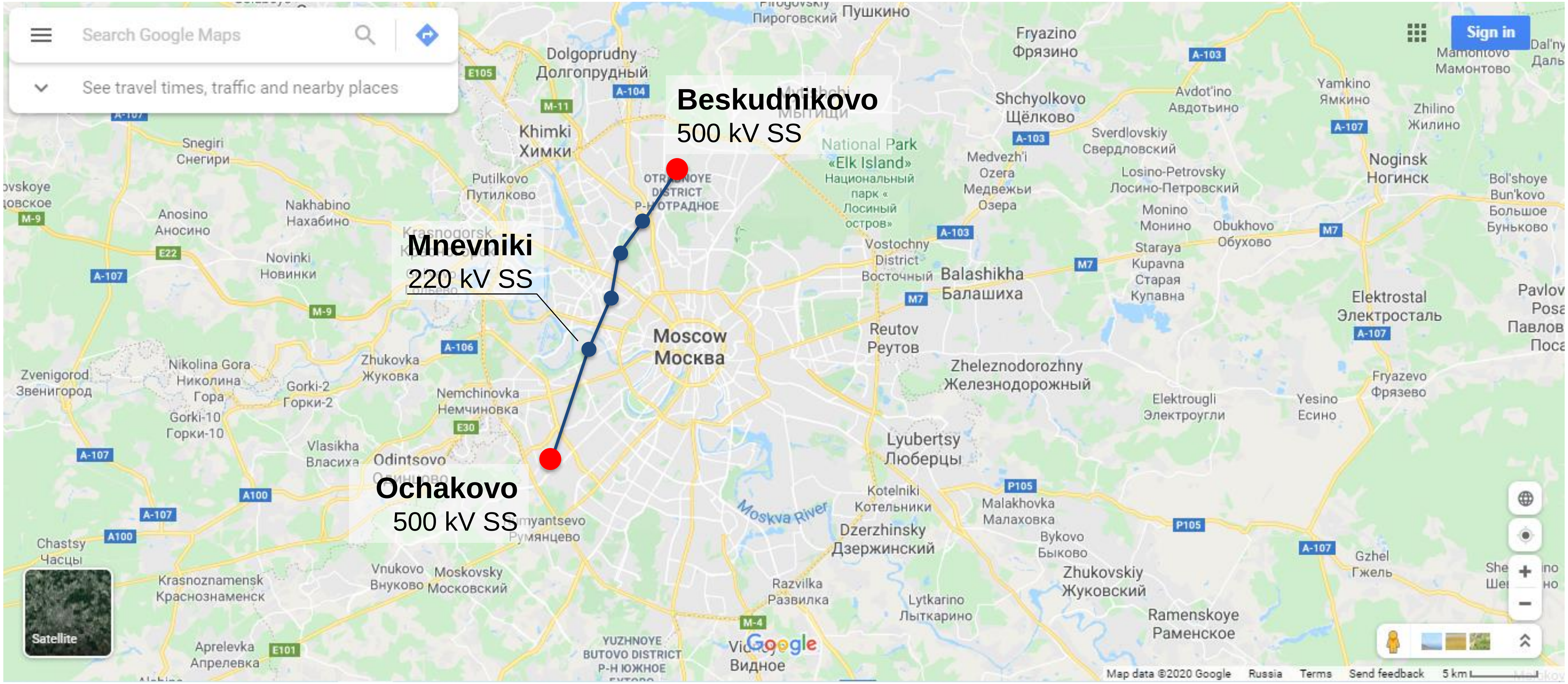
A pilot project – 220 kV SFCL for Mnevniki substation (UNECO)

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



A pilot project – 220 kV SFCL for Mnevniki substation (UNECO)



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Timeline of the 220 kV SFCL project

SuperOx

2019| 2018 | 2017| 2016| 2015

Project (first phase)

State expertize

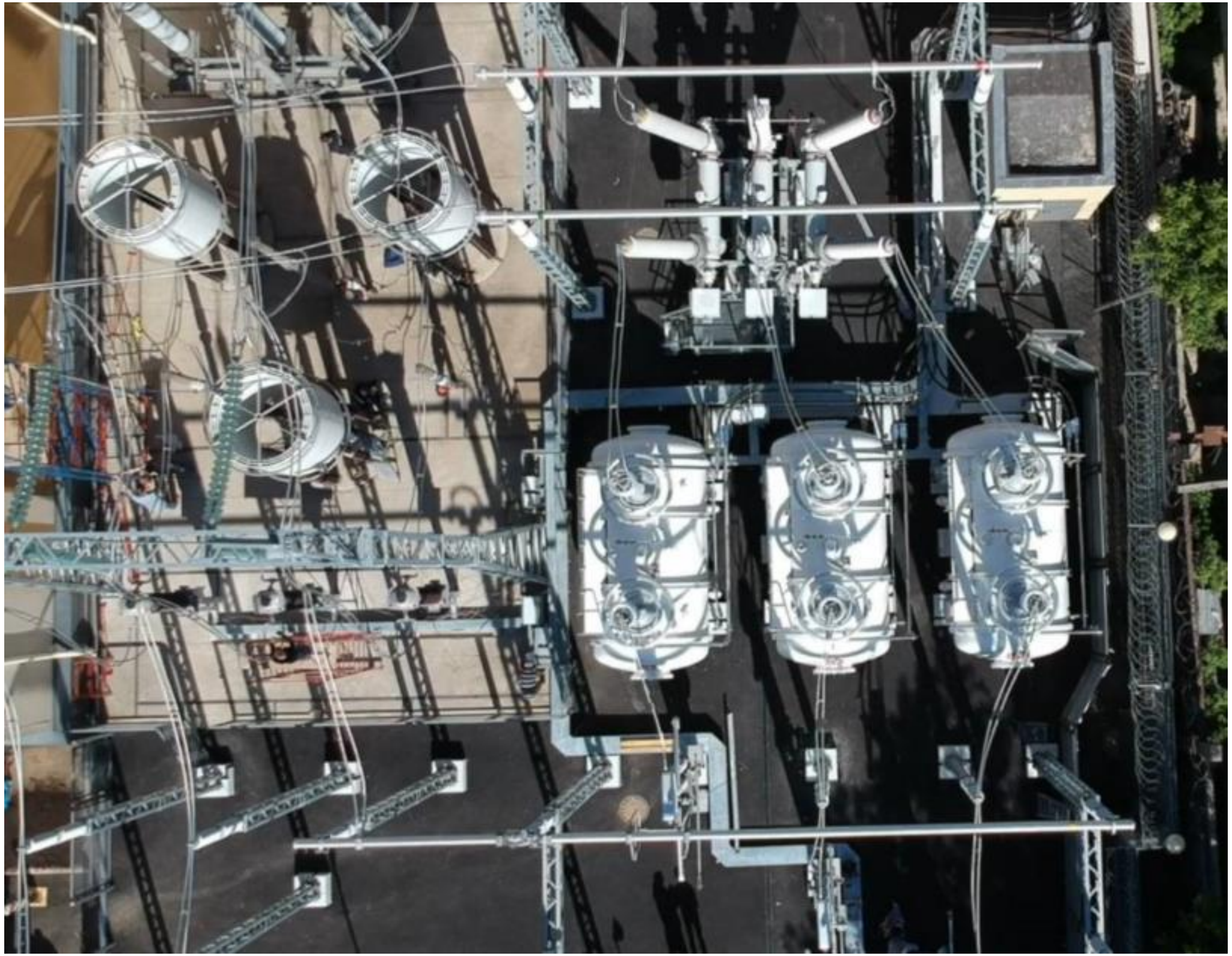
Project (second phase)

Start to build equipment

Start of civil construction
Start to install equipment

Comissioning & tests

Fully operational



Specifications of 220 kV SFCL

SuperOx

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
Critical current	3400 A peak
Nominal operational resistance	< 0,01 Ohm
Fault current limiting resistance	> 40 Ohm
Transition time	< 2 ms
Type of placement	Open
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

Full development cycle – from HTS wire to power system

SuperOx

- Superconductor wire development and production
- High currrent 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

SuperOx

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

SuperOx

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

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Component testing

SuperOx

Each component of 220 kV SFCL was rigorously tested in leading world labs

Engineering was refined until all the components passed strict technical requirements

HTS modules
Russia

Current leads
Russia

Cryostats
Korea

Cryocoolers
Japan

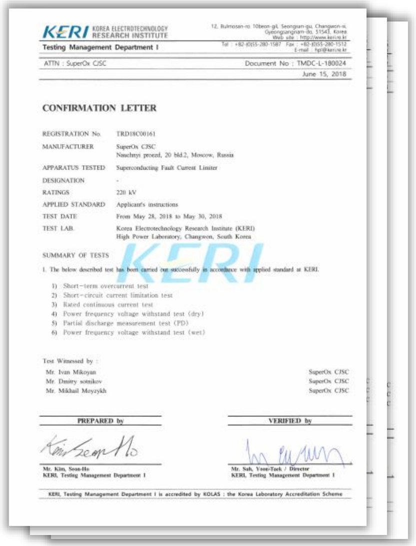
Current leads
Korea

HTS modules
Russia

System testing

SuperOx

- 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



KERI KOREA ELECTROTECHNOLOGY RESEARCH INSTITUTE
Testing Management Department I
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ATTN : SuperOx CJSC
Document No : TMDC-L-180024
June 15, 2018

CONFIRMATION LETTER

REGISTRATION No. TRD18C00161
MANUFACTURER SuperOx CJSC
Nauchnyi proezd, 20 bld.2, Moscow, Russia
APPARATUS TESTED Superconducting Fault Current Limiter
DESIGNATION -
RATINGS 220 kV
APPLIED STANDARD Applicant's instructions
TEST DATE From May 28, 2018 to May 30, 2018
TEST LAB Korea Electrotechnology Research Institute (KERI)
High Power Laboratory, Changwon, South Korea

SUMMARY OF TESTS

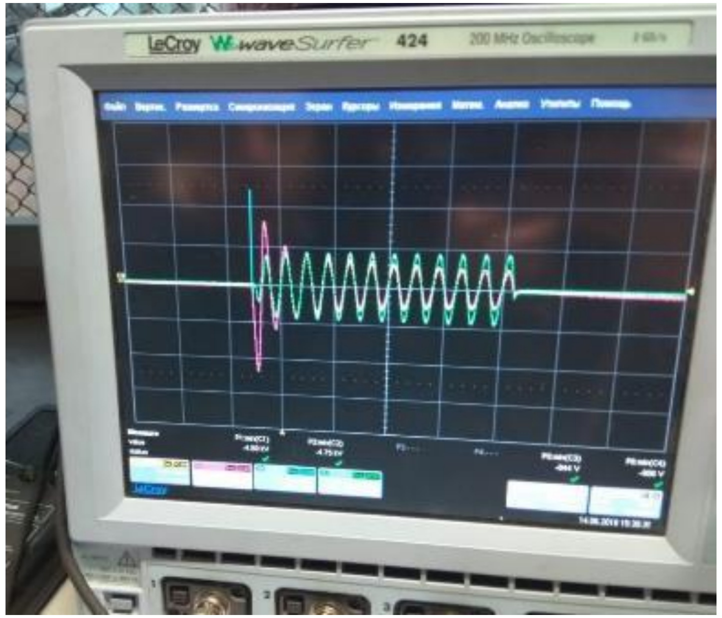
1. The below described test has been carried out successfully in accordance with applied standard at KERI.
   1) Short-term overcurrent test
   2) Short-circuit current limitation test
   3) Rated continuous current test
   4) Power frequency voltage withstand test (dry)
   5) Partial discharge measurement test (PD)
   6) Power frequency voltage withstand test (wet)

Test Witnessed by :
Mr. Ivan Mikoyan SuperOx CJSC
Mr. Dmitry sotnikov SuperOx CJSC
Mr. Mikhail Moyzykh SuperOx CJSC

PREPARED by
Mr. Kim, Seon-Ho
KERI, Testing Management Department I

VERIFIED by
Mr. Suh, Yoon-Taek / Director
KERI, Testing Management Department I

KERI, Testing Management Department I is accredited by KOLAS : the Korea Laboratory Accreditation Scheme



HV and power tests of 220 kV SFCL

SuperOx

Power record of current limiting:

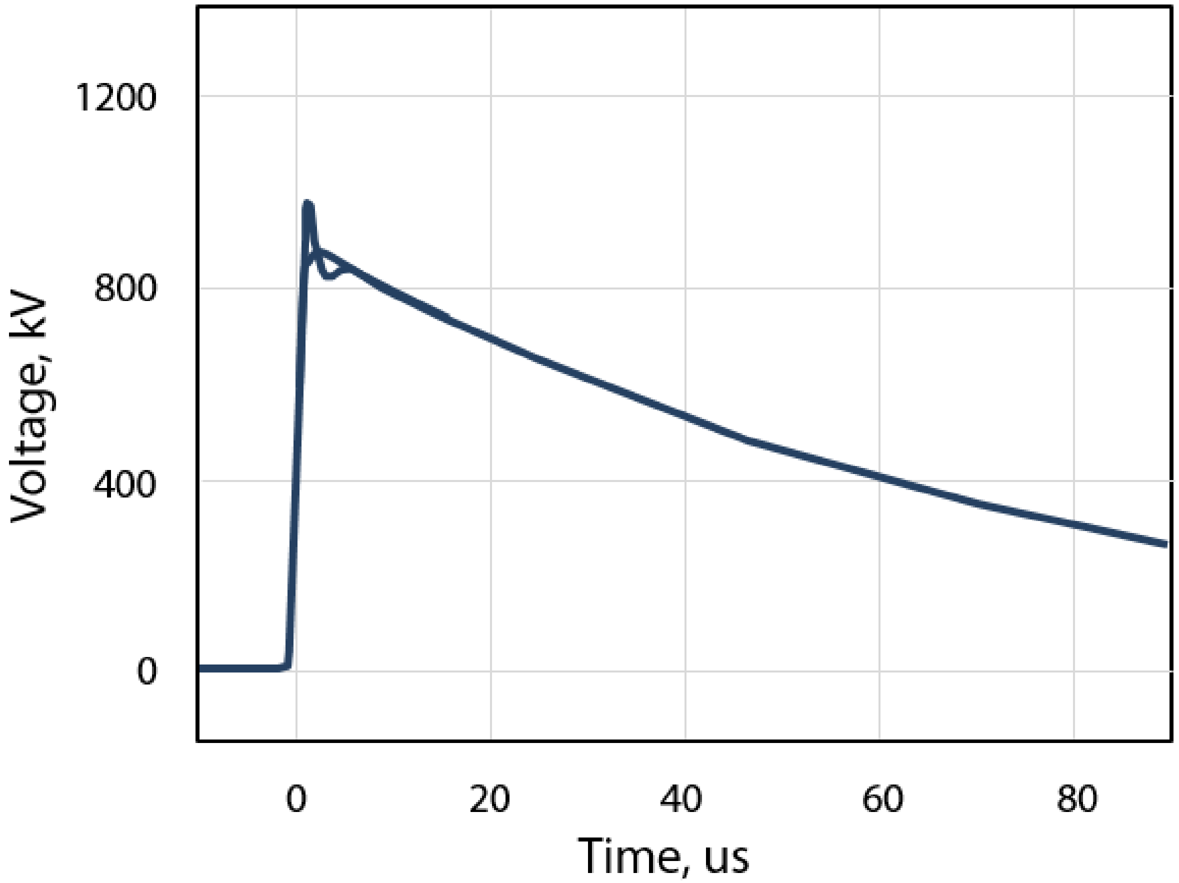
2000 MW → 300 MW

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

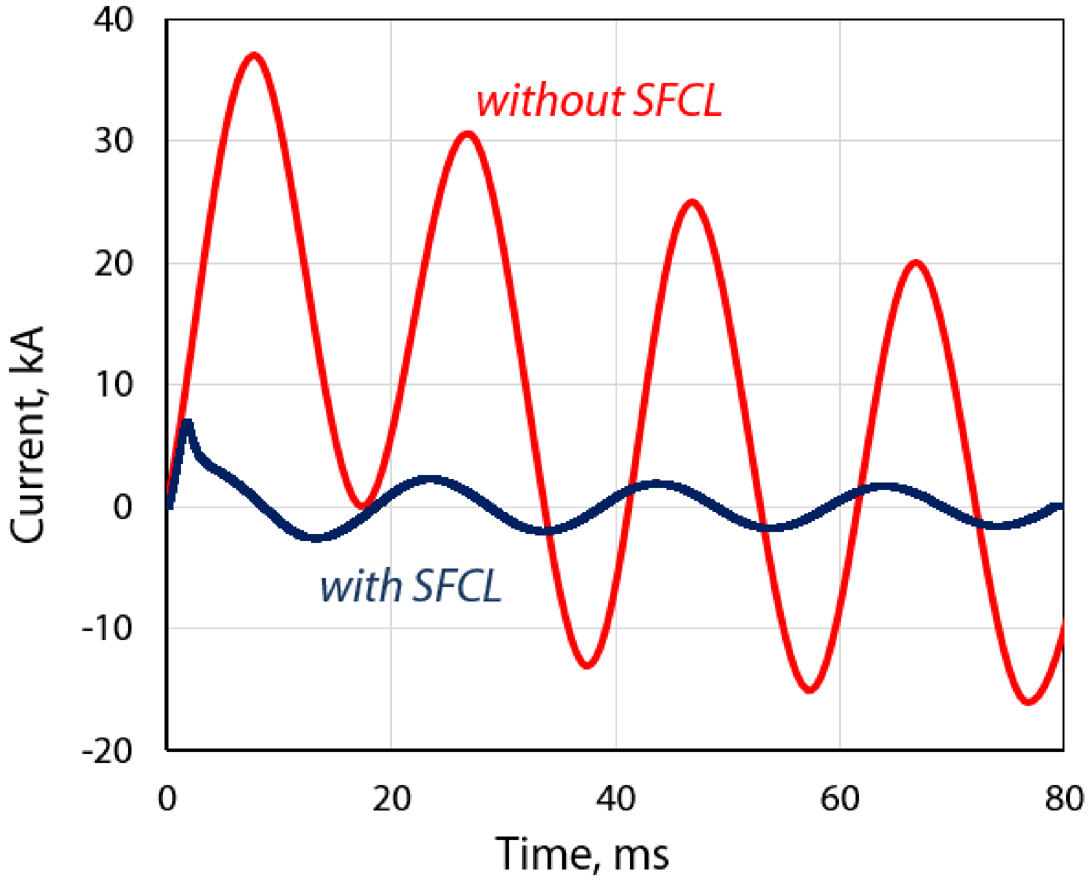
220 kV SFCL phase at the test site in KERI (Korea)

HV and power tests of 220 kV SFCL in KERI

SuperOx



950 kV lightning impulse test

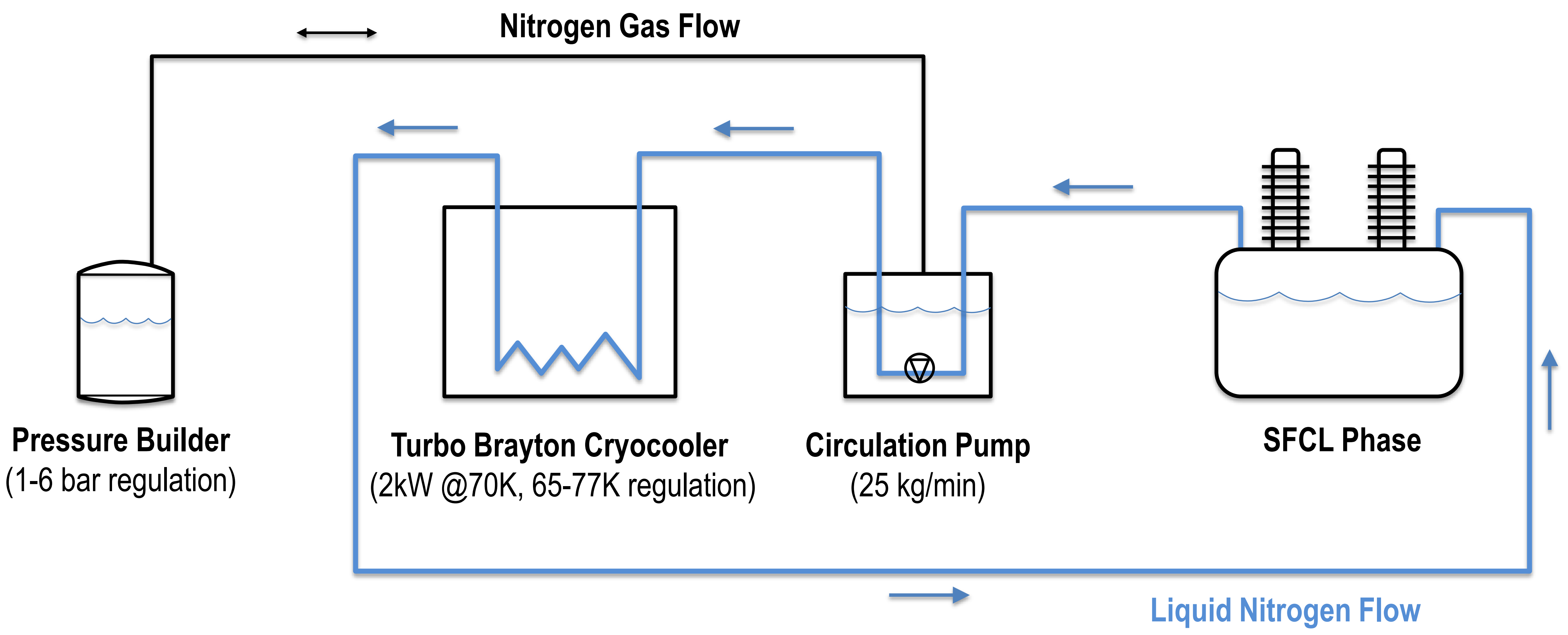


High power test

Cryogenic system design

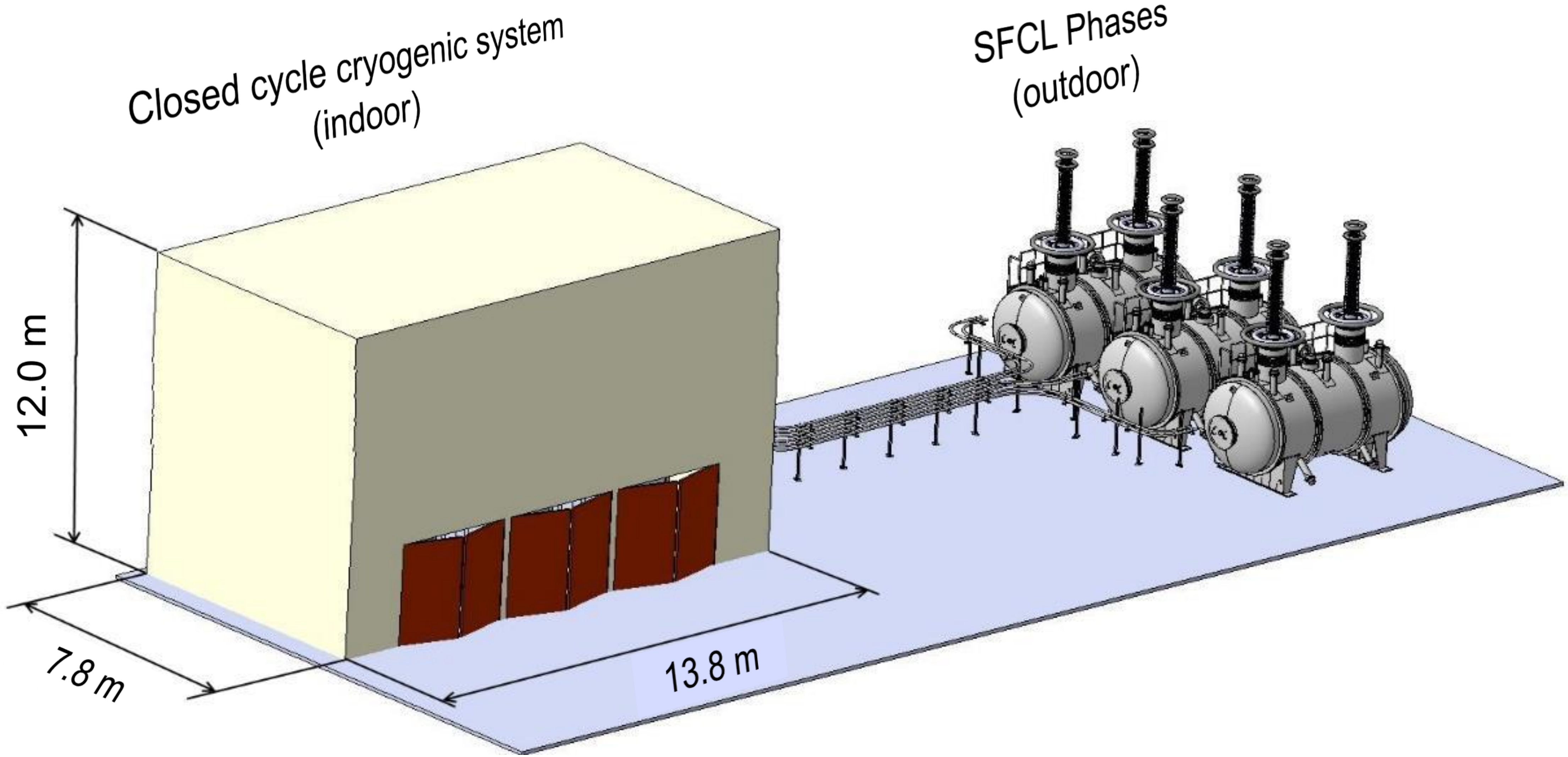
SuperOx

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



Installation site planning

SuperOx

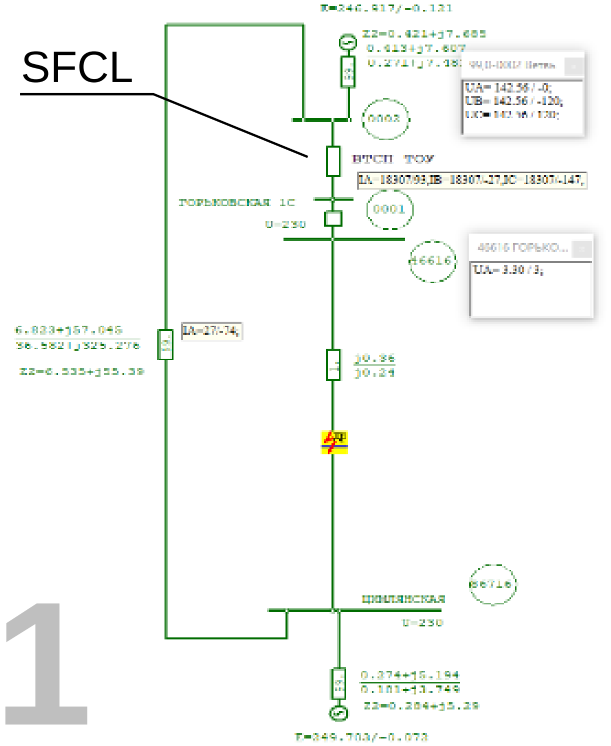


Mathematical model of SFCL for relay protection coordination

SuperOx

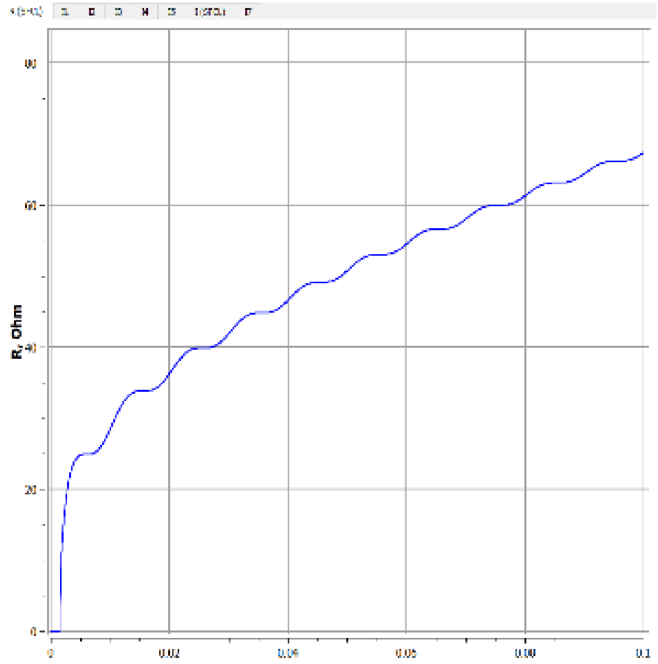
System Operator regulation rules have been developed for operation of SFCL in grid

1



Power grid with SFCL is modelled

2



SFCL resistance *vs* time is calculated with a verified mathematical model

3

Р Е З У Л Ь Т А Т Ы   Р А С Ч Е Т А на уровен
Ом

1-Пояс Узла	Наименование Узла	3х-фазное КЗ I1 (мод/фаза)	
U=250.7/-0 z1=0.133+j5.194 z2=0.13			
21416-	ОЧАКОВО 1С	27862	91
0,8	Общая нейтраль	0	0
21411,1	ОЧАКОВО	9460	90
21467,66	ОЧАКОВО АТ	3745	95
85726,1	НИКУЛИНО 2С	0	91
C2536,3	ТЭЦ-25	3425	90
N0926	МНЕВНИКИ	9	134
N8126	СОЮЗ	11234	92
U=549.2/-0 z1=0.200+j7.460 z2=0.20			
21418-	ОЧАКОВО	42485	91
21411,1	ОЧАКОВО	2355	91
21421,2	ОЧАКОВО	3049	91
21430,3	ОЧАКОВО	3204	91
21444,44		2716	91
C2518,7	ТЭЦ-25	1495	90
C2528,8	ТЭЦ-25	2132	90
C2618	ТЭЦ-26	15689	91
N8418	ПП ОЧАКОВО	11853	93

Grid operation determined:

- Switchgear capacity verification
- Relay protection setup
- Real time digital simulation

Regulatory paperwork made – to enable commercialization

SuperOx

- 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 opeation

SuperOx

- 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

Date	Fault type	Current limitation	Cooling system operation	Relay protection operation
2020-04-16	single phase	Yes	All nominal ($T < 2$ K, no p and L variations)	correct
2020-07-14	two phase	No*		correct
2020-10-12	three phase	No*		correct

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

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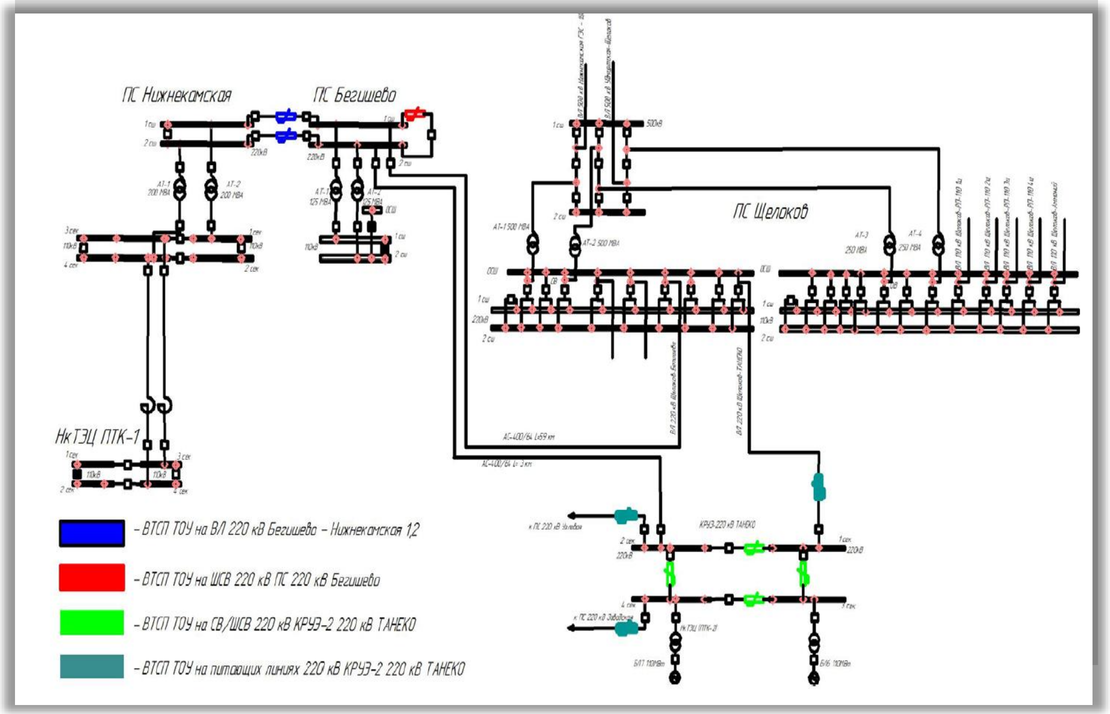
Opportunities for protection of production plants

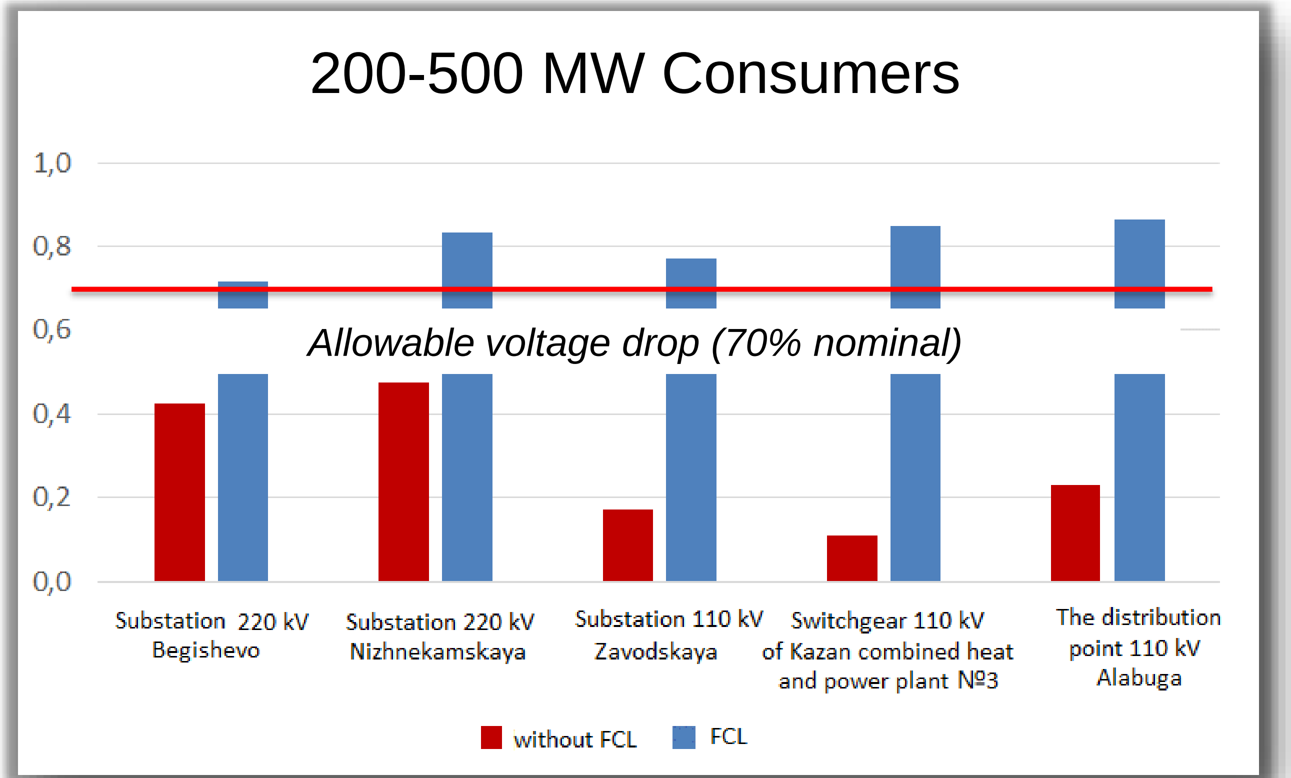
SuperOx

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



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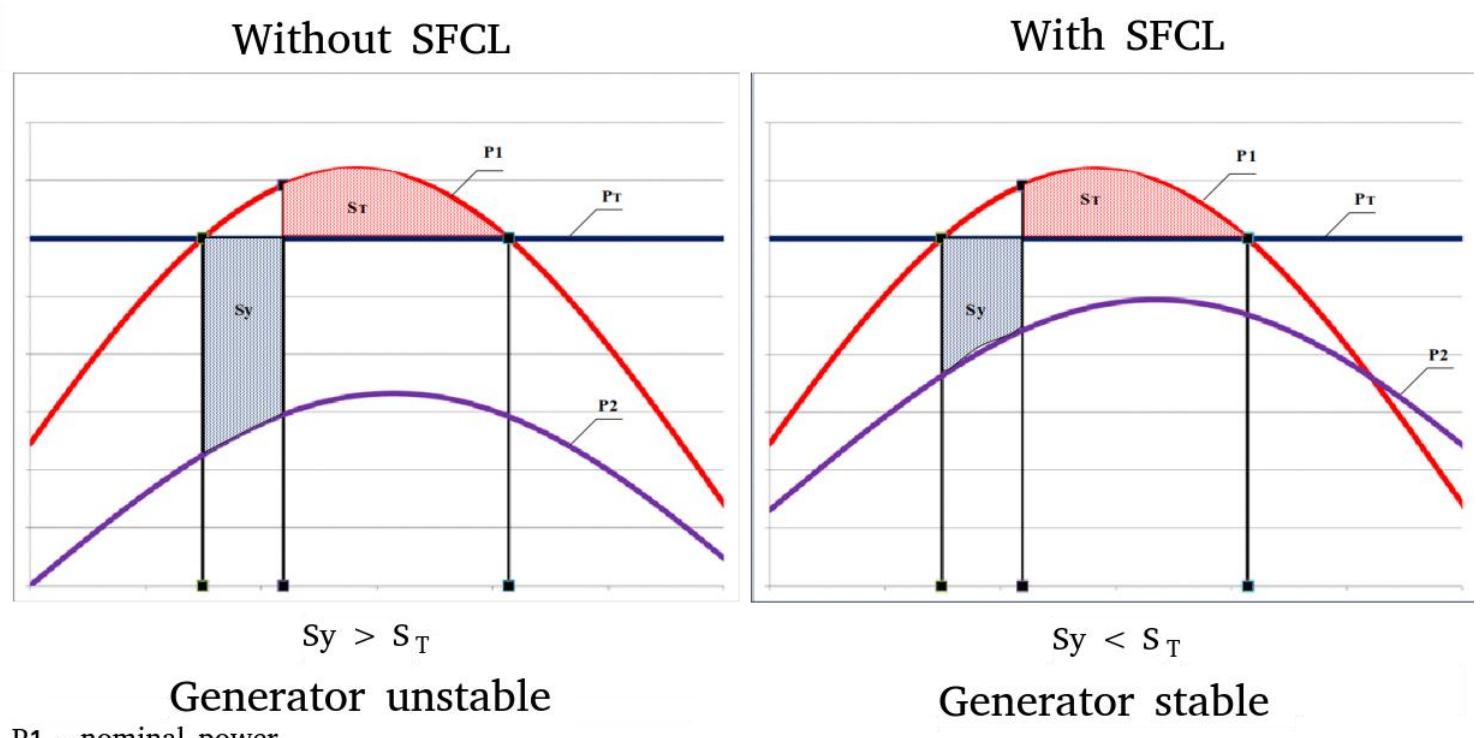
Opportunities for protection of generators

SuperOx

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



P1 - nominal power
P2 - fault power
P_T - turbine power
Sy - acceleration surface
S_T - decelaration surface

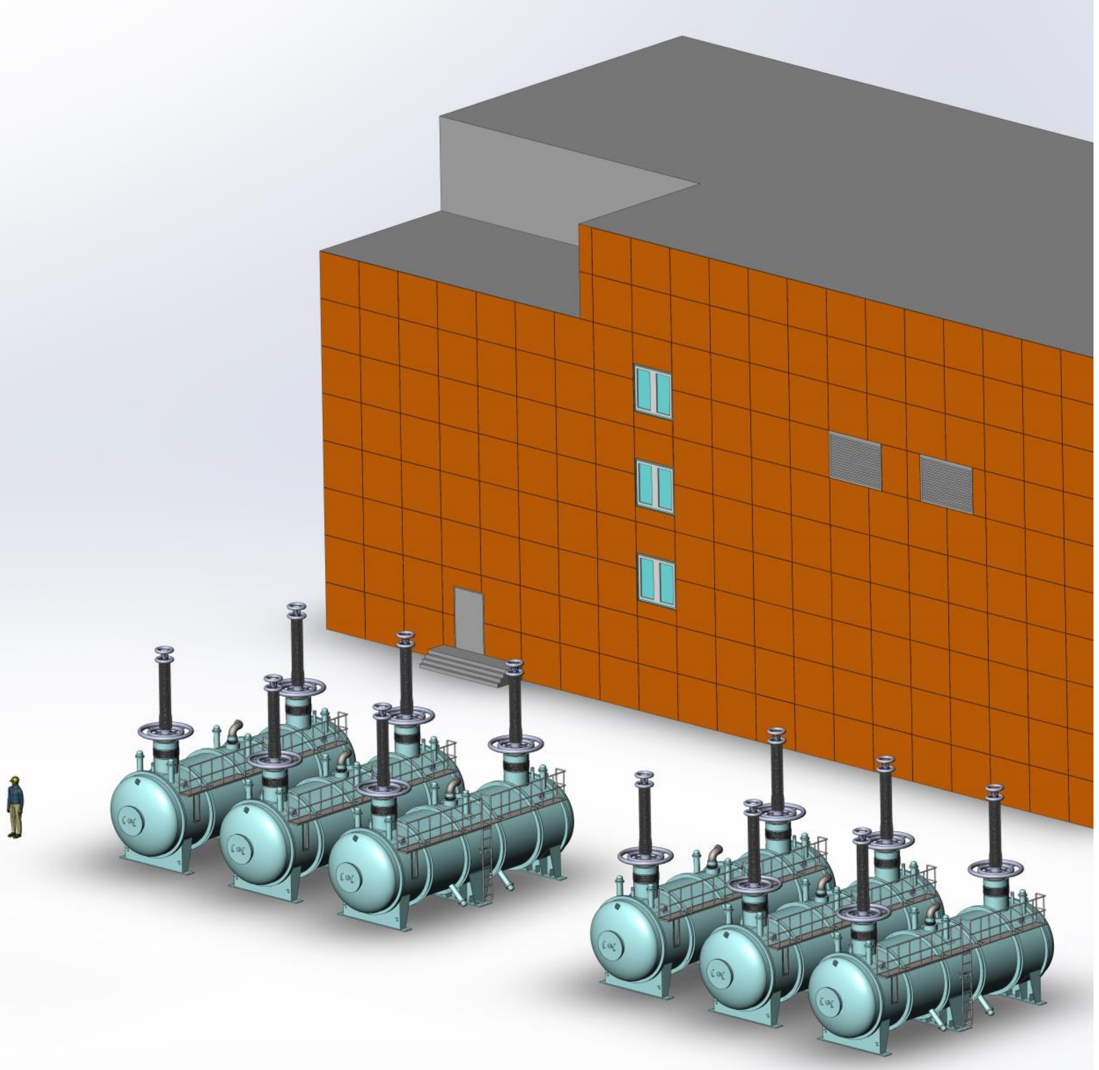
SuperOx is about to start work on next two 220 kV SFCLs

SuperOx

SuperOx is about to start work on next two 220 kV SFCLs

SuperOx

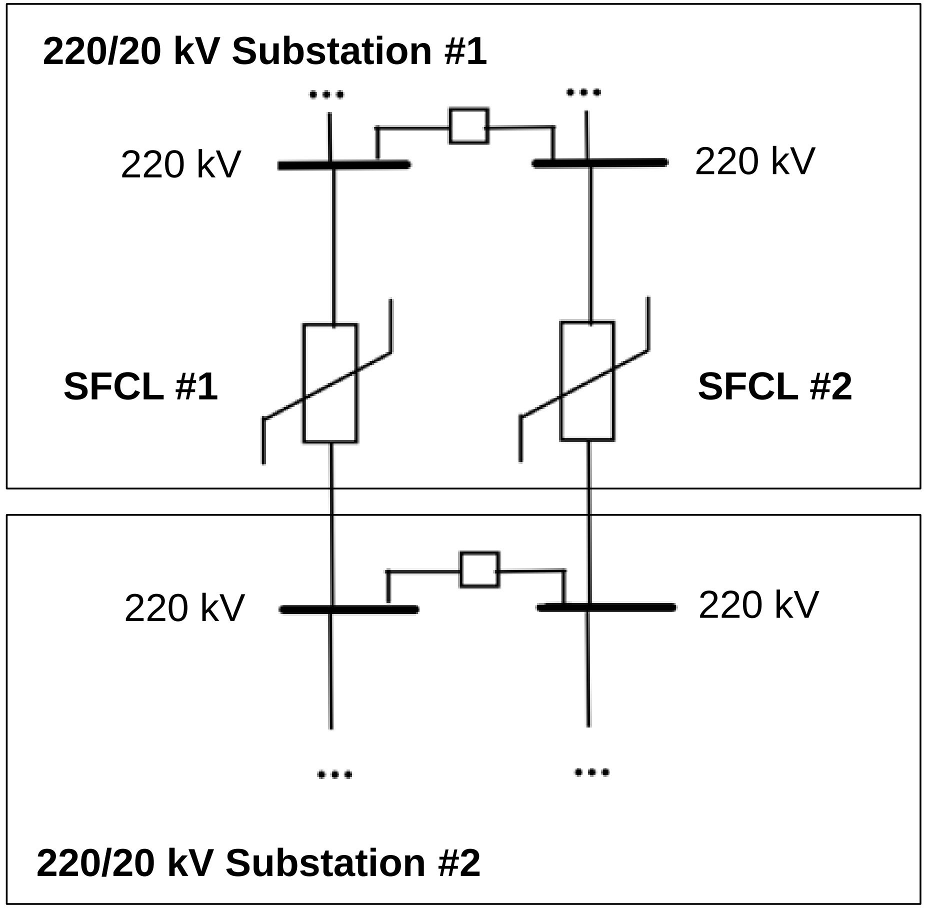
Property	Value (preliminary)
Nominal voltage	220 kV (Line, RMS)
Maximum operation voltage	252 kV (Line, RMS)
BIL test voltage	950 kV Peak
AC withstand voltage	440 kV RMS
Nominal frequency	50 Hz
Nominal current	1200 A RMS
Critical current	TBD (~ 3000 A peak)
Nominal operational resistance	< 0,1 Ohm
Fault current limiting resistance	> 40 Ohm
Transition time	< 4 ms
Type of placement	Outdoor
Climate requirements	-45 deg C … +40 deg C



SuperOx is about to start work on next two 220 kV SFCLs

SuperOx

- 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



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Conclusions

SuperOx

- ❑ 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

SuperOx

SuperOx SFCL Team, June 2019

Thank you!

www.superox.ru/en