EARTH CURRENT MONITORING CIRCUIT FOR INDUCTIVE LOADS

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Abstract

The search for higher magnetic fields in particle accelerators increasingly demands the use of superconducting magnets. This magnet technology has a large amount of magnetic energy storage during operation at relatively high currents. As such, many monitoring and protection systems are required to safely operate the magnet, including the monitoring of any leakage of current to earth in the superconducting magnet that indicates a failure of the insulation to earth. At low amplitude, the earth leakage current affects the magnetic field precision. At a higher level, the earth leakage current can additionally generate local losses which may definitively damage the magnet or its instrumentation. This paper presents an active earth fault current monitoring circuit, widely deployed in the converters for the CERN Large Hadron Collider (LHC) superconducting magnets. The circuit allows the detection of earth faults before energising the circuit as well as limiting any eventual earth fault current. The electrical stress on each circuit component is analyzed and advice is given for a totally safe component selection in relation to a given load.

SUPERCONDUCTING MAGNET SPECIFICITIES

Working at low temperature with negligible resistive losses, superconducting magnets allow high current density with high magnetic stored energy. To limit the power losses in the cables and so reduce the total converter power required, the converters are installed close to their load. The power converter rating is mainly high current, low voltage in opposition to standard warm magnets which normally requires higher voltage when increasing operating current.

The superconducting magnets are often equipped with accurate monitoring and protection systems to avoid their destruction when losing superconductivity state. These systems are based on huge amount of instrumentation, directly connected to the magnets. Part of the protection systems are based on energy extraction systems, which remove rapidly the stored energy in case of resistive transition detected in superconducting conductors; see Fig. 1 – LHC typical superconducting magnet circuit.

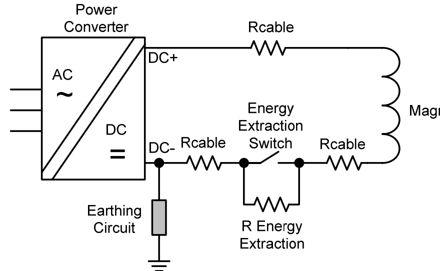

Figure 1: LHC typical superconducting magnet circuit.

Table 1: Typical 600A Circuit Rating

I Nom [A]	R Cables (Total) [Ohms]	R_{EE} Energ. Extract. [Ohms]	L.dI/dt [V]	V Flat Top [V]	V across R_{EE} [V]
±600	0.002	0.7	2	1.2	420

Due to the huge amount of protection systems, the probability to have an earth fault in superconducting magnet circuit is higher than in warm magnet circuit. Furthermore, the mechanical stress on the superconducting magnet during the cool-down to cryogenic temperatures and warm-up of to ambient temperature can induce earth fault.

EARTHING CIRCUIT SPECIFICATION

The superconducting magnets are fed in current by power converters, whose outputs are galvanically insulated from AC side. The DC side shall be grounded for safety reasons to limit the output common mode voltage, through an earthing circuit. No current is flowing through this link as long as no other earth path exists.

As soon as a low impedance path to earth appears, a current loop is created. This earth leakage current can affect the magnetic field precision, which is controlled at a ppm level, representing some mA in most of cases. At higher amplitude, it can damage the magnet or its instrumentation. The earth leakage current shall be then monitored and kept limited in a safe way. In case of superconducting circuits, the common mode voltage can go from 0V (earth fault on node DC-) and increase up to high value (±420V) during energy extraction combined with an earth fault at the level of the energy extraction resistor or at the magnet side.

In case of a second earth fault, the earth leakage current loop will be closed between the two earth faults bypassing the earth fault monitoring circuit and its current limitation. The earth fault shall be then detected before storing high energy inside the superconducting magnets.

EARTH FAULT DETECTION

Following the specification of the earthing circuit (earthing of the DC side, detection of an earth fault, monitoring and limitation of the earth leakage current), different solutions have been studied.

Passive Detection

The passive detection is shown in the Fig. 2 – Passive detection. This method has been widely used for warm magnet circuit in CERN accelerator complex.

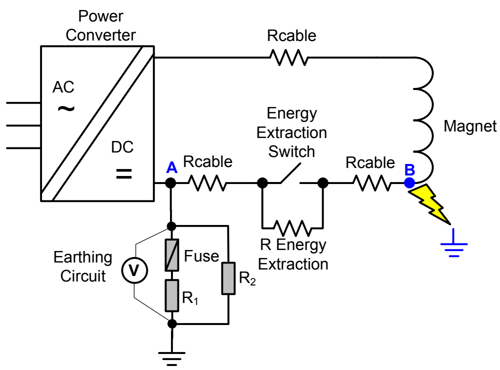

Figure 2: Passive detection.

The earth leakage current monitoring and the earth fault detection are made by measuring the voltage across R1 resistor (typically few Ohms) and the fuse. If the voltage across the sense goes over a defined threshold (typically ±0.5V), an earth fault is assumed. R2 resistor avoids the DC circuit becoming floating when the fuse has blown (typically 1A fuse). R2 value (typically 10 kOhms) limits the earth leakage current in such a case.

This solution relies on the voltage drop across the circuit impedance between the earthing circuit (point A) and the earth fault (point B). The voltage drop shall be above the earthing circuit voltage threshold to detect an earth fault. In case of superconducting magnets, the resistance of the cables can be very low; see Table 1 - Typical 600A circuit rating. In this case, an earth fault would only be detected at high current, inducing high level of stored energy in the magnet. As this magnet could be used as corrector around 0A, no earth fault could never been detected, even in the case of a magnet polarity directly connected to earth.

Another drawback of this solution is the difficulty of determining whether or not the fuse has blown.

Active Detection

An active detection was studied based on a DC current source (typically 100mA) in parallel with R3 resistor (typically 100 Ohms) to create a common mode (10V) higher than the voltage drop across the cables; see Fig. 3 – Active detection.

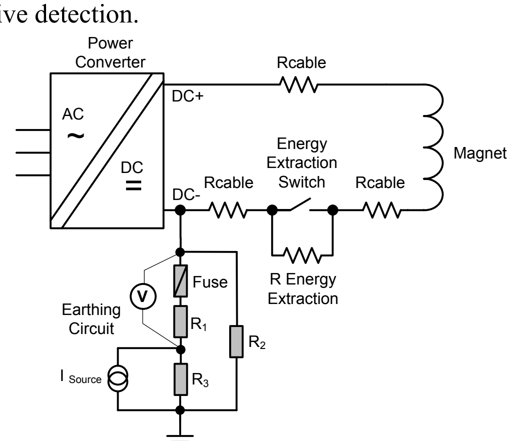

Figure 3: Active detection.

The earth leakage current monitoring and the earth fault detection are made by measuring the voltage across R1 resistor (typically 10 Ohms) and the fuse. If the voltage goes over a defined threshold, an earth fault is assumed. R2 resistor avoids the DC circuit becoming floating when the fuse has blown (typically 1A fuse). R2 value (typically 10 kOhms) limits the earth leakage current in such a case.

In this configuration, the DC output circuit has a permanent common mode as soon as the earthing circuit current source is powered.

The major benefits are that an earth fault can be detected before energising the load and it is possible to detect whether the fuse has blown.

Dead zones where an earth fault cannot be detected is directly depending on the common mode voltage applied, the power converter output voltage rating and its nature (1, 2, 4 quadrants).

EARTHING CIRCUIT IMPLEMENTATION

During design phase of the LHC power converters, CIRTEM french company proposed a mix detection based on the solutions described in the previous paragraph. A switch controlled by the converter electronics (a MOSFET) is used to select passive and/or active detections; see Fig. 4 - LHC power converter earthing circuit principle schematics. This gives the possibility of switching between the both detections in a static way (A and B configurations) or in a dynamic way depending on the state of the converter (C configuration).

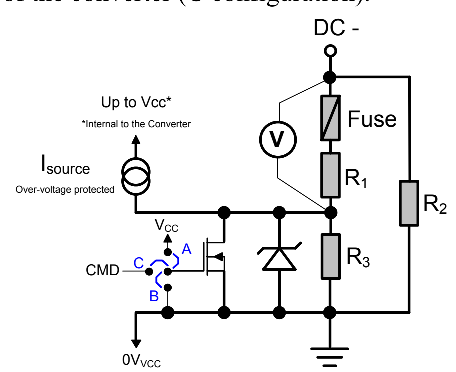

Figure 4: LHC power converter earthing circuit principle schematics.

The dynamic way is especially interesting for warm magnets with high voltage drop across the cables, which prevent from applying a too high common mode voltage at the negative output of the power converter. The active detection is used when the converter is off while the passive detection is used when the converter is on; see Fig. 5 – Active / passive dynamic detection chronogram. This allows detecting an earth fault even before energising the load, limiting damage risk.

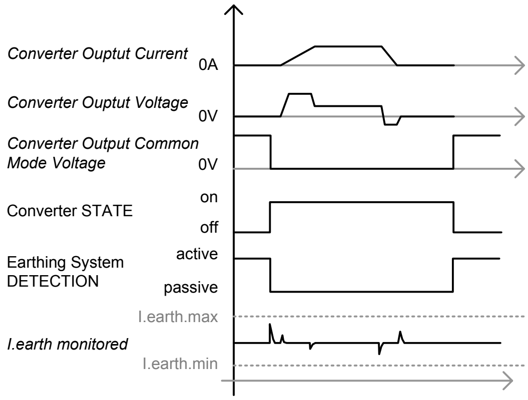

Figure 5: Active / passive dynamic detection chronogram.

This earth current monitoring circuit has been widely deployed in the converters for the CERN-LHC superconducting circuits (1700 systems).

EARTHING CIRCUIT REALISATION

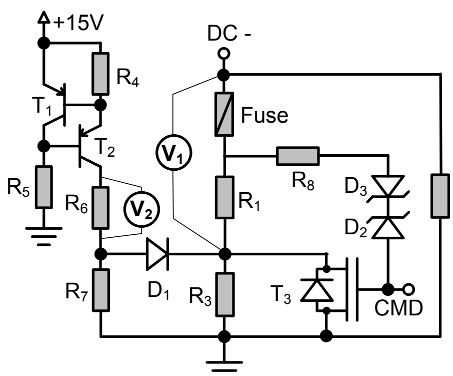

Figure 6: Earthing Circuit realisation.

A 100mA DC current source provided by R4 (6 Ohms), R5 (5 kOhms), T1 and T2, flows to R3 (100 Ohms) in order to provide a 10V floating potential on node DC-. T2 must be able to dissipate up to 1.5W continuously when the voltage drop on R3 is closed to 0V. A sense resistor R6 (6 Ohms) is used to check that the current source is working properly: 0.5V<V2<0.7V. As node DC- may reach high voltages during earthing faults, D1 diode and R7 (20 kOhms) are needed to protect T2 against reverse overvoltage. D1 diode must be rated to the highest possible voltage on node DC-.

The sense resistor R1 (10 Ohms) is used to measure the leakage current flowing to node DC-, assuming that it is high enough so that the fuse (1A) parasitic resistance can be neglected. A huge filtering of the measurement V1 is needed, in order to avoid abnormal tripping while charging or discharging parasitic and EMC capacitances on node DC-. R1 resistor must be able to handle the nominal fuse current continuously and the fuse must be rated to the highest possible voltage on node DC-.

T3 power MOSFET is used to select the active or passive detection controlling its gate CMD. The passive detection is also forced through R8 (2 kOhms) and the D2 and D3 Zener diodes (13V) when a high positive voltage is applied on node DC-. This helps to drastically reduce the rated power and size of R3 resistor, which is also protected against high negative voltage on node DC- by the parasitic diode of T3 power MOSFET. T3 must be able to endorse the nominal fuse current in linear mode with a voltage drop V_{ds} of about 20V.

R2 resistor (10 kOhms) may have to dissipate a large amount of power when node DC- may reach hundreds or thousands of Volts when an earthing fault occurs. It will often be the major contribution of the circuit in term of space needed and price.

TEST RESULTS ON LHC MAGNETS

The usefulness of the earth current monitoring circuit has been demonstrated many times during the hardware commissioning of the CERN-LHC circuits. Several earth faults have been detected before powering the circuits, due to metallic pieces in contact with live parts. As example, a metallic waste piece at the level of the energy extraction resistor of the main quadrupole circuit was pushed by the air-forced cooling and touched the live parts of the circuit, creating an earth fault. Without the earth leakage current monitoring, the problem will not be detected.

The influence of the capacitance of the superconducting load versus earth did not impact too much on the earth current variation during step voltage at the level of the converter outputs, except for long chain of magnets as the CERN-LHC main dipole circuits during the opening of the energy extraction switch. A major reason for that is that magnet current is always changing in a smooth way, avoiding too sharp dV/dt at the level of the power converter output, then limiting earth current being monitored by the earthing circuit. Another main reason is that tripping level was already taken into account the quite high EMC capacitors placed on power converter both DC outputs.

CONCLUSION

This paper presents an active earth fault current monitoring circuit, widely deployed in the converters for the CERN-LHC superconducting magnets. This circuit demonstrates his efficiency with early detection of an earth fault.