ARC DETECTOR SYSTEM FOR EXTRACTION SWITCHES IN LHC CERN

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Abstract

The opening switches, which will be used in case of quenches or other failures in CERN's future LHC collider to extract the large amounts of energy stored in the magnetic field of the superconducting chains of main dipoles (8 chains with 1350 MJ each) and main quadrupoles (16 chains with about 24 MJ each) consist of an array of series/parallel connected, electro-mechanical D.C. breakers, specifically designed for this particular application. During the opening process the magnet excitation current is transferred from the cluster of breakers to extraction resistors for rapid de-excitation of the magnet chain. An arc detector has been developed in order to facilitate the determination of the need for maintenance interventions on the switches. The paper describes the arc detector and highlight results from operation of the detector with a LHC pilot extraction facility.

INTRODUCTION

In long chains of superconducting magnets, inserted into continuous cryostats, such as it is the case in each of the 24 main dipole and main quadrupole circuits of CERN's future LHC collider, damage to the s.c. conductors of coils and busbars will have serious consequences for the operation and availability of the machine. In-situ repair will rarely be possible and replacement of a damaged magnet or busbar is a long and difficult exercise. The huge amount of energy, stored in the magnetic circuits, represents the highest potential risk of damage to the conductors. In case of a quench of a conductor segment, the current driven by the large magnet inductance will lead to a thermal energy deposit in the quenching conductor section. Under normal operating conditions de-excitation of the LHC dipole chains will be achieved by operating the thyristor converters in inversion, herewith feeding the stored energy back into the mains network. However, this is a slow process, the maximum current decay rate being determined by the available inverter voltage (160V). Therefore, inversion cannot be applied in case of a quench and, evidently, in cases where the mains has dropped out. These are the situations where the energy extraction procedure will be applied. The facilities, 32 extraction systems for the 13 kA circuits and 202 systems for the 600 A circuits, are parts of the quench protection systems of LHC, the other elements being the quench detectors, the strip heater discharge supplies and the cold diode stacks for temporary current by-pass of the quenching magnet. The complete systems are described in detail in the references [1] and [2].

It was decided to design and build a detector for monitoring of the natural presence of arc during the commutation process.

THE SWITCH SYSTEM TOPOLOGY

Series-inserted extraction systems have been chosen as only this configuration gives the possibility of reducing, by properly designing the circuit, the maximum voltage to ground along the magnet chain during the extraction process. With two symmetrically placed systems and circuit grounding at the mid-point of one of the two dump resistors the voltage to ground, appearing during the extraction process, will represent only a quarter of the total extraction voltage (490 V instead of 1960 V). In this topology the two extraction switches shall be rated for continuous conduction of the full chain excitation current. In the case of the LHC main circuits the 13 kA will be carried by four, parallel-connected, natural air-cooled, 4.5 kA DC breakers, of which one is redundant. Redundancy in the release process is achieved by installation in series-connection of a second, identical breaker in each branch.

The array of eight breakers is fed through a water-cooled, current-equalizing busway of a quasi-coaxial design, providing approximately the same series impedance for each branch, resulting in a current balance within a few percent. Electro-mechanical over-current relays provide adequate overload protection of each branch.

Figure 1: The VAB49-4000 breaker. 256 such switches are required for the LHC main circuits.

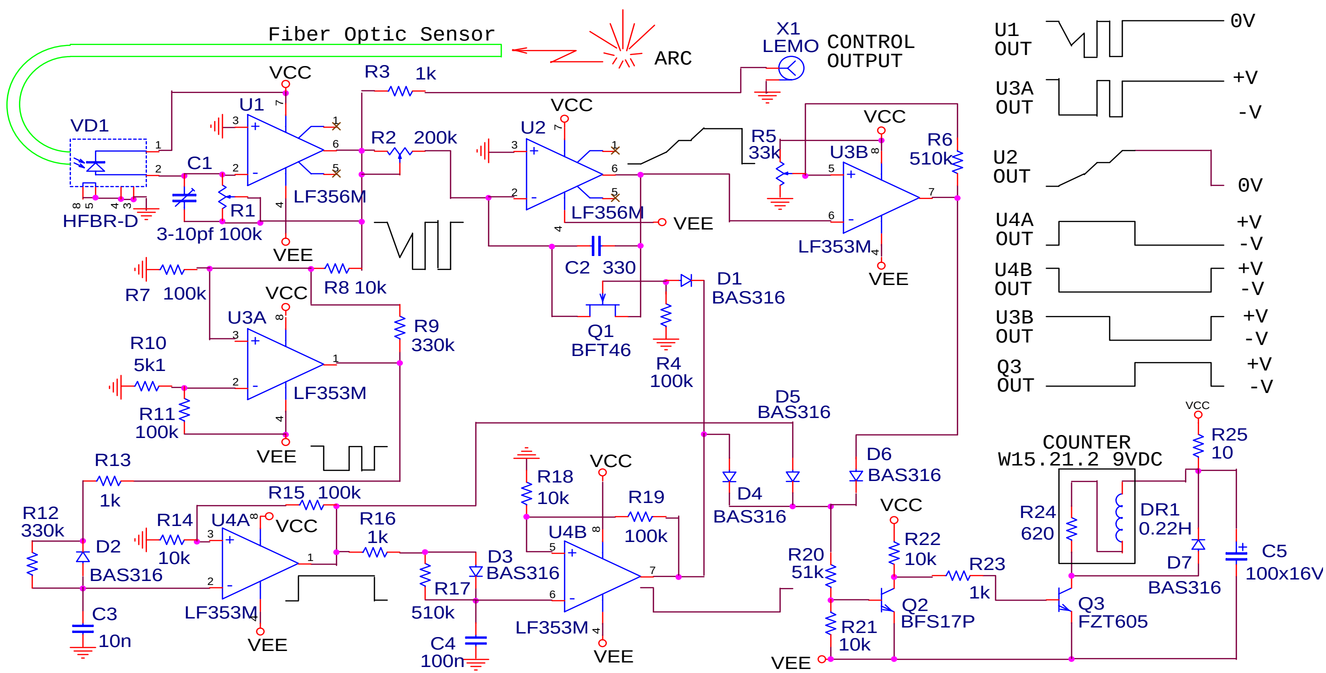

Figure 2: Topology of the arc detector circuit.

Appearance of the breaker developed is shown at figure 1. Instead of designing a completely new device, the basic features of D.C. switch with many years of service were implemented into a new device in which the specific requirements for an extraction breaker were added.

RELIABILITY AND EDURANCE TEST

A reliability and endurance test campaign was carried out in order to evaluate the expected lifetime of all parts of the developed switches, in particular those, which were designed and implemented specifically for the extraction purpose. The campaign comprised mechanical lifetime tests (5 kcycles) and current commutation tests at 13 kA (2 kcycles). The off-load functional tests lead to a confirmation of the concept and design of the new features and components, but did actually also result in a number of minor design changes and adaptations of auxiliary devices, such as armatures for feedback indicators and mechanical springs. The purpose of the commutation tests was mainly to verify the required frequency of replacement, due to erosion, of the arcing contacts. The test was carried out on four switches, applying the 2 kcycles to each breaker mounted in a test circuit with LHC topology. As the principal result of this analysis, the original copper horns and moving contacts will be replaced by contacts made by a tungsten/silver ceramic material (70 % W, 27 % Ag, 3 % Ni – density 15 g/cm^3, hardness HB 180, resistivity 4.5 μΩcm), prior to the installation of the switches in the LHC machine. These ceramic contacts were developed specially for this extraction application. Furthermore, it was decided to design and build a detector for monitoring of the presence of arc during the commutation process in each of the 256 installed breakers. The main reason for taking such measures was the significant erosion of the copper arcing contacts and herewith the risk of no longer protecting the breaker's main contacts. Measurements have shown, that for the maximum LHC commutation current level the replacement intervals in case of copper contacts is short but have a very large spread, from 20 to more than 100 commutations, corresponding to interventions from every 5 months to every 2 years. Preliminary measurements with the tungsten/silver contacts indicate that the interval can be increased to more than 300 cycles before the arcing contacts needs replacement.

In a parallel/series connection of circuit breakers, such as in the LHC extraction switch assemblies, not all of the breakers will get arc during a commutation. This is the reason for equipping the individual breakers with arc presence detectors for maintenance purpose. Due to the mechanical tolerances of the breaker's release systems, the opening procedures of the switches will never be fully synchronised, although the release commands are issued simultaneously by the control electronics. At the extreme limit this results in the faster of the two switches in the 'slowest' branch interrupting the full load current (13 kA) as the current will try to re-distribute between the parallel branches, i.e. move to the branch where the contact separation is delayed. The inductance of the branches will only marginally limit this current re-distribution between the four branches during the commutation since this inductance is small (a few μH) and the generated arc voltage is high. Total opening times of the LHC extraction breakers are typically 5 - 7 ms while the arc duration of 1 - 3 ms is almost constant for any of the breakers and varies only little with the commutation current. Observations made during testing of the LHC extraction switch arrays show that for excitation currents up to more than 8 kA the breakers in a single branch will practically always interrupt this total system current. For higher excitation currents two or more branches may share the commutation task. In most cases both breakers of the last conducting branches will have arc, as the differences in reaction time between the breakers is smaller than the arcing time.

The commutation picture of a specific cluster of breakers for the LHC machine will not remain constant as the arc contact erosion, caused by repetitive openings, will slightly alter the opening characteristics of the release mechanisms of the breakers involved in the commutation. Experience from operating the arrays indicate that this feature leads to certain self-equalising process in which the role of commutation may move to other switches in the array. However, even after a higher number of commutations, attaining the level where some of the arcing contacts need replacement, there will still be breakers, which have practically no erosion.

In order to intervene only on those breakers, which need replacement of the horn and moving arc contact, and not on the others, an arc detection system has been developed.

THE ARC DETECTOR – DESIGN AND RESULTS

The arc detector was developed in a joint collaboration between The Budker Institute, Russia and CERN. It is based on the transmission of an optical signal from the arc to electronic integration and counting circuits. The schematic diagram of the detector is shown in figure 2.

Through a drilled opening in the lower part of the arc shute, at the level of the arc passage before division, light from the arc is captured and conducted by an optical fibre, which is attached outside the breaker.

The end of the plastic fibre is given a conical form and polished. The signal passes a photodiode (VD1) and, after amplification in a trans-impedance amplifier (U1), it goes simultaneously to the input of an integrator (U2) and a peak threshold comparator (U3A). If the signal exceeds the threshold the integration will be activated (JFET Q1). The output signal from the integrator (U2), being proportional to the time integral of the captured light intensity, is sent to an integral comparator. If the integrated signal exceeds a pre-determined integral threshold, the logic circuit (D4, D5, D6, Q2 and pulse amplifier Q3) generates a counting pulse, which is sent to an electro-mechanical counter where the counts are being accumulated.

PSpice was used for modelling and simulation during the design of the arc detector circuit. Each of the eight breakers in the extraction switch array has its own detector circuit, with two such circuits mounted on a single, 3U PCB in SMD technology. Figure 3 shows a typical arc voltage during commutation with 4 parallel breakers.

The detector thresholds were determined experimentally. They have been chosen so to eliminate counts which do not cause any noticeable erosion of the arcing contacts. In the test benches, with breakers equipped with copper contacts, the method has been successful in indicating when interventions are required, herewith projecting a significant economy in time and effort for the maintenance campaigns. Figure 3 shows a typical arc voltage picture from commutation into a 75 mΩ dump resistor of an inductive current of 13 kA DC.

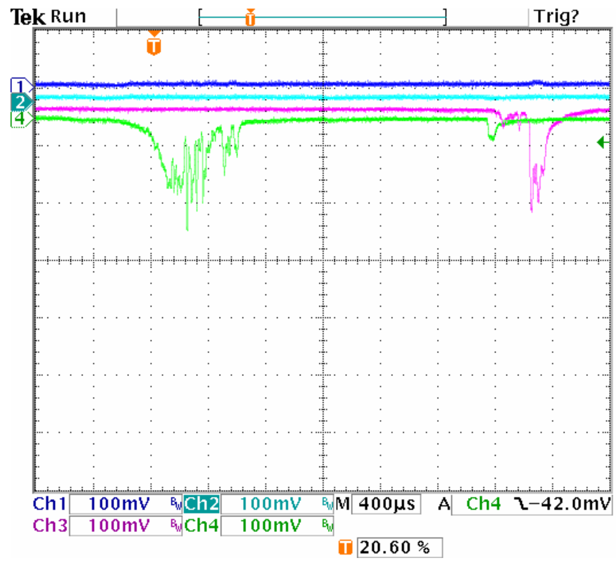

Figure 3: A typical arc voltage picture from inductive current commutation with an LHC extraction switch, showing generated arc in two branches only.

CONCLUSION

Considerable effort and resources have been employed in order to build to the highest standards of reliability the energy extraction switches which will be used for protection of the superconducting dipoles and quadrupoles of the LHC main circuits. The unique extraction breakers have been subjected to various campaigns of severe testing. Although improvements were applied during these test programs, the switches never failed. Their long-term reliability has been significantly improved by the implementation of ceramic arcing contacts and their maintenance has been simplified by the application of the developed arc detector. All 256 switches are equipped with arc detectors and 128 of them have been installed in the tunnel of LHC.

REFERENCES

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[2] K. Dahlerup-Petersen, V. Sytchev and L. Vassiliev. Energy Extraction Resistors for the Main Dipole and Quadrupole Circuits of the LHC. EPAC, Vienna, 2000.