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AUTOMATIC CONDITIONING OF KICKER MAGNETS

C. Lolliot*, M. J. Barnes, N. Magnin, S. Pavis, CERN, Geneva, Switzerland
C. Monier, INSA, Lyon, France

Abstract

Fast pulsed, in vacuum, kicker magnets are used across the accelerators of the CERN complex to inject and extract beam. The kicker magnets are powered by high voltage (HV) pulse generators. The kicker magnets may suffer from electrical breakdown during the pulse. Hence, to prepare them for reliable operation at full voltage, a pulsed HV conditioning is necessary. The magnet is conditioned by first gradually increasing pulse voltage, with a short pulse length, and subsequently increasing the pulse length up to values beyond operational conditions. Before LS2, this conditioning was typically carried out manually, which was a workforce intensive procedure because a magnet conditioning can last for up to several weeks. To overcome this drawback, a standardised industrial controller algorithm has been developed to control the pulse generators. The voltage and pulse length ramps are fully adjustable, and now different modes are available - in particular a voltage logarithmic mode. If a breakdown occurs during the conditioning, the controller will automatically reduce the voltage by a specified percentage and then continue the conditioning procedure. Furthermore, a simulation mode has been developed to allow a quick visualisation of the whole conditioning as well as the simulation of HV breakdowns. This functionality has been implemented in several kicker installations across the various accelerators, as well as in test cages in the lab, and it will be implemented in most installations in the future.

INTRODUCTION

Kicker magnets are used throughout the CERN accelerator chain to inject or extract beam from a ring. These kicker magnets generally have fast rise and/or fall times and are driven by high voltage pulses of up to 40 kV. To achieve fast field rise and/or fall times, transmission line kicker magnets are typically used [1]: these magnets are installed in vacuum. The kicker magnets are terminated either in a short circuit or with a resistor whose value is equal to the characteristic impedance of the system. A pulse generator is used to provide the energy required for powering the kicker magnet: this is either a Pulse Forming Line (PFL) or a Pulse Forming Network (PFN) [1].

As part of the process of preparing the kicker magnet for reliable operation in the accelerators, the magnets must be conditioned under representative conditions, i.e. with High Voltage (HV) pulses.

* christophe.lolliot@cern.ch

HV PULSE CONDITIONING

Considerations for HV Pulse Conditioning

Kicker magnet conditioning is a process to prepare the magnet for reliable operation in the accelerators. Dust, contaminants or small features increase locally the electric field and thus can cause HV breakdown or corona; see Fig. 1. To condition the surfaces and hence reduce locally high electrical field, a voltage is applied: the value is incremented in small steps up to a specified value, slightly above the operating voltage. Failure to increment the voltage slowly can result in HV breakdown in the magnet, which can in turn damage the kicker magnet. The phase of increasing pulse voltage is normally carried out, where possible, with relatively short pulse lengths: this limits the energy that is dissipated in the site of the breakdown and hence minimizes the possibility of damaging the surfaces.

Failure to properly condition the magnets can result in strong HV breakdown and may damage the surface of components. The HV breakdown also degrades the vacuum. An important risk of magnetic breakdown during operation is a transient increase or decrease in the magnetic field, which can cause the injected/extracted beam to be mis-kicked.

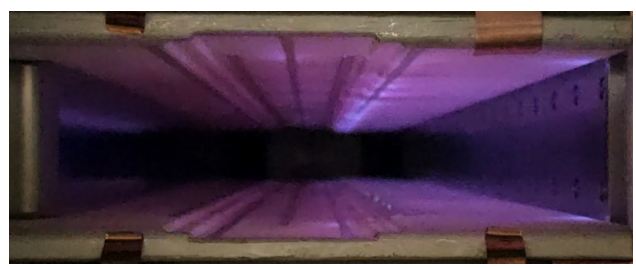

Figure 1: HV corona inside a kicker magnet.

During the conditioning the kicker magnet is subject to gradually higher and higher pulse voltages (ramping mode), and subsequently greater pulse lengths (elongation mode), until the voltage holding capability is sufficiently beyond the nominal operating conditions. Historically, the "pulsed conditioning" was carried out manually: this is a workforce-intensive and also technically non-optimal procedure. During a manual conditioning process, the operator has to survey the vacuum pressure, and monitor and record the conditioning parameters. In addition, in the case of HV breakdown of the magnet, causing a significant pressure rise, the system may interlock, preventing pulse conditioning until a human operator is available to intervene and restart the process.

The HV conditioning by a human operator requires constant attention: voltage and pulse length remain unchanged for long periods, e.g. evening, night and weekends or if the operator has to deal with something else – by contrast a

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computer can survey and operate the condition 24 hours a day, 7 days a week, greatly reducing the conditioning time required. In addition, due to the limited availability of the operator, the voltage increments may be larger than ideal. To overcome these drawbacks a program was developed to control the HV conditioning process: this automated conditioning (ACOND) process has previously been successfully employed for HV pulse conditioning of the LHC Injection kicker magnets.

Original Automatic Conditioning Process

The design of the original ACOND process was based upon the manual conditioning process: in the original ramping mode, an example of which is shown in Fig. 2, there was only the possibility of defining two different voltage increments (i.e. in this example, 2 kV increments in the PFN voltage up to 47 kV and then 0.3 kV increments in the range of 47 kV to 50 kV). This is sub-optimal as experiences demonstrates that reasonably large increments are acceptable to low voltage but smaller increments are required at higher voltage. Hence, because of this requirement, the increment specified, over a range of PFN voltages, was chosen for the end of the ramping range, resulting in unnecessarily small increments at the start of the range. Thus, the number of pulses required, and the duration of the ACOND, was greatly extended compared to having a continuously variable increment. Although it was possible to somewhat circumvent this limitation, by running several ACONDs sequentially, each one covering a limited range of voltages, this complicated the conditioning process and required that an operator was available to set the new ACOND parameters and relaunch the conditioning.

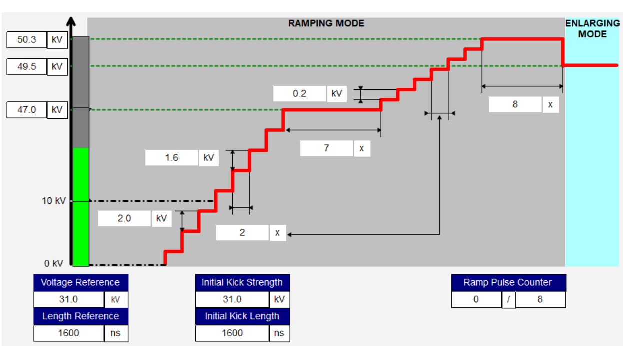

Figure 2: Original ACOND ramping mode.

A feature of the ACOND, was the possibility to define three vacuum pressure thresholds:

- A so-called 'weak spark', which corresponds to a relatively low pressure rise: in this case, the ACOND process reduces the PFN voltage by a pre-defined percentage (typically 2%), and then increase the voltage again as per the ramping parameters
- A so-called 'strong spark', which corresponds to a higher pressure rise: in this case, the ACOND process reduces the PFN voltage by a pre-defined percentage (typically 12% to 15%), and then increases the voltage again as per the ramping parameters
- A relatively high vacuum pressure threshold which will immediately result in the ACOND being stopped until a human operator intervenes

In the case of the strong spark, significant time can be lost while the voltage is ramped up again, as the increment is chosen for the end of the ramping range, resulting in unnecessarily small increments at the start of the range.

Upgraded Automatic Conditioning

Based on extensive experience with both manual HV conditioning and the original ACOND process, the specifications for a new automatic conditioning process (nACOND) were defined. The main goal was to provide more control over the voltage increments during the HV conditioning.

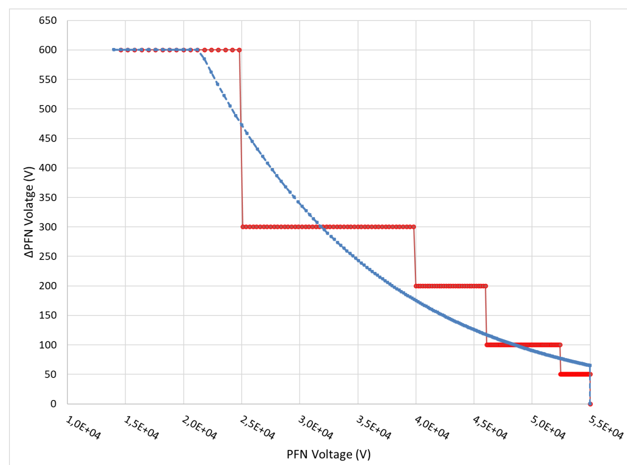

Figure 3: Voltage increment in logarithmic mode.

Figure 3 shows two, more flexible, examples of PFN Voltage Increments (ΔPFN Voltage) versus the absolute value of PFN Voltage:

- The red curve shows the possibility of defining many (in this example five) different increments in PFN voltage, rather than just the two of the original ACOND, during the HV pulse conditioning process
- The smooth blue curve describes a voltage increment, described with exponential equations (known as logarithmic mode, see Eq. (1), which decreases smoothly with increasing PFN voltage, between maximum increments (at low PFN voltage) and minimum increments (at high PFN voltage):

$$\Delta V_{PFV} = M * e^{-E1 * V_{PFV}} \quad (1)$$

The nACOND logarithmic mode, together with maximum and minimum increment values, results in more optimal conditioning since the voltage increments are dependent upon the PFN voltage. This allows relatively large increments at

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low voltage and small increments at high voltage - hence, the process is better tailored to the requirements of the kicker magnet, while limiting the number of pulses and duration of the conditioning. The minimum increment, at high voltages, prevent the conditioning process using unreasonably small steps - which could also be smaller than the minimum control resolution of the power supply used.

Additional flexibility is provided in the nACOND process in the case of a ‘Strong Spark’: in this case the exponential equations used can have a different exponent ($E1$ in Eq. (1)) and/or multiplier (M in Eq. (1)), so the re-ramp-up of voltage is faster than the normal nACOND process. This significantly reduces the number of pulses, and hence, time required to ramp-up the voltage. Once the voltage reaches 95% of the pre-breakdown value, the original exponent and multiplier are used for the exponential equations: thus the increment of PFN voltage is the same as the original ramping.

PROCESS AUTOMATISING

Development

To meet the specifications and requests described above, the kicker magnet conditioning control system has been developed on a Programmable Logic Controller (PLC). The program developed is called ”new Automatic CONDitioning” (nACOND). To make this project generic and facilitate maintenance, a single program block containing all the logic has been developed; this allows an easy integration of the nACOND program into the existing kickers programs.

In particular, two data are very important for the conditioning: the voltage strength of the pulse (in kV), and its duration (in µs). Moreover two different phases exist during the conditioning: the first phase consists of increasing the voltage magnitude of the pulses, while the second phase consists of increasing the duration of each pulse. For some systems, the second phase is not required because the pulse generator does not have the ability to change the pulse length.

For the first phase (increase the voltage magnitude), two operating modes are available and configurable:

- The **linear mode** where the next voltage is calculated from increments defined in the ramp settings; See Fig. 2.
- The **logarithmic mode** where the next voltage is calculated according to an exponential equation defined in the ramp settings; see Fig. 4. The nACOND program automatically calculates the magnitude of the high voltage pulses which are going to be sent to the magnet.

The operator sets the desired mode and voltage increments as a function of voltage. To facilitate rapidly defining the settings, recipes are available.

Control of the Kicker Magnet

A kicker magnet pulse is typically very short time (several µs or less), therefore a PLC is too slow to be able to pulse and

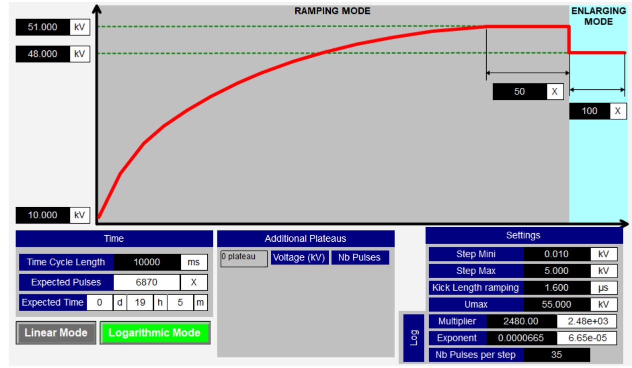

Figure 4: nACOND logarithmic ramping mode.

measure the various signals. To achieve the conditioning, two main systems are connected to the PLC: the Kicker Timing System (KiTS) [2] and the Fast Interlock Detection System (FIDS) [3]. The PLC sends to the KiTS the desired voltage strength and pulse length by Ethernet. Then the KiTS sends the various triggers to the kicker generator to achieve the requested pulses at a constant pulse rate, typically every ten seconds. During the pulse, the FIDS will detect abnormal behaviour of the pulse generator or the magnet. If necessary the FIDS will interlock the PLC. Furthermore, the FIDS sends an important information to the PLC: the detection of a normal pulse, without an HV breakdown. Indeed, this information is mandatory for the PLC to achieve the conditioning, in particular to increase the voltage strength and the pulse length.

Detection of HV Breakdowns

During the conditioning, the vacuum pressure inside the magnet is continuously monitored by the PLC. If an HV breakdown occurs, the vacuum pressure will increase with the severity of the breakdown: the PLC will react to the breakdown and reduce the voltage according to vacuum pressure thresholds defined by the operator; see Fig. 5.

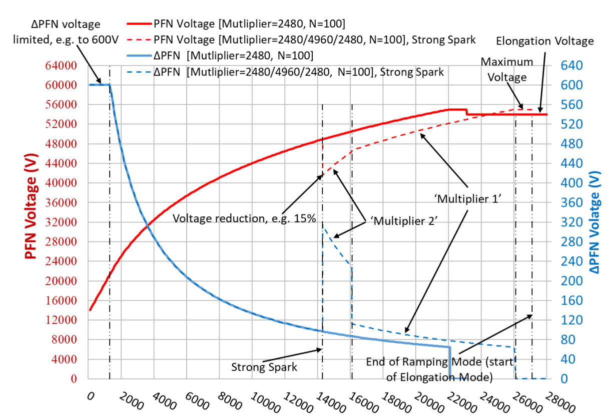

Figure 5: Example of an HV breakdown during logarithmic mode.

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Simulation

As there are many parameters available to define the conditioning, a simulation mode has been developed to allow operators to make sure the conditioning will behave as expected. This simulation results in a graph showing the voltage strength during ramping and the pulse duration during enlarging. In addition, during this simulation, an operator can trigger an HV breakdown simulation to see how the system will react; see Fig. 6.

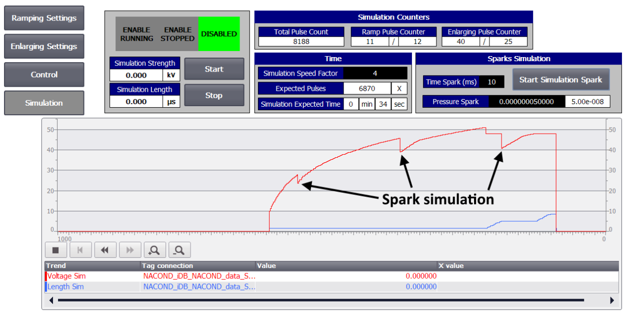

Figure 6: Simulated HV breakdown in Simulation mode.

nACOND Integration in the Accelerators

When a kicker magnet is being conditioned in an accelerator, it is very important to make sure there is no beam in the machine while the kicker is pulsed. Otherwise, the circulating beam will be incorrectly kicked, which could result in damage to the downstream accelerator components. Hence, the nACOND is connected to the Beam Interlock System (BIS) [4]: if the conditioning is running, no beam will be allowed in the machine.

Furthermore, to be able to start a conditioning without having to go on site and using the local touch panel, a **Remote mode** has been developed - this is particularly useful if an expert has to run a nACOND during the night.

CONCLUSION

The new automatic conditioning has been in use for two years. It is regularly used during kicker magnet HV conditioning and it has been proven to be reliable. In addition, it has greatly reduced the workforce and time needed to HV condition kicker magnets.

The nACOND is now available for many kicker in many test cages and in installations across the various accelerators. As the benefits of the nACOND are significant, it is being progressively deployed on the remaining kicker systems at CERN.

Also, in the future, new functionalities will be added to the nACOND, in particular the possibility to start the conditioning from the CERN Control Centre (CCC) through the Software Infrastructure for Low-level Equipment Controllers environment (SILECS).

REFERENCES

[1] M. Barnes, "CAS - CERN Accelerator School: Beam Injection, Extraction and Transfer", in *Proc. CAS'17: School on Beam Injection, Extraction and Transfer*, Erice, Italy, Mar. 2017, pp. 229–283. doi:10.23730/CYRSP-2018-005.229

[2] C. Chanavat *et al.*, "A generic timing software for fast pulsed magnet system at CERN", in *Proc. ICALEPCS'15*, Melbourne, Australia, Oct. 2015, pp. 1003–1006. doi:doi:10.18429/JACoW-ICALEPCS2015-WEPGF127

[3] P. Van Trappen *et al.*, "SoC Technology for Embedded Control and Interlocking Within Fast Pulsed Systems at CERN", in *Proc. ICALEPCS'19*, New York, NY, USA, Oct. 2019, pp. 592–596. doi:10.18429/JACoW-ICALEPCS2019-MOPHA153

[4] B. Puccio *et al.*, "The CERN beam interlock system: Principle and operational experience", in *Proc. IPAC'10*, Kyoto, Japan, May 2010, paper WEPEB073, pp. 2866–2868.