

DETECTING FAILURES IN ELECTRICAL CIRCUITS LEADING TO VERY FAST BEAM LOSSES IN THE LHC

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Abstract

Failures in the powering of LHC magnets could lead to very fast beam losses at collimators, possibly within less than 10 turns. Beam loss monitors would normally detect such losses and trigger a beam dump. However, the available time for detection with these monitors before reaching the damage level of a collimator might not be sufficient, in particular for beams with few particles in the tail of the transverse particle distribution. This has always been of concern and becomes even more relevant since very fast losses have been observed recently at HERA. In this paper, we present particle tracking studies for the LHC to identify failures of critical magnets in the accelerator. We propose a fast detection of such failures in the electrical circuit, either with highly precise hall probes for current measurement or measurements of the induced inductive voltage during the current decay. Where active detection is not possible, additional inductance in series with the electrical circuit can relax the time constraints for a safe detection of the failure.

POWERING FAILURES LEADING TO FAST BEAM LOSSES

Failures in the powering system of the LHC magnets are generally relatively slow events. The natural time constants of the electrical circuits are in the order of few seconds up to some minutes. For the protection of the powering equipment it is sufficient to detect and process failures in the circuits (such as magnet quenches, power converter or cooling failures, etc.) within a time in the order of 50 ms to 100 ms. During this time, the failure is detected by the corresponding system and transmitted to an interlock controller, which will take the appropriate actions for a controlled powering abort in the affected circuits and issue a beam dump request. The powering equipment is designed to withstand the increased electrical and mechanical stress in the beginning of such faults without material degradation.

The finite resistive part together with a low inductance in the circuits of normal conducting magnets can result in fast decaying fields in case of failures. Fast decays of the current in the magnet and consequently of the magnetic field in critical locations with large beta functions have a large effect on the circulating beam – changes of the beam trajectories and possibly fast loss of the beams.

During a failure in an electrical circuit of a normal conducting magnet (after e.g. a converter fault or short circuits), the decaying magnetic field will result in an error field $\Delta B_{error}(t)$ according to:

$$\Delta B_{error}(t) = B_0 \cdot (1 - e^{-\frac{t}{\tau}}) \quad (1)$$

where $\tau = L/R$ is the decay time constant determined by the circuit's inductance and resistance.

Particle tracking [1] can be used to study the effects of these dynamic field errors. Particle loss maps can be obtained, as a function of time, at critical aperture locations such as the collimators, located close to the beams at approximately 6 sigma. Fig.1 shows the loss rates at a transverse collimator for a trip of the D1 circuit in the insertion 5, containing 12 normal conducting dipoles in series. The detection loss level of the BLM installed at the collimator is reached after only 15 turns (approximately 1.4 ms), and only 13 turns (~ 1.2 ms) later the damage loss level of the collimators is reached. In the second simulation for the same system, the natural time constant of the decaying field has been doubled and we observe an increase of available reaction time from 13 to 21 turns (~ 1.9 ms).

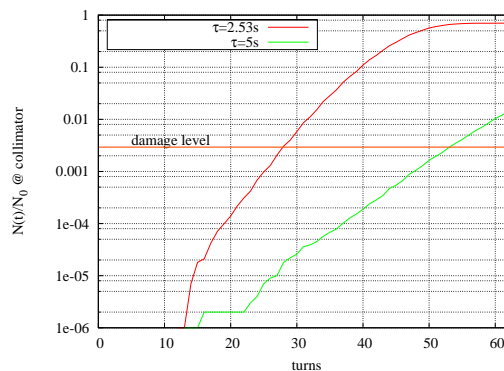


Figure 1: Total number of particles lost at collimator divided by initial number of particles for D1 trip in IR5, for nominal and twice-nominal circuit inductance. [2]

In view of the short reaction time and the potential damage risk, the protection mechanisms for these critical failures should not rely only on the Beam Loss Monitors (BLMs) installed close to the collimators. Two additional solutions have been studied and are described below. The first concept uses a superconducting coil in series with the electrical circuit to increase the natural time constant of the current decay in the circuit and hence increase the time available for detection of the fault. The second concept is based on an active measurement of the induced self-field around the connection cable and a detection of induced voltages due to the high di/dt in the circuit.

INCREASING THE CIRCUIT INDUCTANCE

As seen in the tracking studies for the normal conducting D1 magnets, an increase of the natural time constant of the decaying magnetic field will significantly increase the time available for detection of the failure. Increasing the circuit inductance without increasing the resistance can only be achieved by the use of a superconducting coil in series with the normal conducting magnets. Such additional inductance would provide an additional benefit by lowering the current ripple in the magnet.

The power converter for this circuit is located in the surface building of the interaction point, and the installation of such additional equipment will be fairly straightforward. Due to the lack of cryogenic installations in the surface buildings, the inductance would have to be designed as stand alone, either with an own cryo-cooler unit or to be refilled with liquid helium at regular intervals. Fig.2 shows a schematic example of such a stand-alone solution.

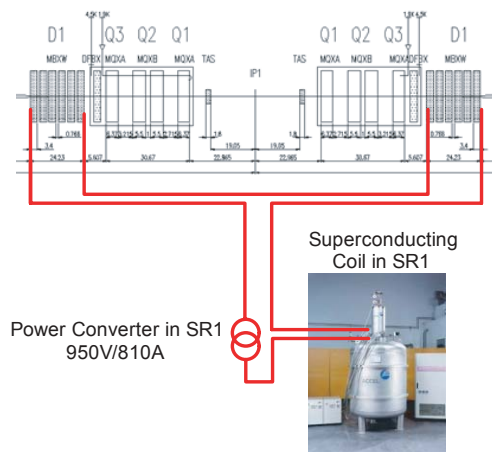


Figure 2: Schematic of a stand-alone cryostat containing a 2 MJ superconducting coil of approximately 4 H with a nominal current of 1000 A and its connection to the D1 circuit.

ACTIVE FAULT DETECTION

A direct detection of failures at the level of the electrical circuit was also investigated, using the existing SPS MSE extraction septum installation [3] as a test bed. For this system the detection of some failures via the existing power converter control system is rather ineffective, due to the very low circuit inductance (and hence low time constant) and the limited speed and accuracy of the DCCTs (DC Current Transformers) deployed for the current measurement.

Alternative detection principles were studied, based on the detection of effects caused by the very high di/dt and the subsequently induced voltages. The MSE circuit has a 23 ms time constant. The decaying current in case of failure has been simulated and compared to measurements per-

formed at the existing installations [4]. The nominal 22 kA current decays initially with a $di/dt > 20 \text{ kA/s}$, increasing to values $> 800 \text{ kA/s}$. This is nevertheless smaller than the theoretical exponential decay value due to filtering capacitors installed in the output stage of the converter.

The time available for a safe detection of a fault is short, as the allowed current error is of the order of $\pm 1 \cdot 10^{-3}$ (corresponding to $\pm 22 \text{ A}$ for a nominal current of 22 kA) [5]. This value is based on a ± 1 sigma orbit excursion in the aperture of the TT 40/TI 8 transfer line. The required accuracy is already in the same order as the specified precision of the power supply ($\Delta i/i_{max}$) of $\pm 2.5 \cdot 10^{-4}$.

Simulations show that a detection has to take place in less than 1.5 ms after the fault to generate an interlock fast enough to ensure that the current is not outside this tolerance window during extraction. The required accuracy, in combination with the tight time constraints and the need for a reliable detection signal, make the fault detection difficult, as an accurate monitoring and measurement of absolute values is subject to long sampling times.

Detection of induced voltage change

In a first approach, the voltage induced over the magnet inductance was used for the detection of the decaying current. Despite the low inductance of normal conducting magnets, the large di/dt provokes an inductive voltage as high as 1.5 V in the magnet coils. This is feasible to detect compared to the change of resistive voltage. A simple electronic circuit was developed as shown in Fig.3. The principle is based on a Sample & Hold structure, which memorizes the voltage drop over the magnet at the flat top when triggered around 10 ms before the beam extraction. This reference value is then compared against an upper and lower boundary value which correspond to the tolerance window for a valid extraction. As soon as the measured voltage value is outside tolerance, an interlock signal will be generated to inhibit the extraction.

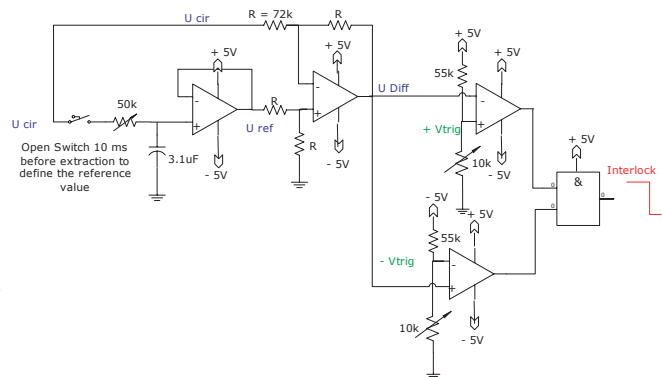


Figure 3: Principle of the detection electronics for a surveillance of the current or the inductive voltage of the SPS extraction septa circuit.

First tests with this principle showed good results, despite no precautions taken in terms of shielding and noise filtering. Fig.4 shows the results of this preliminary test with CH1 indicating the interlock signal, CH2 the current and CH3 the measured voltage at the level of the power converter. Due to the differentiating effect, a surveillance of the circuit voltage is more sensitive than measurements of the circuit current and is to be favored for electrical circuits with large di/dt in case of failures.

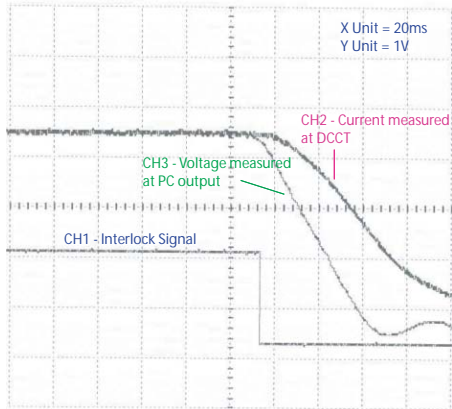


Figure 4: Measurement results for the detection of a powering fault in the MSE circuit of the SPS with a voltage pick-up installed at the output stage of the power converter.

Detection of self-field change

For circuits with a slower current decay, a direct and precise measurement of the current could be used if the noise starts to superpose the voltage signals to be measured. Current transformers (DCCTs) for nominal currents as high as 1 kA are large, expensive and too inaccurate for this application. The circuit current was therefore measured indirectly using a fast and accurate hall probe to measure the induced self-field of the connection busbar. With a guaranteed accuracy of $\pm(0.02\% \text{ of full scale} + 0.03\% \text{ of field}) T$, a bandwidth of more than 100 kHz (-3 dB point at 150 kHz) and temperature stabilization, the magnet current can be continuously monitored.

Using the hall-probe for an indirect measurement of the magnet current on the MSE test system, the interlock signal indicated a failure in the circuit 3.01 ms after a fault was simulated in the circuit by setting the current reference to zero, Fig.5. Since this simulated fault forces the current into the free-wheel diode of the converter output stage and provokes a natural decay of the current in the circuit, this overall detection time of 3 ms includes the time needed by the control system to react to the new set value, the time for the control loop to react, and finally the time for the current to commute to the free-wheel diode. These add up to over 2 ms, so the time required to detect the real current decay can be estimated to be below the required limit of 1 ms.

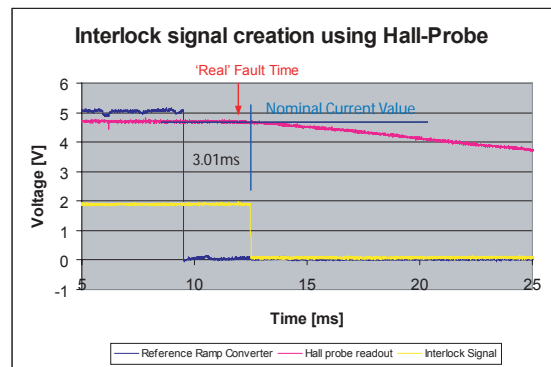


Figure 5: Results for an interlock signal generated from the current readout of the hall-probe.

CONCLUSIONS

Considering the rudimentary mounting and electronic design, the results achieved during first tests are very promising, with the required reaction times of the order of 1 ms achieved. They encourage further studies and the development of a more advanced measurement system for the detection of fast failures, able to withstand the expected EMC levels in the LHC tunnel. A second generation of such detection electronics will be built, based on a digital approach and combining detection principles listed in this document. Digital filtering of signals and trend analysis will further improve the reliability of the generated interlock signals and will provide a general principle to be used in various types of critical circuits of the LHC, its injector chain, or other accelerators. Where active detection is not feasible, passive protection devices can be considered for later installation when the LHC will be operating with high beam intensities.

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