ITER CS Quench Detection System and Its Qualification by Numerical Modeling

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***Abstract*—The ITER Central Solenoid (CS) magnet needs to be protected against overheating of the conductor in the event of the occurrence of a normal zone (NZ). Due to a large amount of stored energy and slow NZ propagation, the NZ needs to be detected and the switchyard needs to open the breakers within 2 s after detection of the NZ. The CS will be discharged on a dump resistor with a time constant of 7.5 s. During operation of the CS and its interaction with the poloidal field (PF) coils and plasma current, the CS experiences large inductive voltages from multiple sources, including nonlinear signals from eddy currents in the vacuum vessel and plasma current variation, that makes the task of detecting the resistive signal even more difficult. This inductive voltage needs to be cancelled by quench detection (QD) hardware (e.g., bridges, converters, filters, processors) and appropriate processing of the QD signals to reliably detect NZ initiation and propagation. Two redundant schemes are proposed as the baseline for the CS QD System: 1) A scheme with Regular Voltage Taps (RVT) from triads of Double Pancakes (DP) supplemented by Central Difference Averaging (CDA) and by digital suppression of the inductive voltage from all active coils (the CS and PF coils). Voltage taps are taken from helium outlets at the CS outer diameter. 2) A scheme with Cowound Voltage Taps (CVTs) taken from cowound wires routed from the helium inlet at the CS inner diameter. Summary of results of the numerical modeling of the performance of both baseline CS QD systems is presented in this paper.**

***Index Terms*—Central solenoid (CS), ITER, quench detection (QD).**

I. Introduction

THE STORED energy in the ITER CS reaches 7 GJ. This huge amount of energy is capable of destroying the CS if it is not discharged quickly because origination of a normal zone (NZ) is very localized, and the stored energy would be deposited in the NZ if it were not discharged on the outside dump resistor. Therefore it is essential to detect the appearance of a NZ and to dump the energy quickly. The electrical method of voltage detection remains the quickest and most reliable primary quench detection (QD) method. QD methods based on helium expelled from the coil or on a local increase in pressure are slow and difficult to distinguish from non-quenching events with large heat release, such as plasma initiation or disruption.

QD in the CS by an electrical method is nonetheless very challenging due to large inductive signals coming from too many sources. Because the quench detection system has to detect only resistive voltage, the inductive signal is frequently called noise for QD purposes.

There are five electrically independent CS modules, six independent poloidal field (PF) coils, plasma current, and passive elements (e.g., the vacuum vessel) to cope with. During plasma initiation the inductive voltage goes up to 11 kV. The level of resistive voltage at which the circuit breaker needs to open to evacuate the energy from the magnet is 300–500 mV. To have a reliable recognition of the NZ, the signal-to-noise ratio needs to be 10. Thus the rejection ratio of the inductive noise must be an incredible 200 000 if someone would like to have a single QD circuit per CS module. We have no technology for that today. We have 20 DPs in a CS module, and if we monitor DP signals, we reduce the voltage-cancellation requirement by factor of 20, which makes it more manageable.

Several implementations of the ITER CS QD have been investigated so far. A scheme with the pickup coils (PCs) was proposed by Y. Takahashi *et al.* [1]. It was shown [2]–[5] that the DP voltage signals give similar noise cancellation as the pickup coils. Because of that, the pickup coils were removed from the viable options for quench detectors due to a high risk of mechanical failure or electrical breakdown. They cannot be repaired.

The next study on QD was performed by a Commissariat a L'Energie Atomique (CEA) group [6], [7]. They explored the initiation of a plasma event as a design driver. They assumed that the disruption can be blanked effectively for 3.5 s because inductive noise will decay to a lower level after blanking and because all the currents in the PF and CS systems are reducing in the initiation event.

The CEA QD scheme of choice is a voltage tap—(VT)-based system of optimized central difference averaging (CDA) with blanking. The CEA group showed that if the voltage threshold were 0.55 V then with 3.5 s blanking it would be possible to suppress the noise to the same level for initiation. This sensitivity implies that the signal-to-noise ratio would be about 1, which is unacceptably low. Also, if the quench were to happen during other points in the scenario, such as at plasma disruption, these parameters will not protect the CS. Therefore, it was decided to develop two independent QD systems with more effective inductive noise suppression. One system would be based on the cowound voltage taps (CVTs); another system, based on regular voltage taps (RVTs), would be a secondary

Manuscript received July 14, 2013; accepted October 24, 2013. Date of publication November 25, 2013; date of current version December 12, 2013. This work was supported by Oak Ridge National Laboratory under Contract DE-AC05-00OR22725 and by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

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Digital Object Identifier 10.1109/TASC.2013.2292304

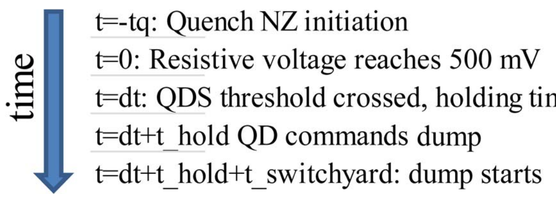

Fig. 1. Timeline of the quench evolution and QD actions.

QD system. The rationale for using two systems is that although CVT is much more sensitive and therefore more reliable if it functions well, it is not repairable. The RVT system is repairable, and, if needed, it can be reinstalled even outside the ground insulation.

A. Requirements

The NZ voltage at the peak current in the CS of 45 kA develops 0.3 V over the length of about 3 to 4 m at 20 K in a 13 T field. The QD needs to suppress the inductive noise to a level of 50 to 60 mV within 1.5 to 2 s after the voltage exceeds the threshold value to make the threshold of 0.3 to 0.5 V reliable and to prevent overheating of the conductor in the quench origination area above specified values.

QD shall prevent dump if NZ voltage is less than 0.3 to 0.5 V.

B. Quench Origination and Evolution: QD System Response

The general timeline of the events monitored by the QD system is as shown in Fig. 1. Let us suppose that, as a result of some perturbation, an NZ is initiated in the CS and it starts growing. The voltage that the QD system is designed to detect contains both resistive and inductive signals, and therefore the resistive signal can be masked by an inductive signal of the opposite sign. Thus, when the NZ voltage reaches the defined threshold, it may not trigger a hold. To trigger a hold, the total voltage would need to exceed the threshold. When the system registers a QD signal corresponding to the threshold (e.g., 500 mV), the holding time starts. If, during the holding time (e.g., $t\_hold = 1.5$ s), the signal does not drop below the threshold, a command for the CS current dump would be issued by the QD analyzing circuit. It takes up to 0.5 s for the switchyard to open and commutate the current into the dump resistor. After that the current drops almost exponentially (slightly faster due to heating of the dump resistors, which increases their resistance) and makes the energy extraction a little more efficient.

Otherwise, if the signal drops below the threshold, the system resets to the condition before the quench event.

II. Quench Detection With the Cowound Voltage Sensors

The cowound sensors are designed to provide a best possible coupling that would reduce noise to minimum. The theory of the QD cowound sensors was described in [8]; experimental demonstration and verification was reported in [9]. Basically, there are three types of noise: (a) transverse-field, (b) longitudinal-field and (c) self-field noise [8].

The first source has to do with the fact that the magnetic field is not radially uniform and not even strictly linear. The loops that are exposed to the flux are different for the strands in the cable and the CVTs that are outside of the jacket. As calculations show [10], the twist pitch of the cowound wire is not important, but there is a net difference between the flux trapped by the CVT and the cable. Fortunately, the difference is negligible for the CS.

The second source of inductive noise comes from the fact that the cable is formed by the multiple twisting operation of the strands. Each cabling stage creates a little solenoid that traps the flux; the flux generates an electromotive force [8]:

$$E = \sum_{i=1}^{N} \frac{\pi r_i^2}{l_{pi}} \dot{B}_p \tag{1}$$

where N is number of the cabling stages, r_i and l_{pi} are the effective radius and twist pitch of the subcable of "i" stage, measured by the centers of the previous stage subcables, $\dot{B}_p$ is the derivative of the longitudinal component of the magnetic field density.

For the CS modules, the longitudinal noise is negligible everywhere, except for the buses and termination extensions, which are sitting in the parallel field [10]; therefore, the twist pitch of the CVTs and RVTs on the vertical runs of the conductor shall be about 1.1 m for the baseline twist pitches established for the CS Conductor Specs in 2008 and for the short twist pitches introduced by ITER in 2011. The recommended twist pitch of the QD tape sensor is 0.94 m.

The third source of the inductive noise comes from the self-field. The CVT is outside of the jacket; therefore, there is a significant flux between the cable and the coaxial VT, explained in [8]. The source cannot be eliminated by a smart twist pitch; it is insensitive to it. The most efficient way to eliminate this signal is to subtract the signals from other DPs in the same module.

The CVT offers the best possible noise cancellation because the coupling between the CVT and the conductor is the possible best, inferior only to the sensor that is embedded inside the cable [9]. However, even this method is not sensitive enough without reasonable management of the signals.

The electrical schematic of the QD based on CVT is shown in Fig. 2, where we show the pairing of signals from the inlets of the CS module DPs. The voltage signals across the DPs are taken from the two wires: one is attached to the inlet of the previous (top to bottom) DP and another wire is attached to the inlet tube of the current DP. For example, after being paired, the pair of voltage taps between the L2 inlet and the L3 inlet go to cable 1 (main signal) and cable 2 (redundant signal). This works for the whole CS Module except for the outmost pancakes, which have the voltage signal only from one pancake, including the bus and the coaxial joint.

The following list contains three guidelines for organizing the signals from the CVT:

1) It is more convenient to extract the wires at the inner diameter (ID) of the module than from the outer diameter (OD) because signals at the OD need to be routed under

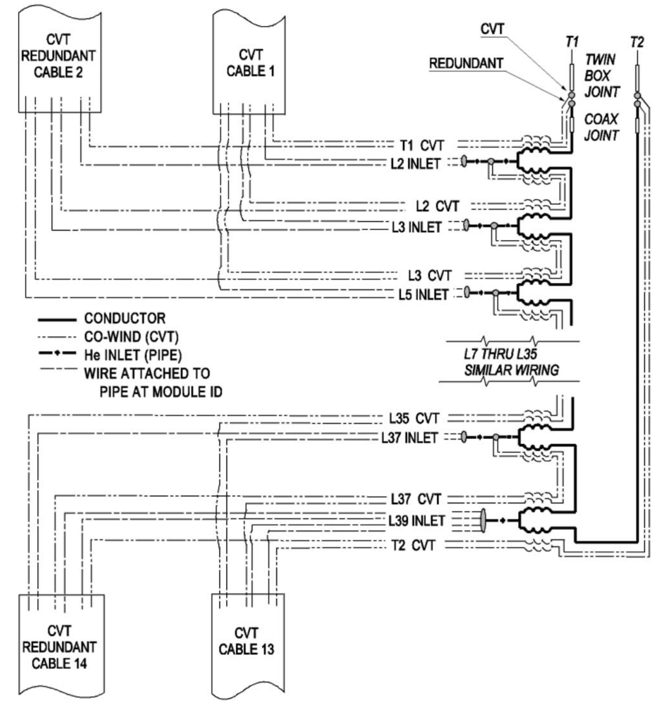

Fig. 2. Electrical schematic of the quench detection of the ITER CS module.

the ground insulation of the plumbing. For the RVT it is inevitable because signals from the inlets would leave the outmost pancakes as single pancakes and make compensation for the RVT difficult or impossible. For the CVT it is possible to compensate for the noise due to the self-field (as explained below).

2) At the ID there is a certain probability that the NZ may originate at one of the inlets and propagate symmetrically. In schematics, where signals are subtracted one from the other, the symmetry may mask development of an NZ and leave the coil unprotected against such an event. That would lead to damage or destruction of the CS. To avoid that, the cancellation of the inductive noise would have to be done by subtracting signals from different parts of the CS. Evidently, that would require elimination of the common-mode high voltage, which can be done by the electrical-optical converters, which would transmit the DP or single-pancake voltages to the control room, where they could be grouped in the configurations where the major noise source for CVT-self-field noise-will be eliminated.
3) The number of the QD analyzing units can be reduced to reduce the cost and increase the reliability of the QD system. To meet these requirements, we proposed a scheme [11] with a minimum of two QD units (plus two for redundant system). One unit will analyze the signal, which is the difference between the QD-circuit-cancelling voltage collected from pancakes (1, 8, 9, 16, 17, 24, 25, 32, 33, 40) and (4, 5, 12, 13, 20, 21, 28, 29, 36, 37) and the QD circuit-cancelling voltage from pancakes (2, 3, 10, 11, 18, 19, 26, 27, 34, 35) and (6, 7, 14, 15, 22, 23, 30, 31, 38, 39).

With this arrangement, the three conditions are met.

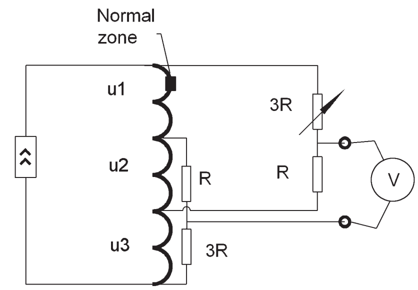

Fig. 3. Central difference averaging schematic for QD.

III. Quench Detection With Regular Voltage Tap Sensors

A. Central Difference Averaging

A relatively good first-order cancellation of the inductive voltage noise can be achieved by "central difference averaging" (CDA), which can be done numerically or by an analog schematic (Fig. 3).

In, this case the voltage on the voltmeter is

$$V = 0.5u_2 - 0.25(u_1 + u_3). \quad (2)$$

The compensation comes from the fact that the coil under QD watch is sandwiched between the adjacent coils; the inductive noise cancellation will be to a higher order than just the cancellation for two adjacent coils (e.g., $u2$ and $u1$). However, it was shown by studies at the Massachusetts Institute of Technology [2], [12] and at CEA [6], [7] that only the CDA does not allow the inductive noise to be cancelled to an acceptable level. An additional level of compensation is necessary.

B. MIK Noise Cancellation

A method called "mutual negatives" or MIK, was introduced in 2007 [4], where "I" and "K" stand for mutual coupling indexes of different circuits. The detailed implementation of the MIK method is described in [13]. The principle is that if one knows all the current derivatives of all sources of the inductive signals, the cancellation of the inductive noise can be done very efficiently. In other words, MIK cancellation means that the measured signal is modified in the postprocessor by subtracting expected inductive voltages from known sources. The attractiveness of this method is that the mutual inductance coefficients can be measured by exciting all the independent currents, one by one with the known dI/dt, and measuring the inductive signals in all the QD circuits.

A similar idea was proposed and was demonstrated on a simple multicoil system [14]. This schematic was not ever implemented in a real complex magnet system, but analysis shows [13] that this method is very promising and forgiving to the accuracy of the dI/dt knowledge or to geometrical changes of the windings due to electromagnetic forces. Thus RVT with MIK was selected to be developed to serve as a backup QD system to the CVT method.

The RVT wiring schematic is shown in Fig. 4.

The signals from RVTs for QD are taken from the OD. The VTs are paired: one is attached to the outlet of the next DP (e.g.,

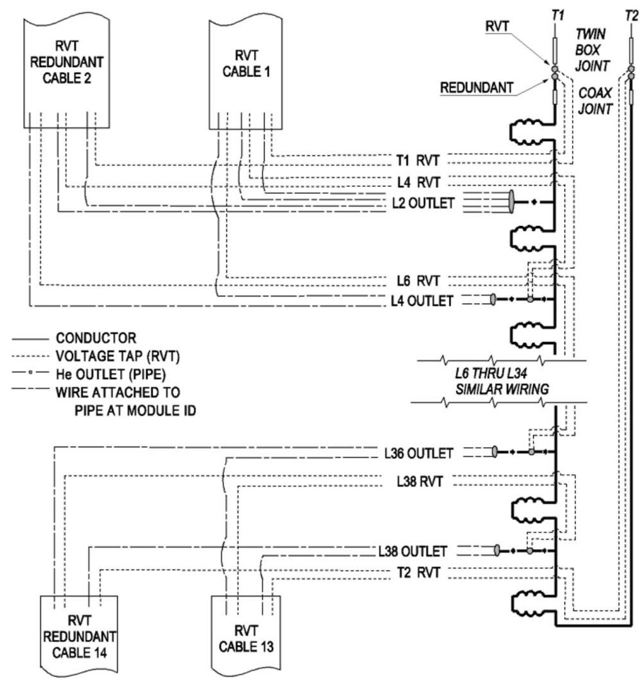

Fig. 4. QD with RVT.

the L4 outlet is paired with the VT that is attached to the tube at the L2 outlet). The tube is attached to the outlet and routed to the ID of the CS, and only there the VT wire is attached, so the helium tube serves as a VT on this run from the OD to the ID of the CS.

Despite having lower sensitivity than the CVT system, the RVT system has some attractive features. In contrast to CVT, it is unlikely, that an NZ will ever originate at the OD, let alone propagate symmetrically due to vicinity of the joint near the outlet. Most important, the RVTs are much better insulated from the conductor than the CVTs, and they can be repaired.

IV. Numerical Modeling

Performance of both CVT- and RVT-based QD systems was modeled numerically using Fortran computer programs simulating the sequence of events shown in Fig. 1. Two current scenarios, a 15 MA normal scenario and a normal scenario combined with a vertical displacement event [15], during which plasma shrinks its diameter and then drifts downward, gradually losing its current, were used for the analyses. Inductances were calculated [16] using stick models to model in fine detail the CS conductor and cowound wire, the PF coils, the plasma, and the passive structure.

The analyses showed that both QD systems are capable of suppressing inductive voltage to 25 to 50 mV with a holding time of less than 1.5 to 1.8 s, which provides a signal-to-noise ratio of 10 for a 0.5 V NZ resistance.

V. QD Summary

The design of the QD in the CS module contains two independent systems.

One is based on the CVT. It has a high sensitivity and excellent cancellation of the inductive noise.

The second QD system, which may be considered secondary, is based on the RVT. It is not protected against inductive noise as well as the CVT system is, but it is more robust and better insulated, and it is repairable.

The combination of these two systems gives us less risky QD system for the CS module than known alternatives.

Acknowledgment

The authors would like to thank G. McGinnis, R. Hussung, P. Michael, F. Rodrigues-Mateos, M. Coatanea, J.-L. Duchateau, J. Schultz, and N. Mitchell for useful discussions and contributions to this project.

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