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Commissioning of the Wendelstein 7-X Quench-Detection-System

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Abstract

The Quench-Detection-System (QD-System) [1, 2, 3] of the fusion experiment Wendelstein 7-X (W7-X) detects quench events within the superconducting magnet system constructed of 50 non-planar and 20 planar coils separated in 7 groups, 14 current leads and the bus bars [4]. In the event of a quench the QD-System triggers the power supply of the magnet system to shut down. The QD-System is one of the various safety protection systems of W7-X. The commissioning of QD-System comprises the three significant steps: wiring check, balancing of Quench-Detections-Units (QD-Units) and parametrisation of the detection criteria.

1. Introduction

The superconducting magnet system of W7-X is constructed of 50 non-planar and 20 planar coils separated in 7 groups, 14 current leads and several hundred meters of bus bars. It is monitored through 486 QD-Units [5]. The QD-Units (Fig. 1) monitor two adjacent coil double layers [6] by a voltage measuring bridge [5] and the current leads and bus bars with a simple voltage measurement. It is important to ensure an uninterrupted monitoring over the whole group of current leads, bus bars and coils. In the special case of joints an overlapping monitoring has to be ensured. The wiring check is described in section 2 including the used measuring parameters, the measurement method and the results.

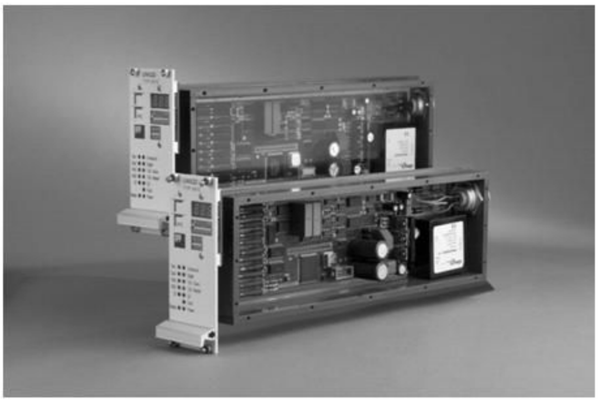


Figure 1: QD-Unit developed in cooperation between the "Institut für Prozessdaten-Verarbeitung und Elektronik" of Karlsruhe Institute of Technology (KIT) and the "Max-Planck-Institut für Plasmaphysik Greifswald".

Section 3 describes the next commissioning phase: the balancing of QD-Units. For each QD-Unit, monitoring two adjacent coil double layers, the measuring bridge has to be balanced to compensate asymmetric manufacturing variations between the inductance of both double layers. The voltage measuring bridge (Fig. 2) of a QD-Unit is adjusted to compensate the inductive voltages to $\Delta U \approx 0$ and measures the voltage difference $\Delta U \neq 0$ between both double layers (DL) in case of a quench event. For the simple voltage measurement of current leads and bus bars only the first path U_1 of the measuring bridge is used: $\Delta U = U_1 - 0 = U_1$. The current can flow through each coil group in both directions. The QD-Units can monitor and measure with bipolar voltage levels.

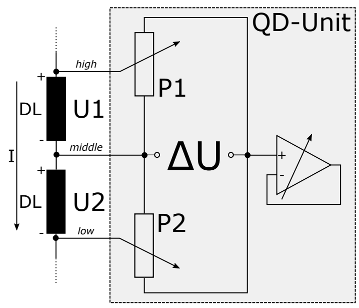


Figure 2: Schematic diagram of the measuring bridge of a QD-Unit. Two double layers are compensated through the potentiometers P1 and P2. For simple voltage measurement U_2 is shorted between *middle* and *low*.

The third and last commissioning step was to parametrise each QD-Unit with its individual detection criteria. A distinction must be made between different coil types (non-planar and planar), bridge or simple voltage measurement and the original and redundant monitoring system. Section 4 describes the various used detection criteria like voltage level ΔU and integration time T_i for the different monitored parts (coils, bus bars and current leads).

2. Wiring Check

The aim of wiring check was to verify the correct connection paths between the QD-Units and the superconducting magnet system with the non-planar and planar coils, the current leads and bus bars. Not only the electrical connections had to be checked, also the correct contacting points of all wires on the magnet system had to be verified. In particular, it was important to prove the correct connecting points for an uninterrupted protection and for an overlapped monitoring (Fig. 3).

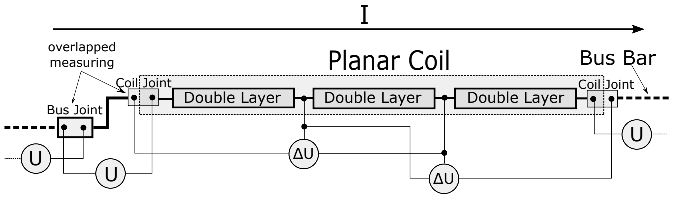


Figure 3: Schematic diagram of a planar coil circuit. Current leads and bus bars are monitored through voltage measuring. Two adjacent double layers of a coil are monitored through the measuring bridge.

Table 1 displays the resistance and the calculated voltage values of the various components with the currents permissible for room temperature operations of 30 A for non-planar and 40 A for planar coil groups.

Table 1: Measurement values.

Component	Resistance	Current	Voltage drop
non-planar coil	22 mΩ/DL	30 A	≈ 610...710 mV/DL
planar coil	17mΩ/DL	40 A	≈ 630...730 mV/DL
bus bar	0.15 mΩ/m	30/40 A	depending of length
joint	0.14 mΩ	30 A	≈ 3.6...4.8 mV
joint	0.14 mΩ	40 A	≈ 5.0...6.2 mV

The defined current direction and the sign and value of measured voltages between every possible measurement points indicate the right or wrong connection of the QD-Wires (Fig. 4).

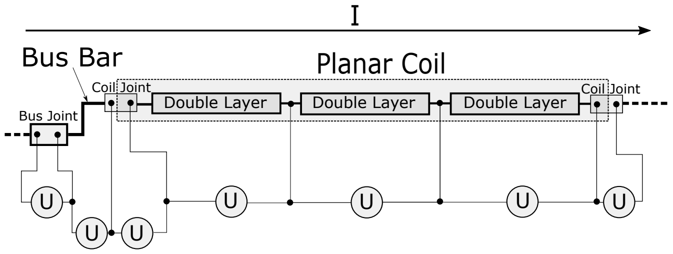


Figure 4: Schematic diagram of wire check. The voltage was measured between each connecting point of QD-Wires. The correct connecting of each QD-Wire was determined with the sign and voltage drop.

The voltages were measured over each double layer of every coil (planar and non-planar), every joint, each current lead and every bus bar section. Prior to the measurements, the exact resistance values of each bus bar section were calculated with the real installed length. In all, more than thousand individual measurements were executed and evaluated. With a self-developed measuring adapter, switchable between planar and non-planar coils, a complete coil was measured together with the two coil joints, the bordering bus bars and nearest bus bar joints. The adapter was connected directly to a computer. All measuring values were acquired, saved and evaluated by a software developed in-house.

The wiring check was performed successfully. There were no interrupted monitoring parts and all wires were connected at the correct positions. Furthermore, there were no ascertainable anomalies during the balancing of the QD-Units, which is another indication for an error-free QD-Wiring.

3. Balancing of QD-Units

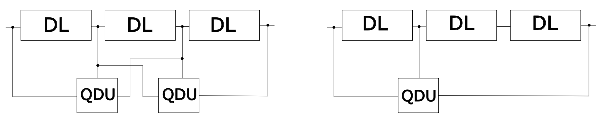
The double layers of a coil differ slightly from one another in their manufacturing characteristics. In particular, the inductance of double layers fluctuates around a value of 3 mH/DL for planar and 8 mH/DL for non-planar coils. Without a balancing of the measuring bridge of QD-Units (Fig. 2) unnecessary misinterpreted quench events could be the consequence. Especially in case of up-and-down ramping of the current with a maximum change of ± 30 A/s, the configured detection levels can be possibly exceeded.

Both potentiometers P1 and P2 of the measuring bridge compensate the inductive asymmetry to $\Delta U = U_1 - U_2 \approx 0$. The QD-Units were adjusted under the following conditions: a superconducting magnet system, an active current ramp of ± 30 A/s and a permitted maximal current of 500 A. The magnet system can carry a current of 500 A even for the case of loss of the superconductivity, for example in case of a quench event. Therefore, the QD-System could be deactivated during the phase of balancing. The balancing of QD-Units is a critical process. There is no way to detect a quench event at a deactivated QD-System. In short sequences of a cycle of positive and negative ramps from 0 to 500 A and back to 0 A, the QD-Units were balanced. Then, the settings were tested with an activated QD-System. This test also included a simultaneous check of the superconducting magnet system.

Both potentiometers P1 and P2 are electronic components and are controlled by a FPGA. In conjunction with a superordinate master control station, a loop of measuring, assessment and adjusting enables an automatic balancing of QD-Units. During a current ramp, the actual voltage difference ΔU is measured and send to the master control station. The station evaluates the measured value and sends back a new setting for the balance. This cycle is repeated until a voltage difference is measured of $\Delta U \approx 0$. It is thus possible to balance up to 4 QD-Units in the short time of ramp between 0 and 500 A.

The ability of QD-Units to compensate asymmetries enables the possibility to compare not only one double layer with another but also to compare two or three double layers with one double layer. The balance settings can be set between an equipartition of the both measuring branches of the bridge, $R_{P1} \approx R_{P2}$, and to gate one of the branches ($R_{P1} = 0$ or $R_{P2} = 0$). Thus wide asymmetries can be compensated. This fact is used for the redundant monitoring. The QD-System of W7-X doesn't use a one-to-one redundancy. It uses a reduced monitoring for the redundant system. Because of not using a one-to-one redundancy, the redundant system is called *backup* system. Fig. 5a displays the *original* and Fig. 5b the *backup* monitoring schema of a planar coil.

The reduced redundancy with the backup system is only used for the coils, the current leads and all bus bar sections are mon-



(a) Original (b) Backup

Figure 5: Original and Backup monitoring schema of a planar coil. At the original system always two adjacent double layers are monitored by one QD-Unit. Only one QD-Unit is used for the backup system.

itored with a one-to-one redundancy. In all, the original and backup system use 486 QD-Units to monitor the complete superconducting magnet system.

4. Parametrisation of Detection Criteria

The final commissioning step was to parametrise the detection criteria. A quench event is detected by a defined difference voltage level $\Delta U \geq U_L$ and an integration time $T_i \geq 0$. If both criteria are fulfilled, a quench event is detected and the power supply of magnet system is triggered to shut down.

First, primary start parameters were defined. All coils and current leads were tested under cryogenic conditions and nominal current after fabrication. The starting parameters for the QD-Units are based on the experiences from these tests and were defined as follows (Table. 2):

Table 2: Start detection criteria.

Component	System	Level U_L	Integration Time T_i
non-planar coil	original	$\pm 150\,mV$	50 ms
	backup	$\pm 300\,mV$	50 ms
planar coil	original	$\pm 100\,mV$	50 ms
	backup	$\pm 200\,mV$	50 ms
bus bar	original	$\pm 20\,mV$	50 ms
	backup	$\pm 40\,mV$	50 ms
current lead	original	$\pm 20\,mV$	50 ms
	backup	$\pm 40\,mV$	50 ms

The start parameters were set before the commissioning steps balancing and parametrisation started. Now, the detection levels U_L could be verified by balanced QD-Units.

During a positive or negative current ramp a voltage is induced ($u = \frac{di}{dt}$) in the coils. Bus bars and current leads are not concerned. Even non-completely balanced QD-Units for monitoring of double layers measure a partial difference of the induced voltage (Fig. 6). The detection levels U_L have to fulfil two requirements: high enough to compensate the partial difference voltages and small enough to detect a quench event at an early stage.

The parametrisation was completed with accepting almost all start parameters, only the detection level of the backup monitoring for current leads was changed from 40 mV to 30 mV.

5. Conclusion

The commissioning of the Wendelstein 7-X QD-System was completed without complications and problems. The wiring

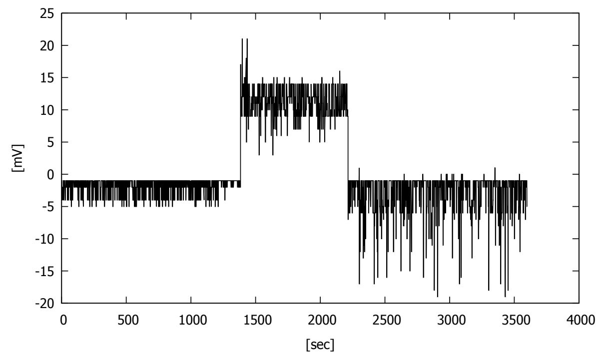


Figure 6: Technically caused residual voltage difference of a balanced QD-Unit during a current ramp (between 1400 s and 2200 s). The minimal detection level must be larger than this residual voltage level.

check showed no errors within the QD-Wiring and the initially triggered switch-off problems during the balancing of QD-Units were solved by deactivating of the quench signalling by the QD-System.

The QD-System ran stably over the entire first experimental time of W7-X. There were no failures of QD-Units or other parts of the QD-System.

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