Configuring the Quench Detection System (QDS) for Superconducting Magnet Operation

Introduction. The use of superconducting magnets is strongly growing in the past few years for a wide range of applications. Such superconducting coils are usually energized by high-current and low-voltage power supplies (in steady state the voltage drop is almost only due to the resistance of the wires).

One critical task when operating superconducting magnets is to monitor and detect its quenching before it leads to critical damages. A quench is an abnormal termination of the magnet operation occurring when part of the superconducting coil enters the normal resistive state. This situation may arise from different causes ranging from a manufacturing defect of the device to an excessive magnetic field inside the magnet itself.

Some power supplies of our catalogue are also designed to easily operate superconducting magnets and have some built-in features that are dedicated to this application. An example is the crowbar protection of the FAST-PS-1K5 and the FAST-Bi-1K5 (**Figure 1**) that protects the power supply unit from the large backward energy that may need to be discharged when a sudden change in conditions (e.g. AC mains loss) happens with large inductive loads. A common way to detect quench conditions in superconducting magnets is to monitor the voltage drop in different parts (taps) of the coil itself to recognize a possible voltage increase.

Figure 1: *FAST-Bi-1K5*

Example. A different number of taps as well as voltage threshold and time windows for the evaluation of the quench are requested and all these parameters are extremely application specific. The Quench Detection System (**QDS**) is the perfect solution to match all these needs: this compact unit has four independent differential floating voltage inputs that can be configured in order to monitor up to four voltage values across a superconducting magnet and it is Ethernet-controlled. The QDS unit is shown in **Figure 2**. Each channel has eleven (11) different bipolar full-scale ranges sampled independently at 100 kHz with a 24-bit resolution.

Figure 2: *QDS - Quench Detection System*

The lowest full-scale range is rated at ±20 mV with a LSB resolution of 2.5 nV. The digital signals are down-sampled to 1 kHz with an averaging filter (AVG block) to reduce the high frequency noise. The 1-kHz data stream is then elaborated by a moving average filter (MAVG block) with a user configurable time window.

The output of the moving average filter is the actual readout of the QDS device. Lastly, the output of the moving average filter is compared with a user-configurable threshold. Once a threshold is crossed the STATUS bit of the correspondent channel is raised (logic state "1"). The quench signal which drives the magnetic relay output signal that a quench has been detected is the logic "OR" of all the STATUS bits. This means that only one channel that crosses the threshold is required to generate a quench signal that drives the magnetic relay output. The STATUS register is latching and needs to be reset (logic state "0") before going back to normal operation.

A schematic of the processing stream is shown in **Figure 3**.

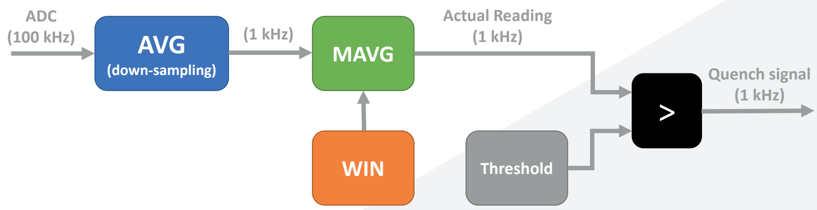

Figure 3: *QDS signal processing block diagram*

The QDS also includes the possibility of driving a **Persistent Switch** - e.g. for the heater - and it has two power outputs that can be enabled/disabled. Both outputs are enabled/disabled simultaneously and they are used to feed alternatively an external switch that may have a 12-V or 24-V rating.

Configuration. Thresholds for detecting a quench can be set as differential values between different channels and/or as absolute channel voltage values. This allows obtaining the maximum flexibility from the device for different applications.

An example of a possible connection of the QDS with a superconducting (SC) magnet with four voltage taps is shown in **Figure 4**. In this example the voltage is also monitored in two points across a superconducting joint. Up to four different quench thresholds can be set, one for each channel of the QDS unit (CH_1, CH_2, CH_3 and CH_4). Each channel can have a different threshold value. The **absolute thresholds** are intended as absolute values, meaning that if a threshold of 1 V is set, a quench signal is generated if the reading is > 1V or < -1V.

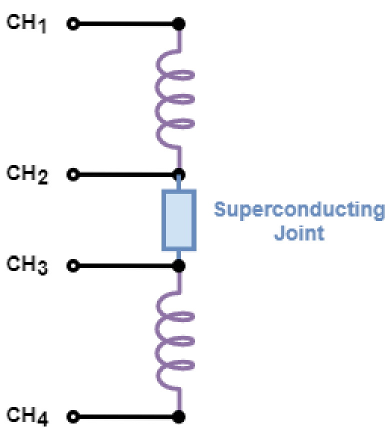

Figure 4: *connection example*

The QDS system also enables the user to set different relative/**differential thresholds** for each pair of channels:

- $|CH_1 - CH_2|$ (also referred to as CH_{12});
- $|CH_1 - CH_3|$ (also referred to as CH_{13});
- $|CH_1 - CH_4|$ (also referred to as CH_{14});
- $|CH_2 - CH_3|$ (also referred to as CH_{23});
- $|CH_2 - CH_4|$ (also referred to as CH_{24});
- $|CH_3 - CH_4|$ (also referred to as CH_{34}).

As it can be seen from the previous formulas, the relative thresholds are all positive values but the polarity/sign is recorded so that it can be read remotely.

The time window for comparing the voltage values to the user-defined thresholds can be also set remotely and it can span from 1 ms to 1 s on the hardware level. Longer integration times (e.g. 10 s) can be obtained on by averaging on the software level.

Persistent Switch. Another important feature of the QDS when operating SC magnets is the possibility of driving a persistent switch. The **Persistent Current Switch** (PCS) is used to connect or disconnect the output of a power source to a superconducting magnet. This switch is also composed of superconducting wires.

Once the superconducting magnet is cooled down (depending on the size of the magnet this operation may even take up to several days or weeks) it gets energized by the power source.

In order to load the superconducting magnet the **Persistent Switch Heater** (PSH) is powered by the PSH (Persistent Switch Heater) output of the QDS. This output delivers a voltage that can be of 12 V or 24 V to match different models of switches. An example of operation in the so-called persistent mode is shown in **Figure 5**. While delivering the current the coil of the PCS is warmed up by some mK which leads to a relatively high resistance of the PCS compared to the "zero" resistance of the superconducting magnet.

Following this the superconducting magnet is energized by a ramping current. The time frame for loading depends on the design of the superconducting magnet and typically takes from several seconds up to days or even weeks.

When the superconducting magnet has reached the final desired current (i.e. field) the current delivery to the PCS is interrupted, it gets cooled down to a superconducting status as well and it closes the loop with the superconducting magnet.

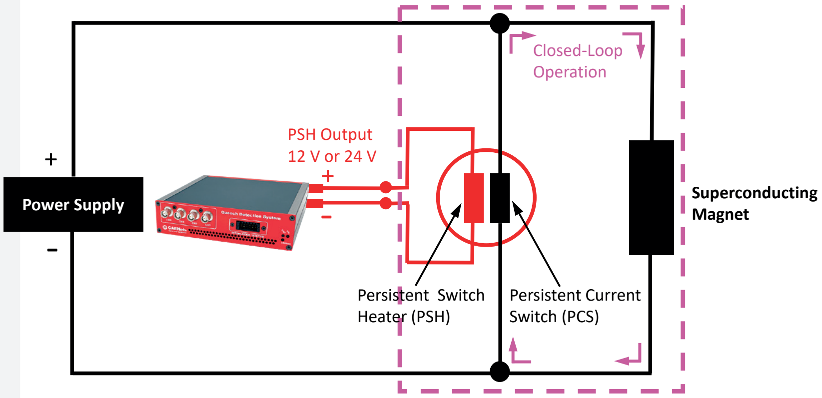

Figure 5: *Persistent Switch*

The delivery of current to the superconducting magnet by the power supply is then shut off due to the short circuit at the output of the source done by the PCS. In principle, the power supply could be completely disconnected.

The superconducting magnet is now working in **persistent mode**: it is in a closed loop with the Persistent Current Switch. The field in the superconducting magnet, in the real case, will not remain constant for an infinite time but it will decay very slowly in an exponential way, following a time constant of L/R, where L is the inductance of the superconducting magnet (in [H]) and R is the equivalent residual resistance (in [Ω]). With a simple example, for values of L = 70 H and R = 80 nΩ, the field will decay of only about 1‰ after 24 hours. A lot of power supplies by CAEN ELS already have the persistent switch driver embedded in the unit. The output from the QDS is then needed in all cases where an equivalent driver is not provided by the power supply manufacturer.

Software. The QDS is provided with a free software application that allows configuring,

Figure 6: *monitoring GUI of the QDS*

monitoring and upgrading the device via the 10/100/1000 Mbit Ethernet connection.

In this software application, the absolute readings of the channels, as well as the differential values can be monitored. A screenshot of the Graphical User Interface (GUI) is shown in **Figure 6**.

Ordering. The Quench Detection System (QDS) is commerically available as a configurable solution for detecting quenches in superconducting magnets. The device is based on a FPGA so that all computations are performed with a negligible delay. The persistent switch output, as described, is also present on the rear side of the device (12 V and 24 V available on the same connector in order to match the specific switch ratings). The QDS is the perfect solution to perform such a critical task, especially when the used power supply does not have these capabilities. The PS1112S low-noise AC adapter is already included in the bundle and guarantees optimal operation of the QDS. Please visit the corresponding product page on our website www.els-instruments.com for more information about this system or to find in our catalogue the right power supply for your superconducting magnet application.

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