FAULT CURRENT LIMITER: INNOVATIVE SOLUTIONS FOR ELECTRIC NETWORKS PROTECTION USING HIGHER TEMPERATURE SUPERCONDUCTING MATERIALS

David Klaus, Christian-Eric Bruzek

A saturated-core fault current limiter with superconducting magnets manufactured by ASG Magnets & Systems Unit is described. The magnet coils are wound using magnesium diboride superconducting wire manufactured by the Columbus Unit of ASG Superconductors.

Magnesium diboride wire, optimised for this application by the Columbus division of ASG Superconductors 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 36kV; 800A FCL and to withstand repeated fault currents without problems, including a fault of 3 seconds duration. The required performance of the FCL was achieved.

The ASG limiter has an "open-core" architecture and magnesium diboride wire has been used for the solenoids (magnets) which provide the saturating flux. The operating principle is identical to that of the closed[1]core arrangement. Any failure of the magnet cooling system or the magnet dc power supply results in the FCL shifting to a high-impedance state, so this approach is inherently fail-safe.

1 Introduction

Electricity supply networks are designed to have as low as possible source impedance because the widely varying demand for power results in widely varying load current magnitudes and it is necessary to maintain the network voltage at a constant level. This can be accomplished for slow demand shift (day/night, summer/winter) by means of transformer tap-changers, but rapid shifts in demand (industry, transport, domestic peaks) must not affect the supply voltage beyond strict limits, typically ± 6%.

Short-circuits in networks occur occasionally, due to cable or plant failure (excavation, insulation breakdown) or transient flashovers on overhead lines (lightning, vegetation). The current, known as fault current, which flows in the short-circuit, is limited only by the necessarily low network source impedance and can amount to tens of thousands of Amperes. Network components such as cables, lines, transformers and switchgear have limited fault current capacities which if exceeded can lead to catastrophic failure potentially causing explosion, fire and vaporisation of materials with attendant toxicity hazard.

If it becomes necessary to increase the load capacity of a network locally (housing or industrial development) this is accomplished by adding transformers or local generation leading inevitably to a reduction of the source impedance and an increase in the magnitude of the fault current (fault level). Enhancements of upstream network capacity or interconnection to increase plant redundancy can also cause the fault level to rise. If the increase in fault level is sufficient to risk exceeding safe levels for the network infrastructure, means to limit the fault current are required.

Figure 1 (cover) Rainbow behind high voltage electricity cables near Great Wilbraham Cambridgeshire, England
© GettyImages, Ian Cumming / Design Pics

2 Fault current limiting

Fault-current limiting has traditionally been accomplished by raising the network source impedance, either by splitting circuits which are normally connected in parallel, or by inserting fixed impedances, usually primarily inductive in nature, into an electricity supply circuit, to restrict the magnitude of the current which flows if a short-circuit occurs. Series reactors or high-impedance transformers usually provide the inserted impedance.

This approach has the desirable effect of reducing the fault current to a safe level so that switchgear and other network equipment remain within their operational capacities i.e. short-circuit ratings are not exceeded. It also has the undesirable effect of increasing locally the network's source impedance, reducing the voltage stability (power quality) as the load current magnitude varies.

Solutions providing the fault limiting functionality whilst maintaining a low source impedance in the absence of a fault can be provided by emerging technologies. The availability of lower cost, higher temperature superconducting materials has been an enabling factor in the development of these technologies. Devices having these characteristics are known as fault current limiters (FCLs).

A fault current limiter must be able to change impedance autonomously, without active sensing or actuation systems which might be prone to failure. This is because FCLs are installed in series connection with other network components which have limited abilities to withstand the passage of fault-current, or in the case of switchgear, maximum fault making and breaking capacities. The impedance change must also occur rapidly, before the first peak of the fault current, so that fault making capacities are not exceeded.

3 FCL Types

3.1 Non-autonomous FCL technologies

It is possible to break an electric circuit, equivalent to inserting an infinite impedance, by embedding an explosive charge inside a locally weakened conductor and detonating the charge electrically if the fault current rises above a safe level, or if the rate-of-rise of the fault current indicates a subsequent excessive magnitude. The conductor is ruptured and the arc is extinguished by the blast. Devices using this approach have been available for a number of years from manufacturers in Europe and the

USA, but they rely on measurement, decision-making and actuation systems which are deemed to be failure-prone by some authorities and any failure leaves a low impedance in circuit so the fault remains unlimited.

Power-electronic based FCLs have also been proposed; again these require active actuation systems, the failure of which would most likely result in the fault remaining unlimited.

3.2 Autonomous FCL technologies

There are currently two main approaches to providing autonomous FCL functionality whereby the impedance inserted is either primarily resistive or primarily inductive.

3.2.1 Resistive Limiters

In a resistive limiter, load current supplying power to customers is passed through a conductor which becomes more resistive if the current exceeds a certain level. In current practice, this conductor comprises a length of superconducting material, maintained at a temperature below the critical temperature of the material. The superconductor is dimensioned to revert to a normal conducting state (quench) if the current exceeds a certain level. A series circuit-breaker operated by a rapid and reliable local protection system is required to interrupt the fault current through the FCL to protect the quenched superconducting circuit from overheating and to allow the superconductor to cool to below its critical temperature so that the series circuit-breaker can be re-closed, reconnecting the FCL. 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 FCL and its series circuit-breaker. Where high-temperature superconducting (HTS) material is used (typically Bi2212, Bi2223 or YBCO, all of which have critical temperatures of around 90K), 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. Any failure of the cooling system results in the FCL shifting to a high-impedance state, so the approach is inherently fail-safe.

3.2.2 Inductive Limiters

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.
Another approach is to provide iron-cored reactors where the cores are

driven into saturation by an applied magnetic field. Under normal conditions, the cores remain saturated, but are driven out of saturation during a fault. In the implementation described here, two reactors are connected in series. During a fault, one of the reactor cores is driven out of saturation during each positive half-cycle of the fault current and the other during each negative half-cycle. This approach is illustrated in Fig. 1.

The saturating flux is produced by the dc solenoids (blue) and the load current passes through the ac coils (orange). The iron cores remain saturated whilst the ac coils carry 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. The inductive reactance of a coil with a saturated core is rather low and when the core is de-saturated, the reactance rises by a large factor – in the case discussed here, it is around 6 times. This rise provides the current limiting functionality.

There is a perceived benefit of this approach in that series reactors, both air and iron-cored, have been used for many years and standards covering their design and qualification exist already.

The "closed-core" arrangement of Fig. 1 was developed initially in the 1960s at IRD in Newcastle (UK) by messrs. Raju, Parton and Bartram using low-temperature superconducting solenoids (frequently referred to as magnets) to provide the saturating flux.

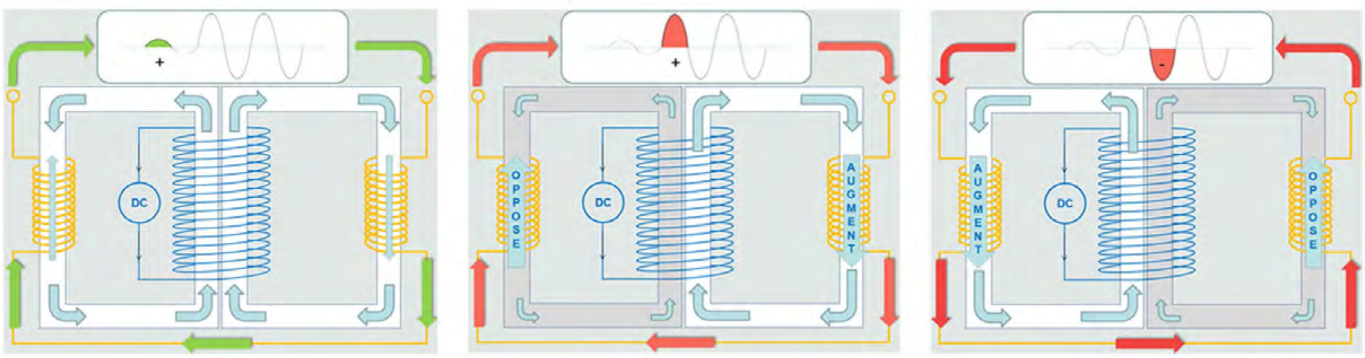


Figure 1 Closed-core arrangement (left) under load current (centre & right) during a fault

The saturating solenoid is required to provide a high flux-density and to keep the size, mass and power requirements within practicable limits, superconducting tape or wire may be used. In a three-phase limiter, it is possible to use a single solenoid to saturate the cores of the six ac coils.

The ASG limiter has an "open-core" architecture and magnesium diboride wire has been used for the solenoids (magnets) which provide the saturating flux. The operating principle is identical to that of the closed-core arrangement. Any failure of the magnet cooling system or the magnet dc power supply results in the FCL shifting to a high-impedance state, so this approach is inherently fail-safe.

4 ASG FCL Design

The open-core arrangement is shown schematically in Fig. 2. The ac coils are wound onto straight triangular section core posts which are enclosed in an oil-filled stainless-steel tank.

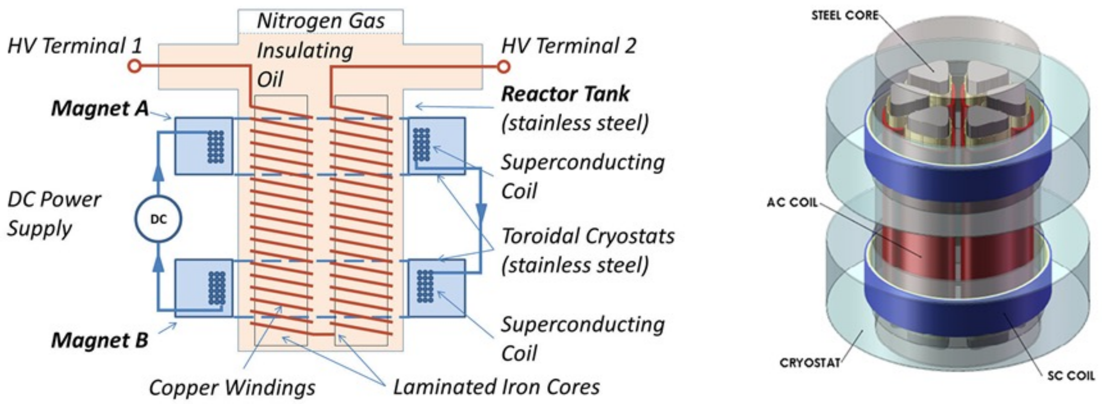


Figure 2 Closed-core arrangement (left) under load current (centre & right) during a fault

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 which provides electrical insulation facilitating up-scaling of the voltage rating to transmission-voltage levels. The installation of the superconducting magnets outside the oil tank allows access to the magnets for maintenance even while the FCL is operating. A 3-year trial of a limiter rated 11 kV; 1250 A using this technology was undertaken in 2012-2015 in northern England, during which at least 9 significant network faults occurred and were limited effectively by the device.

4.1 36kV; 800A FCL Development

The 11kV FCL mentioned previously 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, both 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 limiter would reduce the fault current magnitude by 40%.

4.1.1 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 (65K), a cheap, abundant, and environmentally friendly fluid, which makes HTS tape an attractive solution for many superconducting devices. Their performance in magnetic field increases at lower temperatures. However, their costs remain high. Despite an industrialised process based on powder-in-tube (PIT) technology, 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.

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	3-0.5 mm	I_c @70 K, 0.5 T 350-400 $A.cm^{-1}$	Length < 1500 m	80-120 €/ kA/m
YBCO		4-12 mm		I_c @70 K, 0.5 T 500-800 $A.cm^{-1}$	Length < 500 m	
MgB_2	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				

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. Multiple MgB_2 fibres, typically in a nickel matrix, are drawn to form the wire or tape.

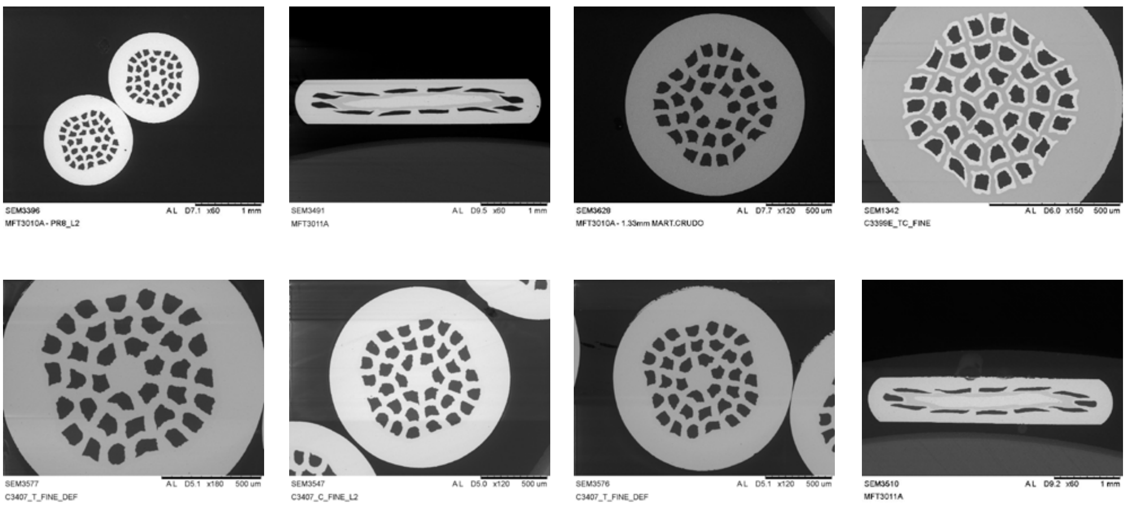


Figure 3 Cross section of multifilamentary MgB_2 tapes and wires (MgB_2 filaments in black)

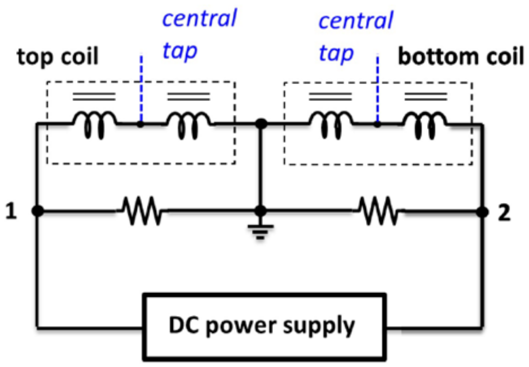
Magnesium diboride wires and tapes (Fig. 3) are available in long lengths and their cost is comparatively low, as indicated in Table 1. However, to be superconducting, this material must be kept below around 25 K requiring more sophisticated cooling systems than providing liquid N2. Consequently, the cost of the cooling 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 15-25K remains still affordable. This extra cost in comparison with HTS cooled in liquid N2 was found to be counterbalanced by the low cost of MgB_2 tapes especially when considering large FCL systems.

4.1.2 MgB_2 Magnets

The 36kV saturated core FCL comprises 6 (2 per phase) iron-cored reactors in which the iron cores are driven into saturation by the magnetic field produced by two superconducting magnets, arranged as a Helmholtz pair. The magnets 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 wire has been optimised for this application to allow small operation of the FCL up to a temperature of 28K.

The magnets have been designed to withstand the not insignificant mechanical and electrical stresses associated with this application. The two coils are connected to the power supply as shown in figure. In normal condition the two coils will operate in series. However when a fault occours the AC windings will induce a not neglible current on the superconducting magnets, this effect is limited by a copper shield.



These conditions lead to the generation of a great force along the axis of the superconducting magnet; in the radial direction the force is more contained.

A voltage tap is made available from the middle of each of the two coils for quench detection purposes. A dump resistor is connected to each of the two coils in order to allow fast discharge during possible quench.
A quench analysis has been carried out in order verify if maximum temperature and voltages during quench meet the standard design criteria.
The total charging time, starting from zero current up to the nominal value In, is less than 30 minutes.
The main design parameters of the MgB_2 windings are shown in table:

Parameter	Value	U.M.
Total length of conductor (one coil)	22.1	km
Inner radius of the cryostat	841	mm
Outer radius of the cryostat	1097	mm
Height of the cryostat	785	mm

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 the epoxy-encapsulated magnesium diboride coils.
The magnets are cryogen-free and vacuum insulated. Heat is extracted from the copper cooling structure by means of Gifford-McMahon coldheads. The coldheads are supplied with high-pressure helium and contain a reciprocating mechanism which 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 volt 3-phase supply and consumes 80-100 kilowatts.

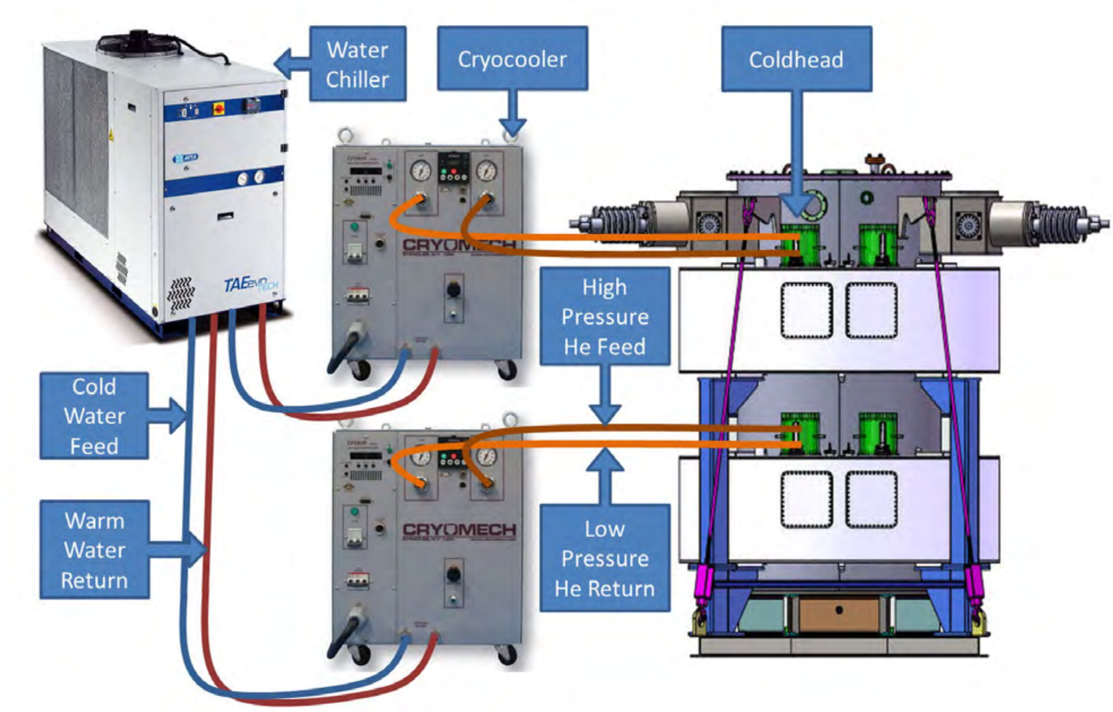


Figure 4 Schematic layout of the FCL magnets cooling system

Each chiller is used to cool two helium compressors (see Fig. 4), each of which removes heat from a coldhead, one on the lower magnet and the other on the upper. This allows one chiller to be out of service, whilst maintaining three active coldheads on each magnet, which are able to provide sufficient cooling.

5 FCL Deployment and Operation

5.1 FCL Layout at site

The arrangement of the two magnets and the reactor tank, cores and coils is as shown in Fig. 2. The general arrangement of the magnets, reactor tank & radiators is shown in Fig. 5. The assembly is about 3.7 m high and weighs 36 tonnes.

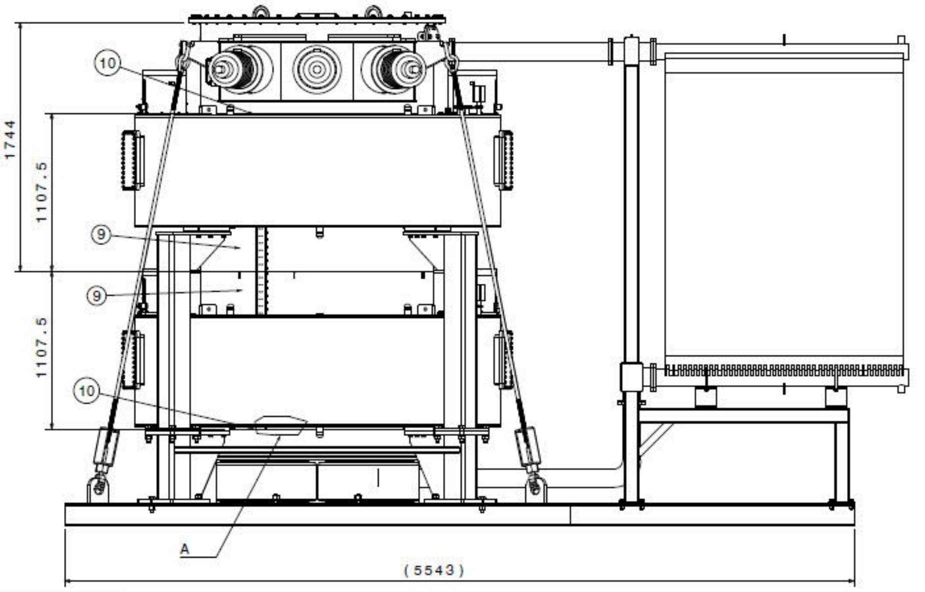


Figure 5 General Arrangement of 36kV FCL Reactor tank, radiators & SC magnets

Fig. 6 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.

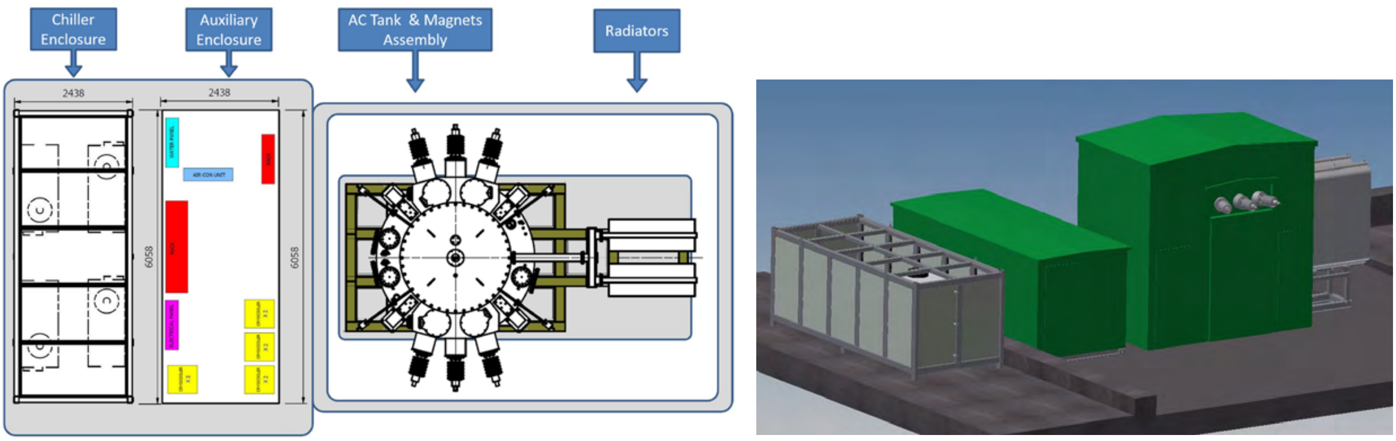


Figure 6 GTypical layout of the three FCL enclosures

The left-hand enclosure, which is fitted with 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. 6 & 7) 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. 7 shows the actual components of the FCL in the Genoa factory.

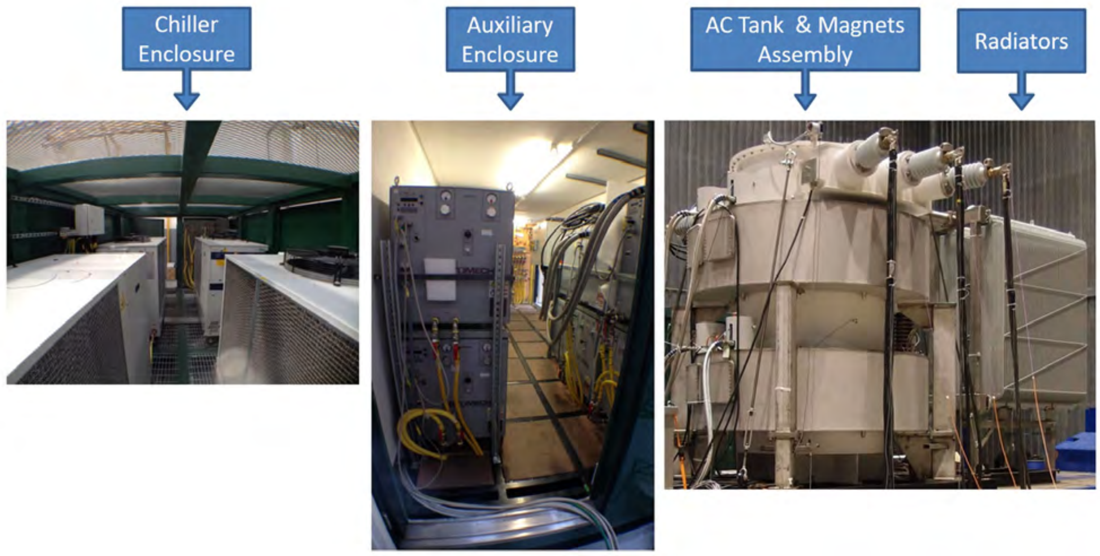


Figure 6 L-R Chiller Enclosure, Auxiliary Enclosure & Reactor Tank/Magnets/Radiators Assy

5.2 Control System and SCADA

A sophisticated control system, developed over the course of several FCL projects, autonomously looks after the operation of the cooling systems, providing alarms via SMS messaging and allowing remote interrogation/ control via 3G modems. The FCL control system is shown schematically in Fig. 8.

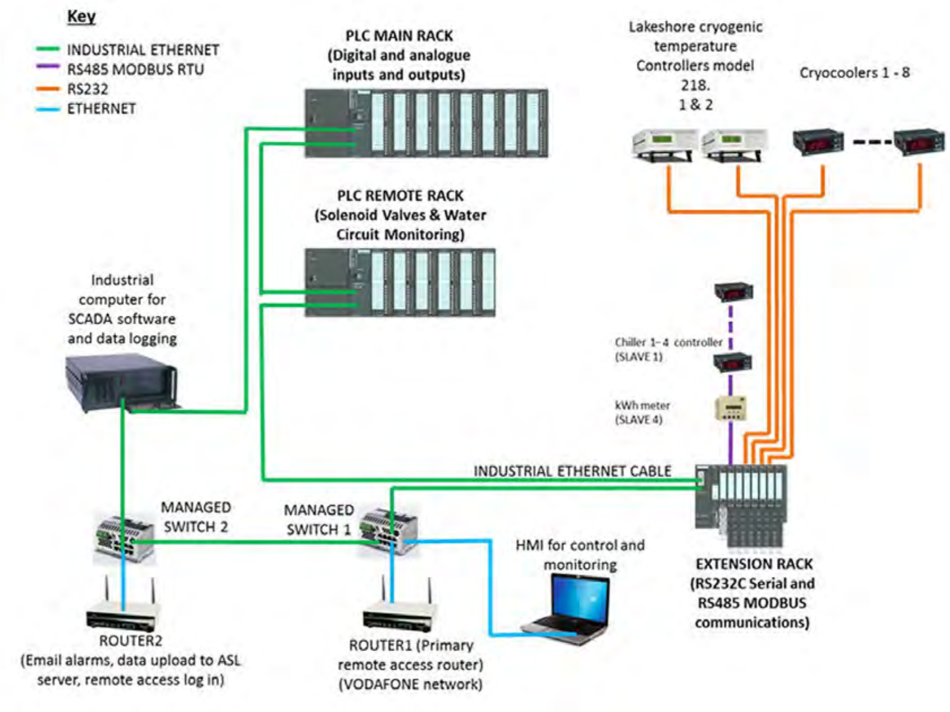


Figure 8 FCL control & SCADA systems

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. 9) 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.

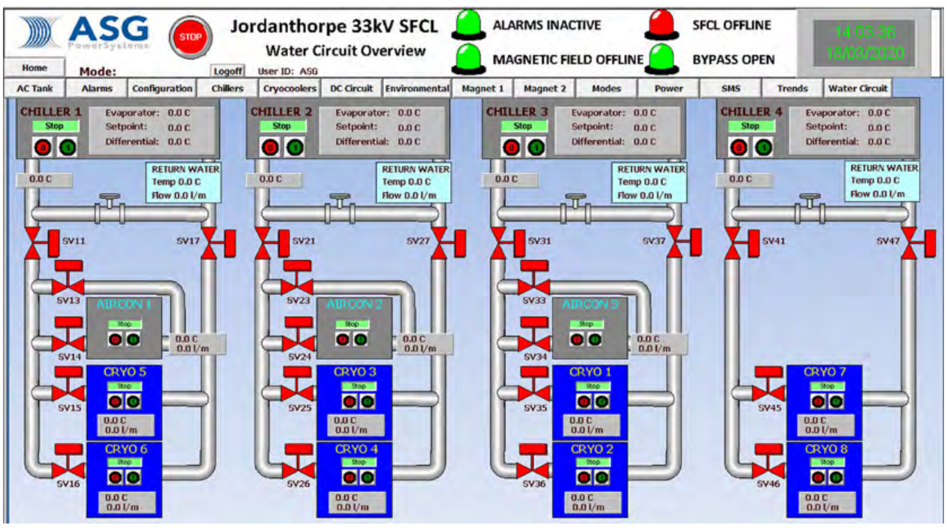


Figure 9 Cooling water system SCADA screen

5.3 Connection into Network

A number of FCL demonstration/trial projects have 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. Fig. 10 shows two examples of how the FCLs were connected into the networks.

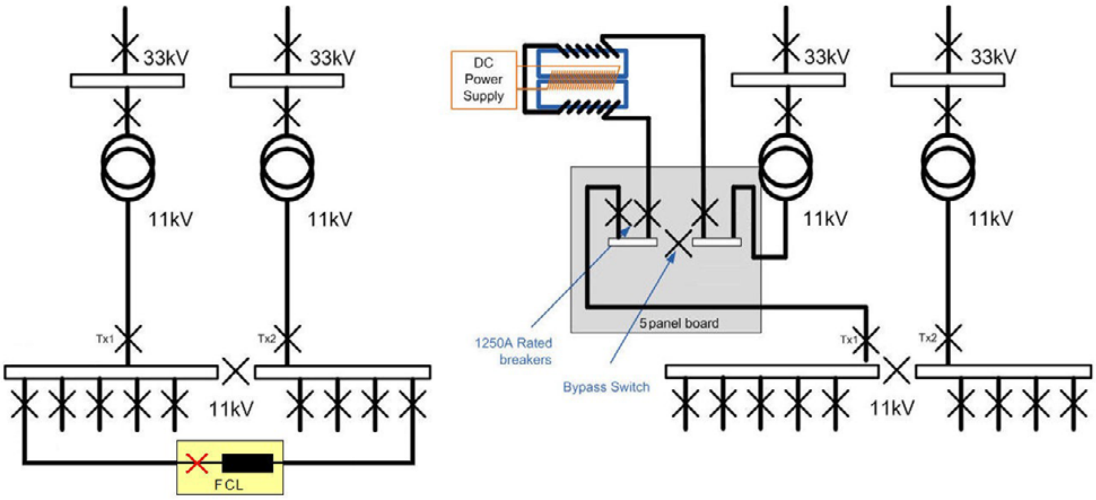


Figure 10 Bus-section (left) and transformer tail (right) FCL deployments

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 (33kV) 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 33kV supply is lost, the other transformer must supply all of the load current. 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 current if the Tx2 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 36kV FCL which is central to this article, the continuous current rating is 800A and the short-time rating is 1400A for 15minutes.

6 Performance and Testing

6.1 Thermal Testing

Fig. 11 shows the FCL assembly comprising the two superconducting magnets, reactor tank and radiators for cooling the reactor tank oil, undergoing thermal testing at 800A continuous current, during which the oil temperature rise remained below the limit of 60 K.

Figure 11 FCL during Thermal Test at IPH, Berlin

6.2 Short-circuit 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 University of Bologna. Results from the model were compared with the results of full-scale short-circuit tests with a prospective symmetrical rms fault level of 8kA and an initial peak of 21kA. The limiter reduced the fault current to 5kA rms symmetrical and 14kA peak – the calculated and measured results are shown in Fig. 12.

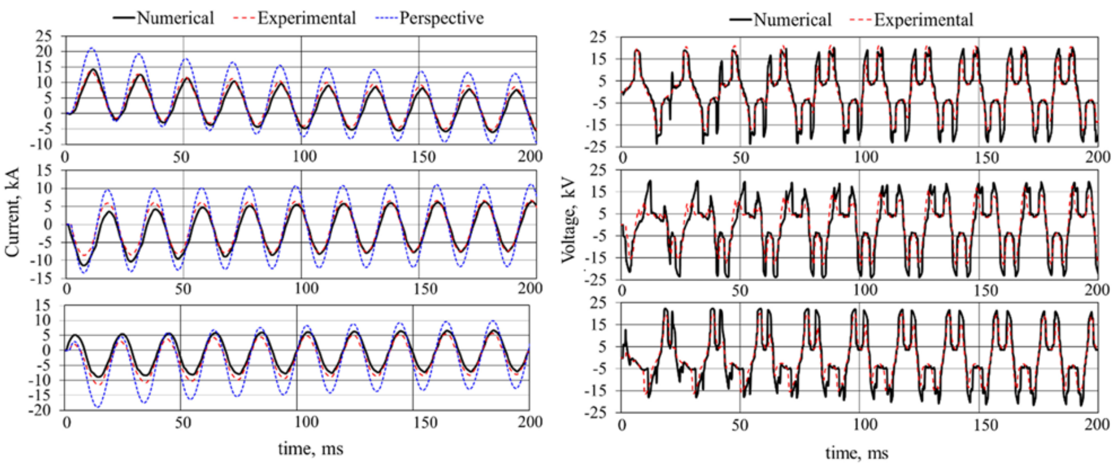


Figure 12 Results of short-circuit tests showing prospective and limited (measured and calculated) currents (left) and (measured and calculated) voltage drops across the device (right)

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.

7 Conclusions

Magnesium diboride wire, optimised for this application by the Columbus division of ASG Superconductors 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 36kV; 800A 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 COVID19 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 36kV 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.