Quench detection in ITER superconducting magnet systems

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Abstract. The quench of one of the ITER magnet systems is an irreversible transition of the conductor from superconducting to normal resistive state. The normal zone propagates along the Cable in Conduit Conductor, dissipating a large power. The detection has to be fast enough (1 - 2 s) to initiate the dumping of the magnetic energy and avoid irreversible damage of the systems. The experience of CEA is based on the operation of the superconducting tokamak TORE SUPRA for more than 20 years. In support to ITER, CEA was also very involved during these last 3 years in quench detection investigations, in the framework of ITER contracts. The primary quench detection in ITER is based on voltage detection, which is the most rapid detection. The very magnetically disturbed environment during plasma scenario makes the voltage detection particularly difficult, inducing large inductive components across the pulsed coils (10 kV) or coil subcomponents. Voltage compensations have therefore to be designed to discriminate the resistive voltage associated with the quench. A secondary detection based on thermohydraulic signals system has also to be investigated to protect the environment in case of a non detected quench, especially for the largest ITER system, which is the TF system with a stored energy of 40 GJ.

1. Introduction¹

The quench of one of the ITER magnet systems is an irreversible transition of the conductor from superconducting to normal resistive state. The normal zone propagates along the Cable in Conduit Conductor (CICC), dissipating a large power. The detection has to be fast enough (1 - 2 s) to initiate the dumping of the magnetic energy into the external resistors and avoid irreversible damage of the systems. The ITER system magnet has been designed such as to avoid any quench but, in spite of this, this event must be considered and consequently the magnet system has to be protected against quenches, which raises the problem of the quench detection.

The original experience of CEA about quench detection and protection is linked to the operation of the superconducting tokamak Tore Supra since 1989. Only one quench of the system was experienced during the whole period. The safety system was unintentionally tested in December 1989 after a quench of coil BT4 due to an important irradiation of the magnet following a very severe plasma disruption. The safety system was very effective to protect the coil and it was possible to energize the coil a few hours after the quench [1]. In this paper an overview is given about the quench detection methodology,

¹ This work was supported by ITER Organization in the framework of contracts CT/08/1049 ad contract CT/09/4300000014. The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.
concentrating only on the most likely quench initiated in the high field zone where the temperature margin is the smallest. More details can be found in [2], [3], [4], [5].

2. Main causes of a quench and propagation phase

2.1. Main possible causes of a quench in a tokamak

Quenches can be triggered by events either internal or external to the superconducting coils. Hereafter, several events likely to trigger a quench in ITER magnets are listed and explained:

- Heat deposition, due to external events. In tokamaks, this can be coming from plasma events such as disruptions or plasma displacements. Such events can also make the operating conditions of the conductor vary, leading to a decrease of the temperature margin

- Insulation weakness: in ITER at each plasma discharge, the Poloidal Field (PF) and Central Solenoid (CS) systems are submitted to very large voltage to the ground (10 kV) which can result in arcing especially in the bus bars regions. A large voltage is present in the TF coil system only during the fast safety discharge. It can happen that insulation fails (possibly because of the aging, or under an excessive applied voltage), then a short circuit current circulates to the ground carbonising the insulation, and eventually an arc forms.

- Conductor quench: A conductor can quench due to a non-predicted weakness or overestimation of the critical properties at the design stage. Under aging and cycling some degradation can also take place causing the conductor to quench, this can be the case for Nb₃Sn due to strain. The quench can be initiated also in a joint due to some defect or design imperfection causing excessive heating.

- Loss of coolant: a breakdown of the cryoplant, resulting in the injection of “hot” helium in the coil will certainly lead to quench if not detected.

- Loss of vacuum: the magnets as well as the cryoplant power, are designed taking into account the thermal insulation provided by the vacuum in the cryostat. This vacuum between the coil and the 80 K thermal shield strongly reduces the heat losses by suppressing the convection process. If this vacuum is lost, the magnets will experience a breath of hot gas, and convective exchange with the gas will start. It will result in a heat deposition in the range of 2000 W/m on the conductor. If not immediate, it will shortly lead to temperature increase in the magnet. A Paschen breakdown associated with an arc can happen if the surface exposed to vacuum is taken to high voltage simultaneously to vacuum degradation.

In ITER and in fusion magnets in general, the main defaults, which can be envisaged, are related to leaks, high voltages, and weak points in the conductor or insulation.

2.2 Propagation phase and primary resistive detection

Propagation of quench in superconducting magnets has been extensively studied in the “adiabatic” case relevant of Magnetic Resonance Imaging and Nuclear Magnetic Resonance impregnated magnets [6]. However, propagation in an ITER magnet is not “adiabatic”. ITER magnets are made of CICC such as the Toroidal Field (TF) CICC presented in FIG. 1., where the strands are in tight contact of helium. In the early stage of the propagation, the joule heating generated in the normal zone is transferred to the helium, which consequently
expands. This expansion of helium is the vector of the propagation in two directions with which a propagation velocity $v_p$ (one front) can be associated.

![Image](217x558 to 398x731)

**FIG. 1. ITER TF CICC ($\Phi_{\text{CICC}}=39.7 \text{ mm}$)**

This velocity plays a very important role as the resistance of the normal zone and the corresponding resistive voltage are the parameters of the primary quench detection. As a matter of fact, only the resistive detection can be sufficiently rapid to protect the coil. Due to helium, the propagation velocity is less than in the adiabatic case. Interesting analytical models have been developed 15 years ago [7] but it is clear now that only dedicated codes such as Gandalf [8] and Vincenta [9] can help to estimate the propagation quench velocity $v_p$.

The propagation velocity is a function of the following parameters:

1) Increasing function of volumetric power in the CICC after quench (W/m$^3$)

$$P = \rho J^2$$

$\rho$ = current density in the CICC  $I$ = current in the CICC  $S_{\text{CICC}}$ = CICC section (copper + non copper)  

$$\rho = \rho_{\text{cu}} / \eta_{\text{cu}}$$  $\rho_{\text{cu}}$ = copper resistivity  $\eta_{\text{cu}}$ = copper ratio in the CICC

2) Decreasing function of temperature margin (K)

$$\Delta T_{\text{ma}} = T_{\text{cs}} - T_{\text{op}}$$

$T_{\text{cs}}$ = current sharing temperature  $T_{\text{op}}$ = operating temperature of the conductor

3) Increasing function of length of the quenched initial zone: $L_q$

4) Energy (J/m) and power (W/m) of the initial heat deposition

The resistive voltage $V_t$ at time $t$ after the quench initiation is: $V_t = \rho J (L_q + v_p t)$.

In addition the enthalpy of the steel section of the jacket, which can be different according to the coils, plays a role in slowing down the propagation.

The parameters of the quench detection corresponding to several coils are given as an illustration in TABLE I. The energy to quench the coil is applied in the highest magnetic field zone on a one meter length. The energy is two times the minimum quench energy applied within 100 ms in case of ITER coils and 50 ms for JT-60SA. This is a typical disturbance representative of a disruption. Gandalf has been used for this estimation.
TABLE I: PARAMETERS OF QUENCH DETECTION FOR SEVERAL COILS

<table>
<thead>
<tr>
<th>coils</th>
<th>I (A)</th>
<th>( \rho ) (( \Omega )m)</th>
<th>J (A/mm(^2))</th>
<th>P ( \text{(W/m}^3)</th>
<th>( \Delta T_{\text{ma}} ) (K)</th>
<th>L(_q) (m)</th>
<th>v(_p) (m/s)</th>
<th>V(_t) (1 s) (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER CS</td>
<td>40000</td>
<td>1.08 ( 10^{-9} )</td>
<td>86.4</td>
<td>8.04 ( 10^6 )</td>
<td>0.7</td>
<td>1</td>
<td>2.8</td>
<td>0.5</td>
</tr>
<tr>
<td>ITER TF</td>
<td>68000</td>
<td>1.05 ( 10^{-9} )</td>
<td>91.4</td>
<td>8.8 ( 10^6 )</td>
<td>0.7</td>
<td>1</td>
<td>4</td>
<td>0.6</td>
</tr>
<tr>
<td>ITER PF3</td>
<td>37000</td>
<td>3.8 ( 10^{-10} )</td>
<td>68.2</td>
<td>1.8 ( 10^6 )</td>
<td>2.1</td>
<td>1</td>
<td>0.7</td>
<td>0.04</td>
</tr>
<tr>
<td>JT-60SA TF</td>
<td>25700</td>
<td>5.5 ( 10^{-10} )</td>
<td>109.0</td>
<td>6.5 ( 10^6 )</td>
<td>1.5</td>
<td>1</td>
<td>2.1</td>
<td>0.3</td>
</tr>
</tbody>
</table>

3. Detection and action time available in case of a quench initiation

A quench detection is followed by the opening of current breakers to discharge the current into external resistors and protect the coil. The different phases are presented in FIG. 2.

**FIG. 2. Different phases in case of a quench detection in an ITER coil**

- \( V_t \) is the resistive voltage detection threshold
- \( \tau_p \) is the propagation time, needed for the quench to produce a voltage equal to \( U_Q \): **Phase A**
- \( \tau_h \) is the holding time, a period dedicated to the identification of a quench, for differentiating it from an electromagnetic perturbation: **Phase B**
- \( \tau_{cb} \) is the maximum time needed for the current breakers to open: **Phase C**
- exponential safety discharge of the coil current (time constant \( \tau_{fsd} \)): **Phase D**

During all the detection phase (Phase A→Phase C), the current stays constant in the quenched coil where the quench is propagating. A design criterion for superconducting magnets stipulates that the temperature never exceeds 250 K in an adiabatic approach for the initial quenched cell at the end of the safety discharge [10]. All helium heat capacity and thermohydraulic effects are neglected. Also neglected are the heat capacity of the jacket, and conduction heat transfer to adjacent turns. It aims at avoiding large axial differential thermal expansions in the coil. This method enables to calculate the maximum available detection and action time \( \tau_{DA} \) (equation (1)). The calculation includes the heating at constant current during the time \( (\tau_p + \tau_h + \tau_{CB}) \) and the heating during the fast discharge of time constant \( \tau_{FSU} \) during the energy dump after the current breaker opening. Knowing the opening time of the current breaker, it is then possible to deduce from equation (2) the filtering time \( \tau_H \).
The volumetric heat capacity of the CICC (only cable) is given by:
\[
C_p(T) = \frac{\tau_{FSD}}{dT} = \frac{1}{2} \tau_{FSD} J^2
\]

(1) \( C_p \) is the volumetric heat capacity of the CICC (only cable).

The different characteristic times of the quench detection are given in TABLE II for the ITER CS and TF systems, illustrating the derivation of \( \tau_H \) from (2).

**TABLE II: ILLUSTRATION OF THE DIFFERENT CHARACTERISTIC TIMES OF THE QUENCH DETECTION**

<table>
<thead>
<tr>
<th>coil</th>
<th>I (A)</th>
<th>( \rho ) (( \Omega )m)</th>
<th>J (A/mm²)</th>
<th>( \tau_{FSD} ) (s)</th>
<th>( \tau_{DA} ) (s)</th>
<th>( \tau_{CB} ) (s)</th>
<th>( \tau_{P} ) (s)</th>
<th>( \tau_{H} ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITER CS</td>
<td>45400</td>
<td>1.08 ( 10^{-9} )</td>
<td>98.1</td>
<td>7.5</td>
<td>3</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
</tr>
<tr>
<td>ITER TF</td>
<td>68000</td>
<td>1.05 ( 10^{-9} )</td>
<td>91.4</td>
<td>11.6</td>
<td>2.2</td>
<td>0.5</td>
<td>0.7</td>
<td>1</td>
</tr>
</tbody>
</table>

For \( V_t = 0.4V \):

For \( V_t = 0.4V \):

**Main solutions for voltage compensations**

**4.1 Voltage across the coil**

The voltage \( U_i(t) \) across an ITER coil or an ITER coil subcomponent, neglecting the joints and the current leads, is presented in equation (3).

\[
U_i(t) = R_i I_i + L_i \frac{dI_i}{dt} + \sum_{k=N}^{k=N} M_{ik} \frac{dI_k}{dt}
\]

(3)

The first term in equation (3) is the resistive term to be detected in case of a quench, in the range of 0.1 to 0.5 V.

The second part is the inductive part, which is made of two components:

- The inductive voltage due to the self inductance of the component
- The inductive voltage due the mutual inductance with \( N \) other circuits. These circuits can be other ITER coil components, passive structures or the plasma.

The inductive voltage can be very high in ITER depending on the coil or on the regime such as dwell, plasma discharge or safety discharge of the magnets. It can reach 10 kV across the CS modules or the PF coils during normal operation [11].

**4.2 Voltage compensation**

To eliminate the large inductive voltage components, it is necessary to compensate the voltage across the coil subcomponent to be monitored for the primary resistive quench detection. This means to electrically oppose to the monitored voltage including the resistive voltage, a similar inductive voltage taken across another subcomponent.

The two main compensation methods envisaged for the ITER magnet system are presented:

- the classical compensation by a magnetically as identical as possible subcomponents
the compensation by an integrated test wire situated within the insulation of the conductor in the monitored coil, which is presently one of the reference solution for the ITER TF system. One shall note that the implementation of this wire is costly and difficult especially if the conductor jacket is of square shape.

4.2.1 TF system [4]

The first method applies naturally for the TF systems of large superconducting tokamaks, which are magnetically symmetric during a plasma discharge. This method has been selected for the TF systems of TORE SUPRA, W7-X, KSTAR, JT-60SA and SST1. It can be applied also in ITER by balancing the voltage of two coils or in a more refined way by balancing subcomponents of coils such as double pancakes (DP). Adjustment of the balance is necessary during commissioning.

4.2.2 CS and PF systems [2]

There are no perfectly magnetically symmetric coils subcomponents. A similar solution can be however found using DPs. For instance for the CS, the central difference averaging is used, by balancing one DP voltage against the average of the voltage of the two neighbouring DP voltages (see equation (4)). There are, in the case of the ITER CS system, 120 detectors corresponding to the 120 DPs of the CS. A similar system is applied for the PF system.

\[
\Delta U_{\text{harm}}(t) = U_{\text{harm}}(t) - \frac{\alpha_{i} U_{\text{harm}+1}(t) + \beta_{i} U_{\text{harm}-1}(t)}{2} 
\]

For the CS and PF systems the resulting compensated voltage is not zero due to the imperfect symmetry (see FIG. 3.).

![FIG. 3. Envelope of the maximum of the absolute values of the compensated voltages in CS1L DP during a reference ITER plasma discharge (from TrapsAV)](image)

The selection of \(\tau_{h}\) has to be done according to equation (2), but also by estimating the expected residual inductive voltages after compensation. This estimation is very delicate. CEA has developed a dedicated code (TrapsAV) for the ITER pulsed coils, based on a very precise estimation of the magnetic field map in the tokamak along the plasma scenarios. It enables to calculate the induced magnetic fluxes and to characterize the typical parameters of the quench detection, which are \(V_{t}\) and \(\tau_{h}\). \(\tau_{h}\) has to be selected according to equation (2), but in addition it must be larger than \(\tau_{\text{dis}}\), the largest time during which the inductive signal is
exceeding $V_t$. It has been shown in addition that a 3 s blanking of the quench detection for the ITER CS is necessary and acceptable [2] at quench initiation.

5. Secondary quench detection [5]

A failure of the primary resistive quench detection in spite of redundancy, must be considered. An ultimate secondary and safety related later quench detection is therefore envisaged, accepting substantial damage in the coil in this case. For the ITER TF system, the secondary quench detection is based on thermohydraulic sensors (temperature, pressure, massflow) implemented in the Cold Termination Box (CTB). The CTB is situated at 17 meters from the coil, outside the cryostat, at the end of the cryogenic feeder, where maintenance is possible (see FIG. 4.). The time constant of these sensors is large due to the slow propagation of the quench.

![FIG. 4. Location of the secondary quench detection for the ITER TF system](image)

The transient reaction on the secondary detection sensors has been investigated using Gandalf code, supposing for the TF ITER system an undetected quench (no primary detection) and quench propagation at constant current. As a result, an important backflow occurs in the inlet feeder situated near the quenched zone. It can be used as a secondary detector (see FIG. 5.). As these sensors are considered as safety-class more studies are still necessary for the final selection.

![FIG. 5. Mass flow in feeder channels for an undetected TF quench](image)
5. Conclusion

The primary quench detection in ITER superconducting magnets is based on resistive voltage detection. The selection of the detection parameters is based on the use of the Gandalf code to estimate the quench propagation and on TrapsAV, a code developed at CEA to investigate inductive components in the ITER pulsed coils. For pulsed coils the voltage incertitude can be large due in particular to the complex routing of the wires. For the TF system the estimation is hardly possible as the coil balance is in theory perfect. For this reason the commissioning of the detection system has to be prepared in details, with a first phase dedicated to coil self current ramping and a second phase dedicated to the behaviour of the coils during plasma discharge. In case of failure of the primary detection, a secondary detection is implemented based on thermohydraulic sensors. This safety related sensors are located in the CTB where maintenance is possible.

The observation of existing tokamaks in operation with superconducting magnets can be very helpful to prepare the final selection of the quench detection system and the commissioning phase.

6. References