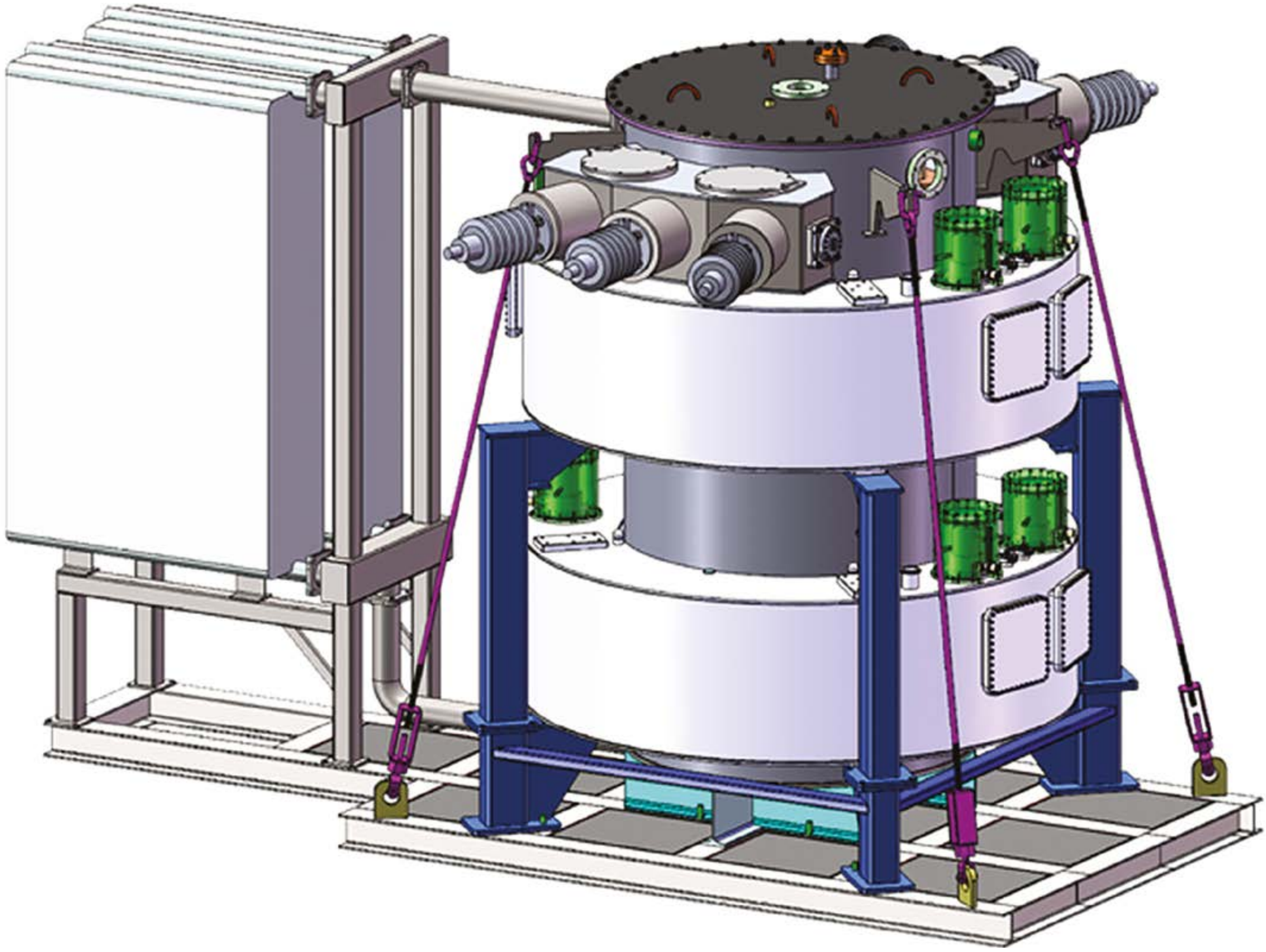


Application of magnesium diboride in saturated core fault current limiters

Using superconducting magnets to provide the saturating flux

ABSTRACT

A fault current limiter (FCL) is a nonlinear device with negligible impedance under normal conditions, which is able to switch to a high impedance state as soon as the current passing through it exceeds a given threshold. Among the various FCL topologies, saturated core fault current limiters have recently reached the demonstration phase in medium- to high-voltage networks. ASG Power Systems has assembled and tested a 36 kV rated saturated core type fault current limiter which uses superconducting solenoids to provide the saturating flux. The evolution and functionality of this implementation will be described here in detail.

KEYWORDS

cryogenics, electricity supply industry, fault current limiters, superconducting materials

1. Introduction

A fault current limiter must be able to change impedance autonomously, without active sensing or actuation systems that might be prone to failure. This is because FCLs are installed in series connection with other network components that have limited ability to withstand the passage of fault-current, or in the case of switchgear, maximum fault making and breaking capacities. Two broad categories of FCL using superconductivity, generally referred to as resistive and inductive, have been developed. They operate in very different ways.

A fault current limiter must be able to change impedance autonomously, without active sensing or actuation systems that might be prone to failure

2. Superconducting FCL types

2.1 Resistive FCL

In a resistive limiter, load current feeding customers is passed through a superconducting circuit which is dimensioned to revert to a normally conducting state (quench) if the current exceeds a certain level. A series circuit breaker operated by a rapid and reliable local protection system must interrupt the current through the FCL to protect the quenched superconducting circuit from overheating and allow for the said circuit to cool to below its critical temperature, and for the FCL to be reconnected. Cooling down may require a few minutes and to maintain the continuity of power distribution during the temperature recovery operation, conventional reactors may be connected in parallel with the superconducting circuit. Where high-temperature superconducting material is used (typically Bi2212, Bi2223 or YBCO, all of which have critical temperatures of around 90 K), cooling may be achieved by immersing the HTS circuit in liquid nitrogen. Today YBCO tapes having a high resistance in the normal state are used in state-of-the-art resistive FCLs.

2.2 Inductive FCL

In an inductive FCL, the fault limiting impedance takes the form of inductive reactance, which can be inserted into the load current path in a number of ways, including using a resistive limiter connected in parallel with a conventional series reactor. The technology described here is inductive, but no load-current flows in the superconducting circuit, which is only required to carry dc current. The load current is passed through iron-cored reactors, the cores being driven into saturation by magnetic flux produced by solenoids, in which superconducting wire is used to provide the required field density (around 1 Tesla) while keeping the size, mass, and power requirements of the solenoids within practicable limits. The fault current itself, while opposing the saturating flux, de-saturates an iron core, and the impedance of the series reactor rises to provide the current limiting functionality. This approach provides FCLs which can remain in the circuit permanently because they revert immediately to a low-impedance state following clearance of the fault, continuing to supply customers who remain connected with load current.

3. Saturated core limiter development

3.1 Closed-core arrangement

The closed-core FCL was developed initially in the 1980s at IRD in Newcastle (UK) by Messrs. Raju, Parton and Bartram [1] using low-temperature superconducting magnets. The approach saw its first practical application in California in 2003 when a demonstrator provided by Zenergy Power was installed in a distribution network [2]. Fig. 1 shows the active components of the device (left) and the installed FCL (right). In the left-hand image, the ac coils which carry load current are on the outer vertical

The principle of operation of the FLC is that the core is saturated during normal operation and de-saturated under fault condition, thus providing the current limiting functionality

Figure 1. Closed-core arrangement showing active parts (left) and installed device (right)

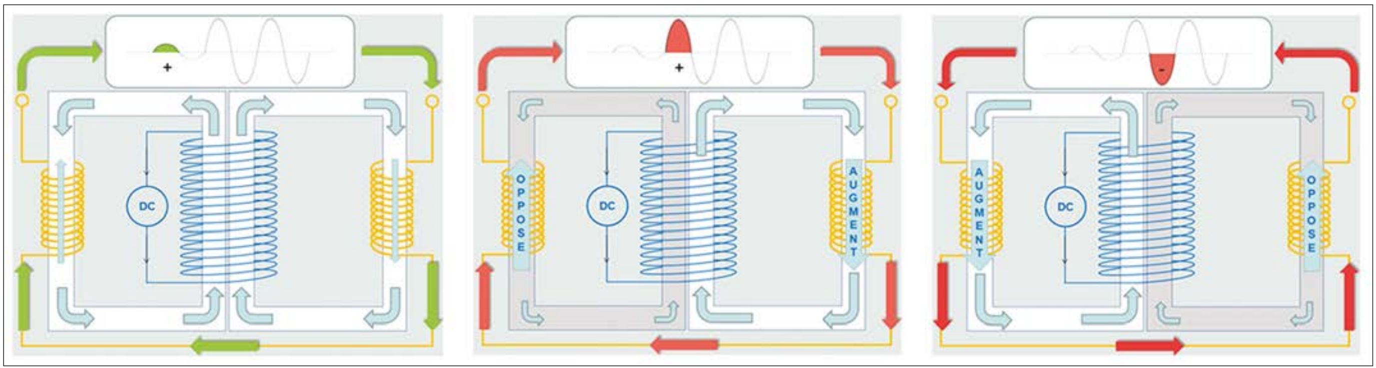


Figure 2. Closed-core arrangement (left) under load current (centre and right) during a fault

The open-core FCL arrangement allows the ac coils to be immersed in oil, providing a number of benefits

core limbs, and all six cores are driven into saturation by the superconducting magnet in the centre. The HV circuits (ac coils and feeds) are air-insulated, which requires significant clearances to earth and between phases.

Fig. 2 shows the operating principle. The iron cores are always saturated and remain so while the ac coils (orange) supply load current (green). When a fault occurs, the fault-current (red) in the ac coils drives one of the cores out of saturation (coloured grey) during each half-cycle, causing the inductive reactance of the ac coil on the de-saturated core to rise, providing the current-limiting functionality.

3.2 Open-core arrangement

The open-core arrangement, also pioneered by Zenergy Power, is shown schematically in Fig. 3. The ac coils are wound onto straight triangular section core posts which are enclosed in an oil-filled stainless-steel tank.

4. Components of the saturated core FCL

The open-core arrangement has a number of advantages. The oil-filled tank can be fitted with radiators to provide ONAN or assisted cooling of the oil; the oil provides electrical insulation facilitating up-scaling of the voltage rating to transmission-voltage levels, and the installation of the superconducting magnets outside the oil tank allows access to the magnets for maintenance even while the FCL is operating. A three-year trial of this technology was undertaken in 2012-2015 in northern England, during which at least nine significant network faults occurred and were limited effectively by the device. The installation is shown in Fig. 4. The green glass-reinforced plastic (GRP) housing contains the reactor tank and magnets assembly, and on the left-hand side are two 6 m enclosures that house the cooling and control systems – more about these to follow. In 2012 Zenergy Power became insolvent. ASG Power Systems was launched subsequently to take ownership of the intellectual property relevant to the saturated core FCL technology and to complete the manufacture and testing of the 36 kV; 800 A FCL for which the reactor tank assembly had been manufactured in

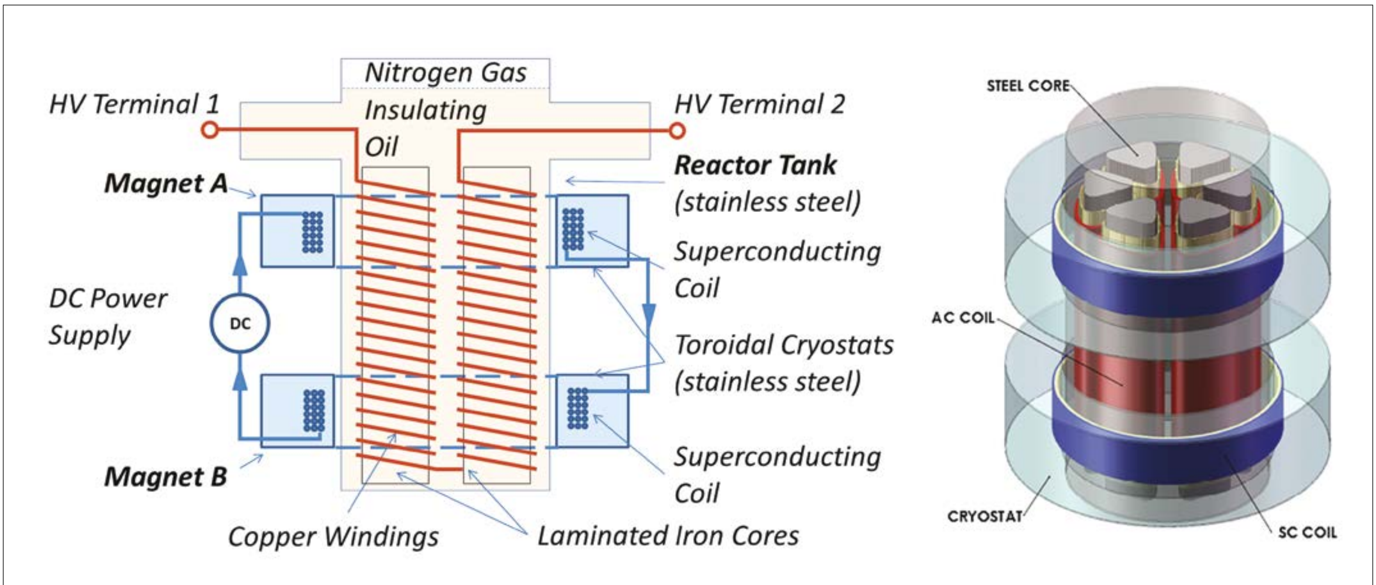


Figure 3. Open-core arrangement showing active parts of one phase (left) and 3 phases (right)

the USA by PTTI in Raeford, North Carolina.

5. Selection of superconducting material for the DC coils

The selection of the superconducting material impacts the DC coil design and cost. Today, three superconducting materials are available in sufficient quantity with high enough performance to be considered for power devices. Their main characteristics and costs are reported in Table 1. The first two are high-temperature superconducting (HTS) tapes made from Bi2223 and YBCO and are both commercially available. They are cooled using subcooled liquid nitrogen (65 K), a cheap, abundant, and environmentally friendly fluid, which makes HTS tape an attractive solution for many superconducting devices. Their performance in the magnetic field increases at lower temperatures. However, their costs remain high. Despite an industrialised process based on Powder-in-tube (PIT) technology [3], Bi2223 tape requires a bulk silver matrix that represents more than 50 % of the tape cross-section, which is costly. For YBCO tapes, the production processes remain costly and complex and result in low yields.

The third material is magnesium diboride (MgB_2), available in round wires or tapes. These benefit from the high-yield and low-cost PIT process [4]. Multiple MgB_2 fibres, typically in a nickel matrix, are drawn to form the wire or tape.

Figure 4. 11 kV; 1250 A open-core FCL installed in the primary substation

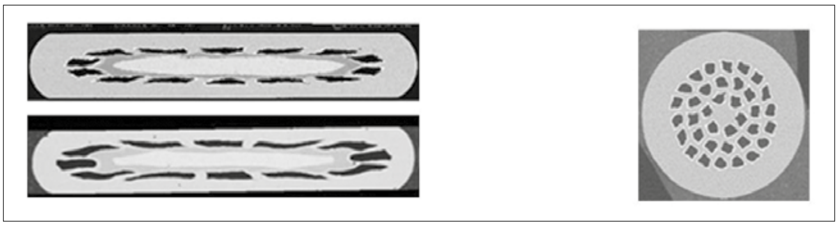


Figure 5: Cross-section of multifilamentary MgB_2 tapes and wires *(MgB_2 filaments in black)*

Compared to other HTS technologies, MgB_2 needs a more expensive cooling system since it is operated at a temperature range of 15-20 K, but that extra cost is compensated by the lower price of superconducting wires

Magnesium diboride wires and tapes (Fig. 5) are available in long lengths, and their cost is comparatively low, as indicated in Table 1. However, to be superconducting, this material must be kept below around 25 K, requiring more sophisticated cooling systems than providing liquid N_2. Consequently, the cost of the superconducting system increases, and its efficiency decreases. However, a DC superconducting magnet required for a saturated core inductive FCL can be designed with low cryogenic losses and with a cryogen-free cooling system. Based on this technology, the investment required for operation in the range 15-20 K remains still affordable. This extra cost, in comparison with HTS cooled by the liquid N_2 was found to be counterbalanced by the low cost of MgB_2 tapes, especially when considering large FCL systems.

Table 1. Main characteristics of superconducting wires and tapes

	Shape	Width	Thickness	Performance of commercial tapes and wires		
Bi2223	Laminated powder-in-tube (PIT) tapes	4.5 mm	0.3-0.5 mm	I_c @70 K, 0.5 T 350-400 A.cm^{-1}	Length < 1500 m	80-120 €/kA/m
YBCO	Laminated thin film coated tapes	4-12 mm		I_c @70 K, 0.5 T 500-800 A.cm^{-1}	Length < 500 m	
MgB2	Laminated PIT tapes	4-8 mm	0.5-0.7 mm	I_c @20 K, 1T 300-400 A.mm^{-2}	Length < 3000 m	3-5 €/kA/m
	Cylindrical PIT wires	Ø 0.8 - 1.5 mm				

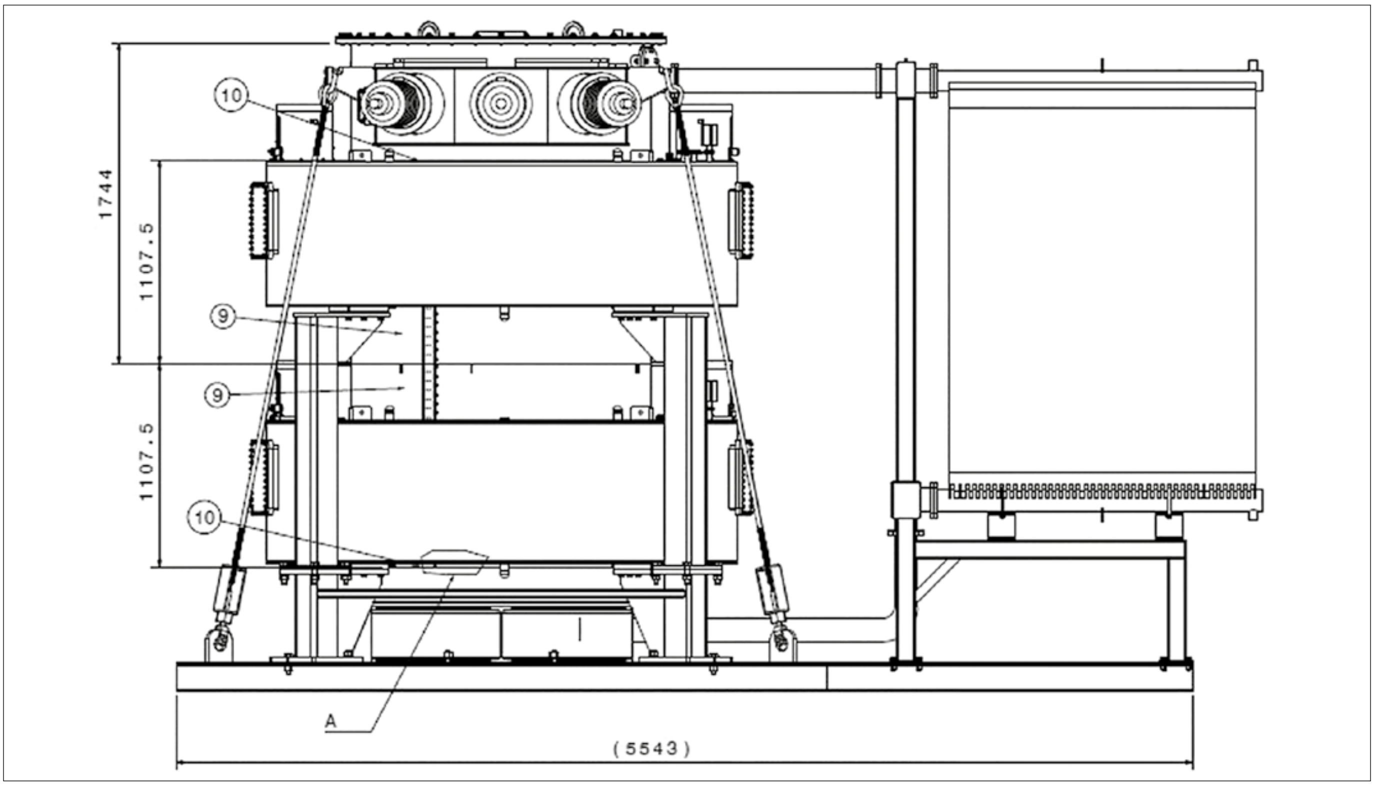


Figure 6. GA of 36 kV FCL reactor tank, radiators and SC magnets

The 36 kV saturated core FCL comprises 6 iron-cored reactors in which the iron cores are driven into saturation by a DC magnetic field produced by two superconducting solenoids

6. 36 kV; 800 A FCL development

The 11 kV FCL mentioned in the previous section (and see reference [5]) was equipped with superconducting magnets manufactured using high-temperature superconducting (HTS) tape made from Bi2223. In response to a request for a 36 kV rated device, it was decided to investigate the possibility of using MgB_2 wire to reduce the cost of the magnets, which would need to be much larger physically, in order to accommodate the larger diameter oil tank and to provide the considerably higher saturating flux density needed to achieve the required current-limiting capability of 40 % - which is to say that the fault current magnitude would be reduced by 40 %.

6.1 FCL design

The 36 kV saturated core FCL comprises 6 (2 per phase) iron-cored reactors in which the iron cores are driven into saturation by a magnetic field produced by two superconducting solenoids (henceforth referred to as "magnets"), arranged as a Helmholtz pair. The magnets, manufactured by ASG Superconductors in Genoa, Italy, comprise 3816 turns of multi-filament magnesium diboride wire arranged in 30 layers on a stainless-steel former, with a winding height of 410 mm and an internal diameter of 1.8 m. Each magnet contains about 23 km of MgB_2 wire. The windings are encapsulated in epoxy resin and maintained at around 16 K by means of thermal conduction through a copper heat removal structure, cooled by reliable and low maintenance Gifford-McMahon coldheads. The arrangement of the two magnets and the reactor tank, cores and coils is as shown in Fig. 3 in section 4. The general arrangement of the magnets, reactor tank and radiators is shown in Fig. 6. The assembly is about 3.7 m high and weighs 36 tonnes.

When a fault occurs in the network, the high currents in the reactor AC windings produce magnetic fields which combine with the saturating fields, driving one of the two reactor cores in a given phase (depending on the polarity of the AC half-cycle) out of saturation, causing the reactor's inductance to rise, as shown in Fig. 7, limiting the fault current. Advantages of this type of limiter include reliable and immediate action, including limiting the first current peak, immediate recovery of the low-impedance state following fault clearance, and the capacity to withstand faults of long duration, up to 3 seconds in this case.

Fig. 8 shows the FCL assembly comprising the two superconducting magnets, reactor tank and radiators for cooling the reactor tank oil, undergoing thermal testing at 800 A continuous current, during which the oil temperature rise remained below the limit of 60 K. A full series of short circuit and high voltage withstand tests has also been completed.

6.2 FCL layout at site

Fig. 9 shows a typical site layout. The FCL main assembly of the reactor tank, radiators and magnets is installed on a concrete plinth in an oil bund. The two 6-metre containers are mounted side-by-side on a second plinth, close to the main assembly.

The FCL main assembly of the reactor tank, radiators and magnets is installed in 6-meter containers on a concrete plinth in an oil bund

The left-hand enclosure, which is fitted with a mesh floor and ceiling, contains water chillers to dump the heat, removed from the magnets by the cooling system, into the atmosphere. The right-hand (labelled "auxiliary" in Figs. 9 and 10) enclosure contains the helium compressors, each of which is connected to a chiller by a pair of water pipes. Each helium compressor is connected to a coldhead on one of the two superconducting magnets by means of a pair of vacuum-insulated helium pipes. The auxiliary enclosure also contains the PLC and SCADA systems, which provide the control and HMI functions, an uninterruptible power supply for backup and three aircon units for controlling the humidity in the enclosure. Fig. 10 shows the actual components of the FCL in the Genoa factory.

6.3 Cooling system

The superconducting magnets need to be cooled to below 20 Kelvin, and this is accomplished by conduction of heat through copper components in contact with epoxy-encapsulated magnesium diboride coils. The magnets are cryogen-free and vacuum insulated. Heat is extracted from

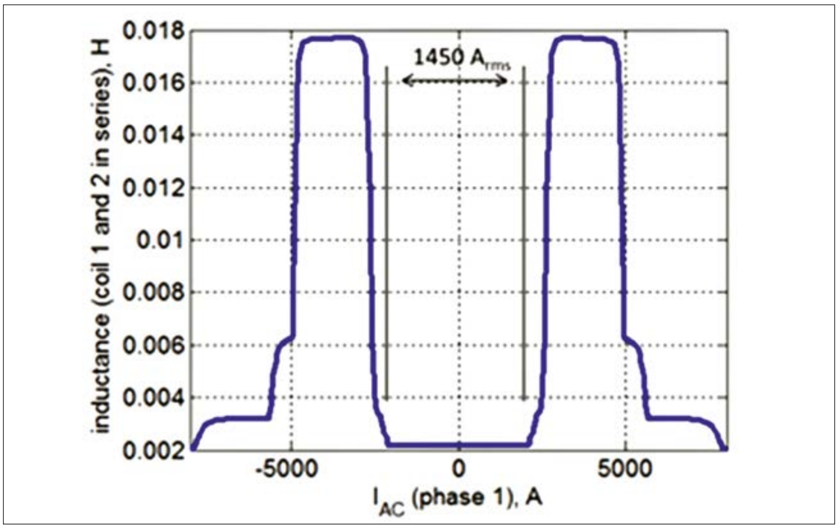


Figure 7. FCL AC coils inductance vs AC current

Figure 8. FCL during Thermal Test at IPH, Berlin

The superconducting magnets need to be cooled to below 20 Kelvin, and this is accomplished by conduction of heat through copper components in contact with epoxy-encapsulated magnesium diboride coils

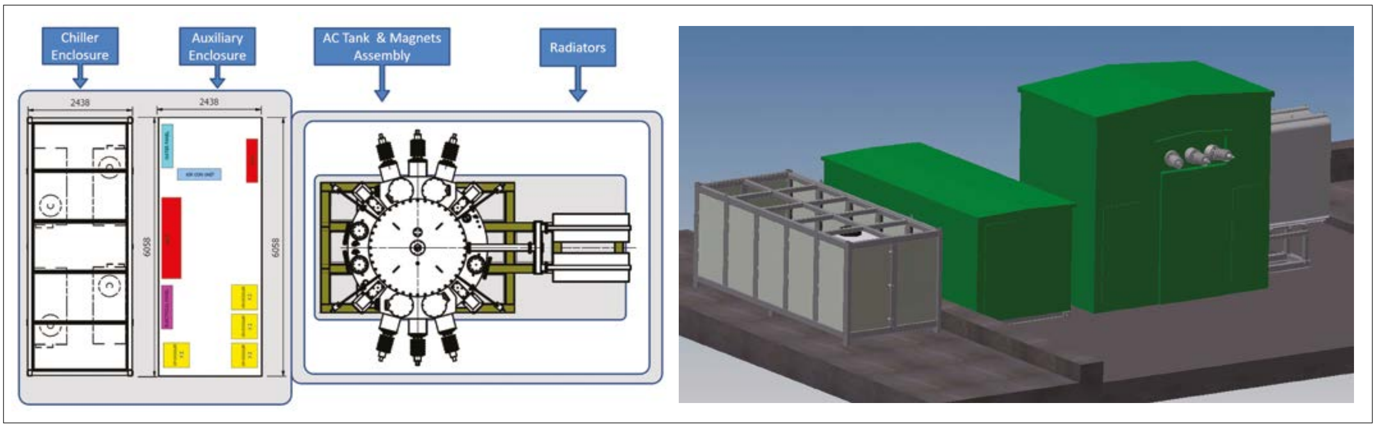


Figure 9. Typical layout of the three FCL enclosures

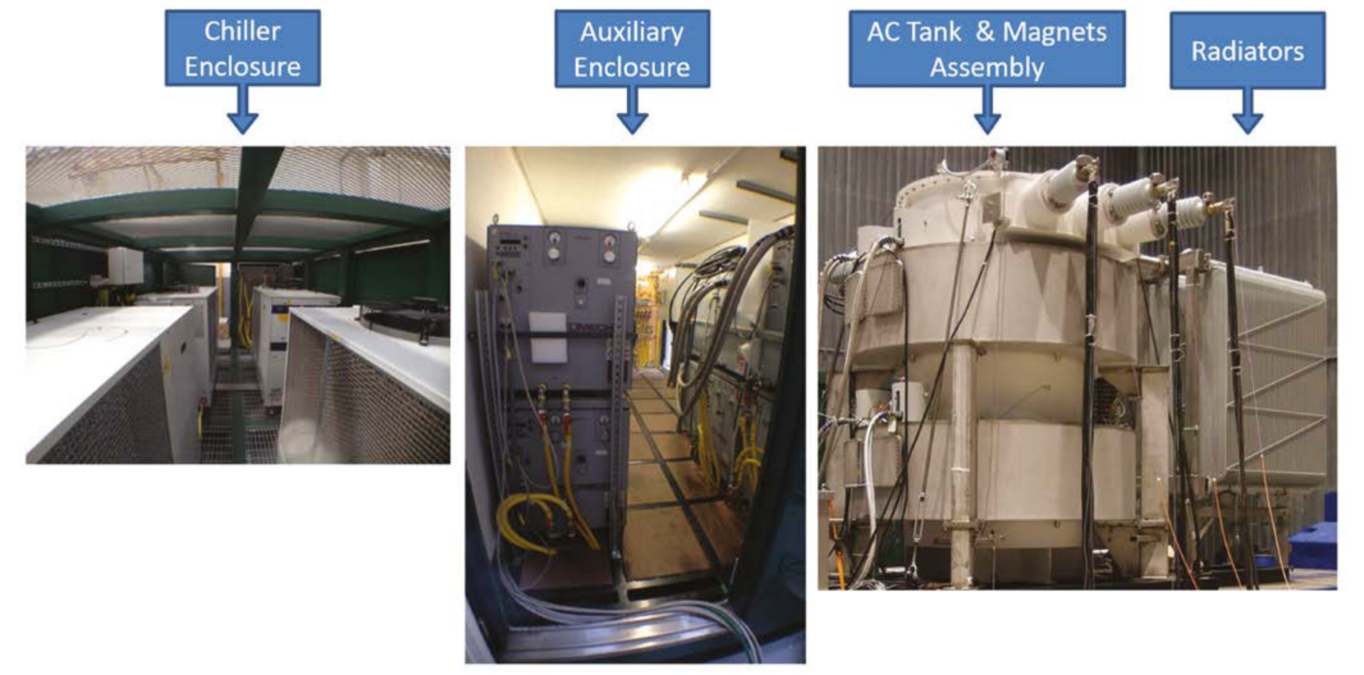


Figure 10. L-R chiller enclosure, auxiliary enclosure and reactor tank / magnets / radiators assembly

the copper cooling structure by means of four Gifford-McMahon coldheads on each magnet. The coldheads are supplied with high-pressure helium and contain a reciprocating mechanism that repeatedly lowers the pressure, removing heat. There is redundancy in this setup; three coldheads are sufficient to provide the required cooling for each magnet. The eight helium compressors are water-cooled by means of four chillers. The whole cooling system runs from a 400 V 3-phase supply and consumes 80-100 kW.

Each chiller is used to cool two helium compressors (see Fig. 11), each of which removes heat from a coldhead, one on the lower magnet and the other on the upper. This allows for one chiller to be out of service while maintaining three active coldheads on each magnet, which are able to provide sufficient cooling.

6.4 Control system and SCADA

A sophisticated control system, developed throughout several FCL projects, autonomously looks after the operation of the cooling systems, providing alarms via SMS messaging and allowing remote in-

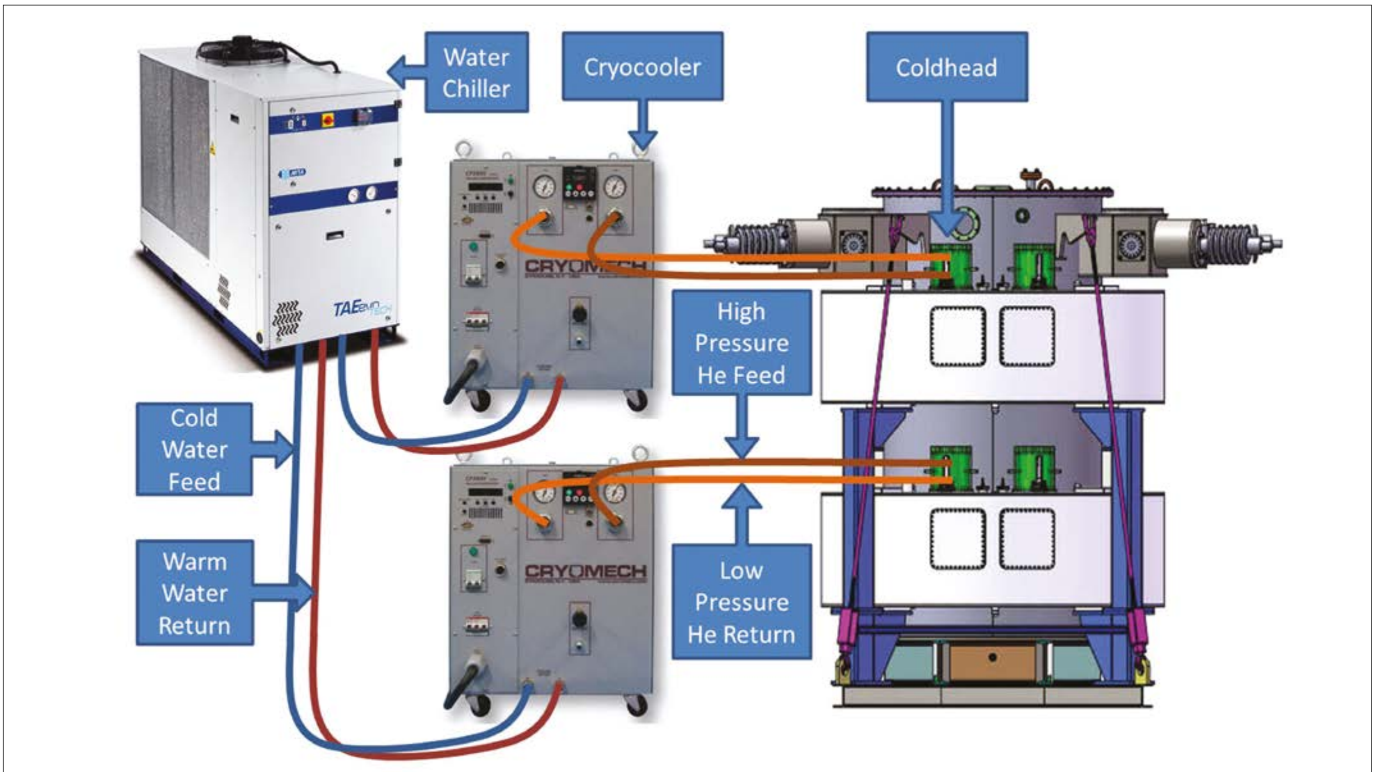


Figure 11. Schematic layout of the FCL magnets cooling system

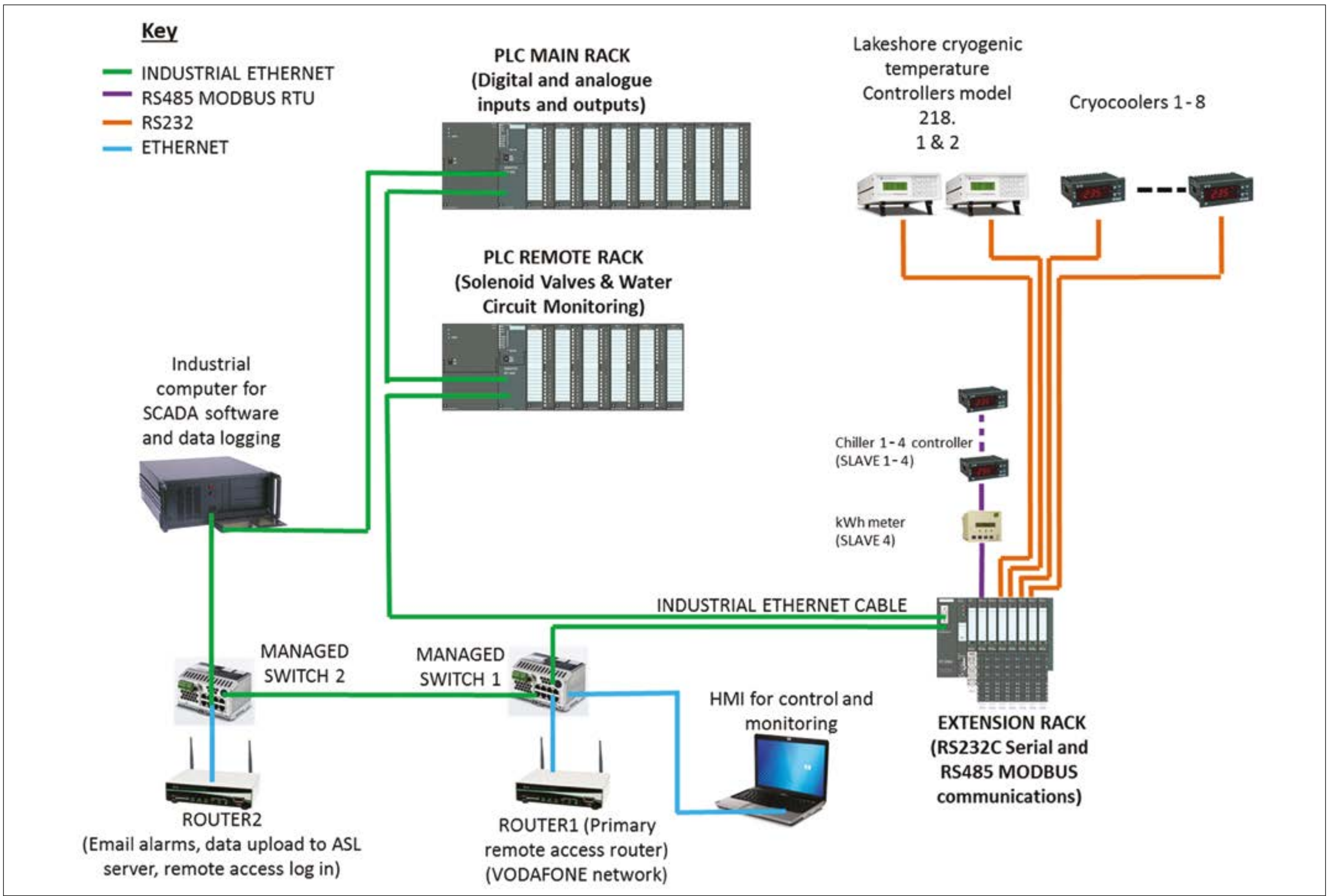


Figure 12. FCL control and SCADA systems

terrogation / control via 3G modems. The FCL control system is shown schematically in Fig. 12.

The SCADA system is accessed locally by means of two industrial PCs in the auxiliary enclosure and can be accessed remotely via the internet. The main cooling system screen (Fig. 13) displays the temperatures and flow rates of the cooling water and the oil temperatures in the helium compressors. Further screens display details about the chillers, compressors, superconducting magnet internal temperatures, the external environment, etc.

A sophisticated control system, developed throughout several FCL projects, autonomously looks after the operation of the cooling systems, providing alarms via SMS messaging and allowing remote interrogation and control

7. FCL deployment

The authors have been involved in a number of FCL demonstration / trial projects [5] carried out successfully in the UK between 2009 and 2015 during which both resistive and saturated-core limiters were installed in distribution network substations. Fig. 14 shows two examples of how the FCLs were connected into the networks.

FCLs in the UK trials were connected either as a bus-section connector (left) or in a transformer tail (right). The SFCLs were both added because the upstream (33 kV) fault level had increased. Similar deployments may be used when a transformer is upgraded, or a new transformer is added to an existing busbar, in all cases allowing the busbars to remain interconnected, maintaining the plant redundancy level. If a 33 kV supply is lost, the other transformer must supply all of the load currents. In the bus-section deployment, the SFCL only has to carry the load current to the other busbar, allowing a lower-rated SFCL to be used. In the transformer tail deployment, which is simpler to implement as existing switchgear does not need to be modified, the SFCL must carry all of the load currents if the T x 2 supply is lost, but it can be bypassed because the fault level is now ~ ½ of the previous level. For this reason, FCLs intended for transformer tail connection are designed to have a short-time overcurrent capacity to provide time during which the bypassing can be implemented. In the case of the 36 kV FCL which is central to this article, the continuous current rating is 800 A, and the short-time rating is 1400 A for 15 minutes.

8. Current limiting performance

In order to investigate the performance of the FCL and its interaction with the power grid, a numerical model of the device was developed and coupled with the circuit model of the power network. The model was developed for ASG at the

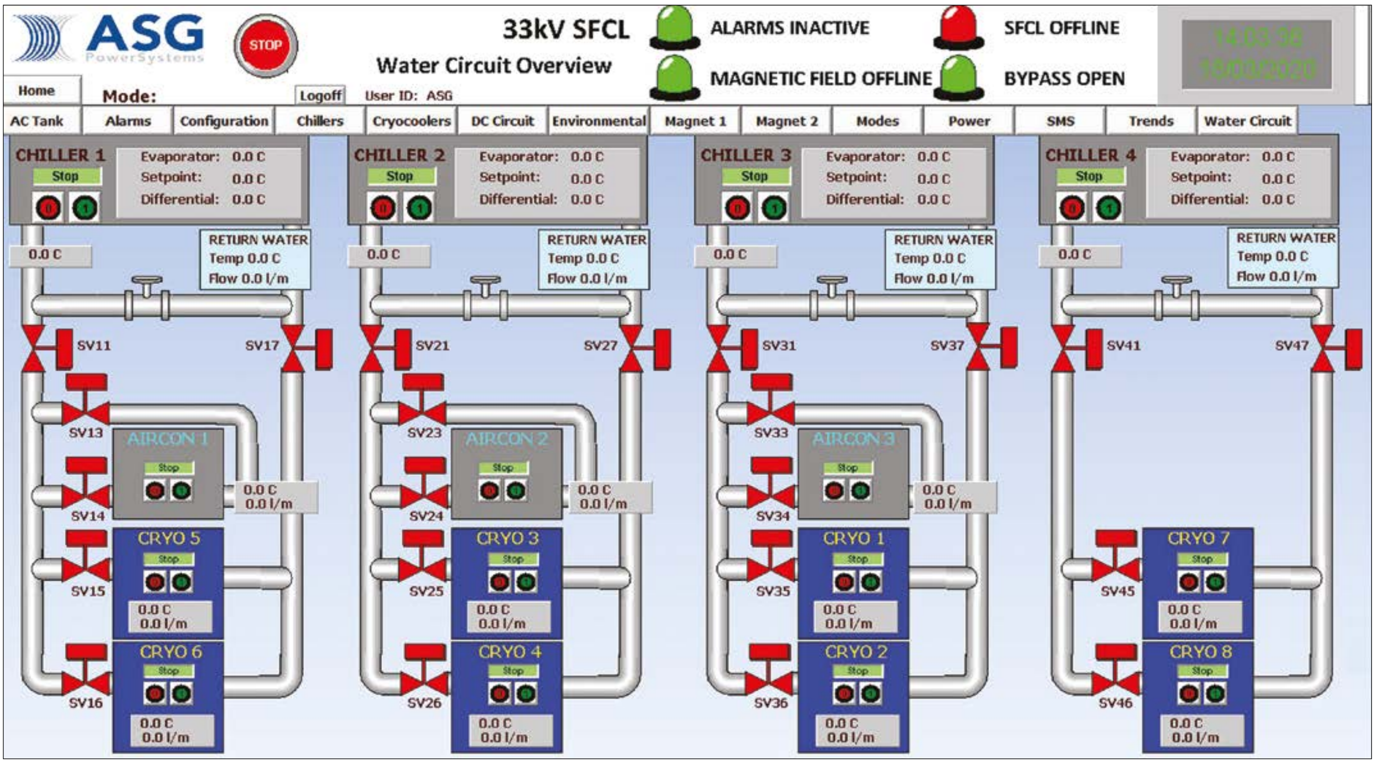


Figure 13. Cooling water system SCADA screen

A number of FCL demonstration projects has been carried out successfully in the UK between 2009 and 2015, during which both resistive and saturated-core limiters were installed in distribution network substations

University of Bologna [6]. Results from the model were compared with the results of full-scale short-circuit tests with a prospective symmetrical RMS fault level of 8 kA and an initial peak of 21 kA. The limiter reduced the fault current to 5 kA RMS symmetrical and 14 kA peak – the calculated and measured results are shown in Fig. 15.

These results show that the FCL performs according to its specification and that the model is able to reproduce the measured data from full-scale test results. Additionally, the model is sufficiently general in nature to allow variations on the FCL design to be evaluated and therefore, the modelling methodology is applicable to a wide range of FCL designs.

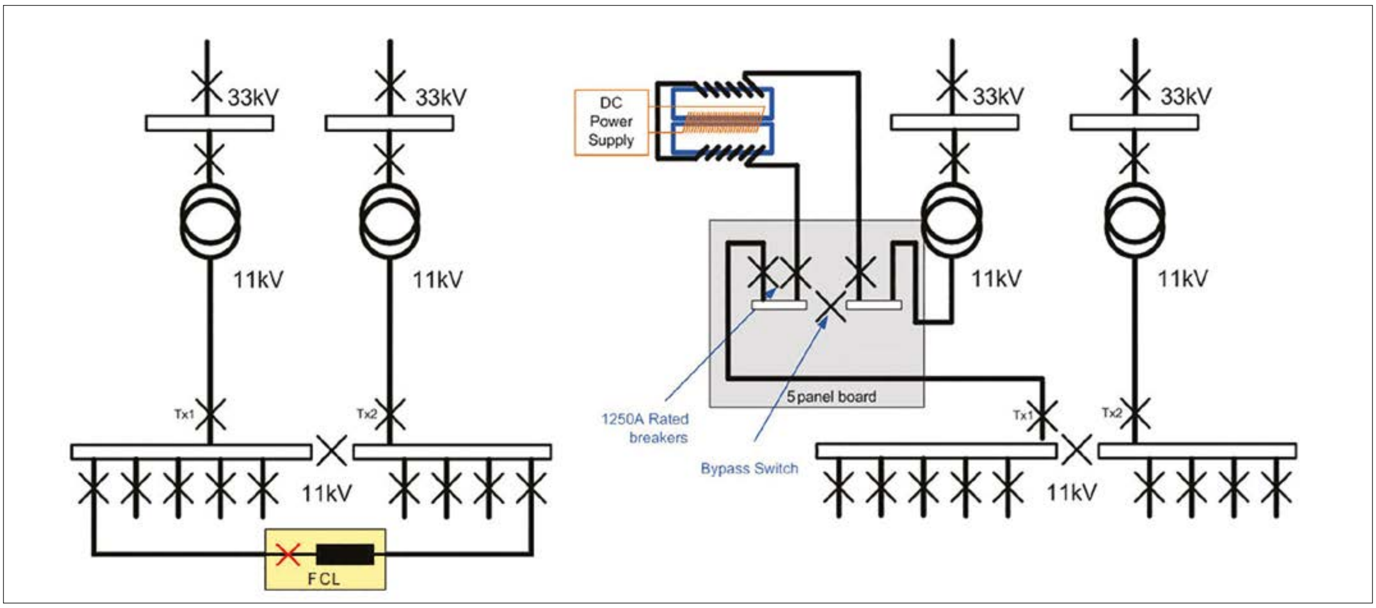


Figure 14. Bus-section (left) and transformer tail (right) FCL deployments

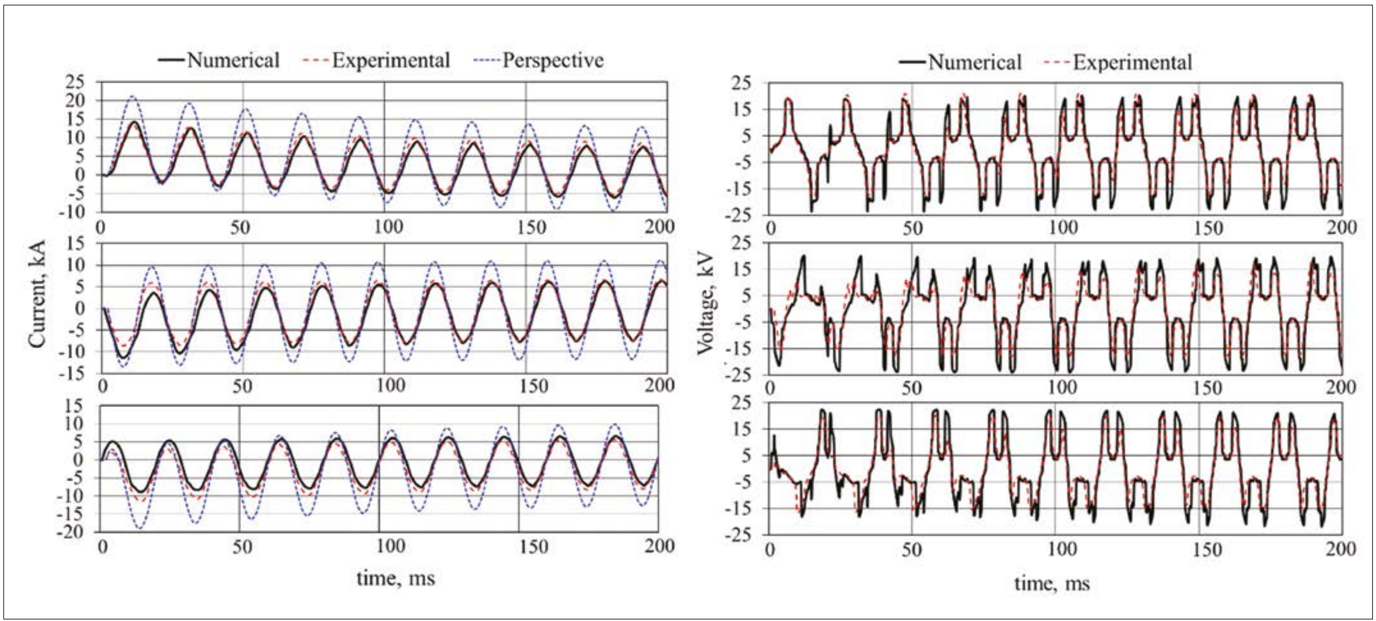


Figure 15. Results of short-circuit tests showing prospective and limited (measured and calculated) currents (left) and (measured and calculated) voltage drops across the device (right)

9. Conclusions

Magnesium diboride wire, optimised for this application by the Columbus division of ASG Superconductors (Genoa and La Spezia, Italy), has been incorporated into dry-cooled superconducting magnet assemblies by ASG in Genoa. The magnets have been shown to effectively saturate the cores of a 36 kV; 800 A FCL and to withstand repeated fault currents without problems, including a fault of 3 seconds duration. The required performance of the FCL was achieved. Plans for installation of the device have been delayed by the COVID-19 epidemic – it is hoped that when some service experience has been gained, a further article will be published. The open-core architecture applied here at 36 kV uses well-established design and manufacturing principles (developed over many years in transformers) and can readily be upscaled to accommodate higher voltages and currents. ASG Power Systems is able to offer FCLs for distribution and transmission applications – please contact the authors for more information.

Bibliography

[1] B. P. Raju, K. C. Parton, and T. C. Bartram, *IEEE Trans. Power Appar. & syst.*, 101, pp. 3173-3177 (1982)

[2] F. Moriconi, F. De La Rosa, F. Darmann, A. Nelson, L. Masur, *Development and deployment of saturated-core fault current limiters in distribution and transmission substations*, IEEE Trans. Appl. Supercond., Vol. 21 (3), pp. 1288-1293, (2011)

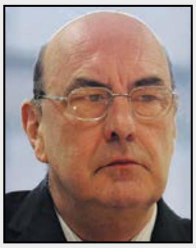
[3] S. Kobayashi, *Development and Manufacture of Bi-2223 Wires*, Research, Fabrication and Applications of BI-2223 HTS Wires, edited by K. Sato, World Scientific Publishing Co. Pte. Ltd. Singapore, pp. 137-150, 2016

[4] V. Braccini et al., *Development of ex situ processed MgB2 wires and their applications to magnets*, Physica C: Superconductivity, vol. 456, no. 1/2, pp. 209–217, June 2007

[5] D. Klaus et al., *Superconducting fault current limiters – UK network trials live and limiting*, CIRED Conference Procs, Paper 0285 (2013)

[6] Morandi et al., *Development of a Saturated Core Fault Current Limiter with Open Magnetic Cores and Magnesium Diboride Saturating Coils*, IEEE Transactions on Appl. Supercond., Vol. 27 (4), pp. 1-7 (2017)

Authors



David Klaus has spent thirty years in senior roles in R&D and product development with major suppliers of high-voltage equipment, including Schneider Electric and Reyrolle Switchgear. He co-founded Applied Superconductor in 2004 to bring high-technology products to the electricity industry and is now Chief Technology Officer with ASG Power Systems.

Christian-Eric Bruzek received a PhD and engineering diploma in material sciences at Lille University, France. He worked at ALSTOM in the superconducting department as a technical manager before joining Nexans as R&D project director, where he managed the developments of fault current limiters and superconducting cables. He recently joined ASG as business development manager of innovative power systems. He was chairing the International Superconductivity Standardization Committee and participates in CIGRE working groups. His current interests are grids and power system innovations to reduce CO_2 emissions.