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**MODELLING OF THE QUENCHING PROCESS IN COMPLEX
SUPERCONDUCTING MAGNET SYSTEMS**

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Modelling of the quenching process in complex superconducting magnet systems

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Abstract—The superconducting twin bore dipole magnet for the proposed Large Hadron Collider (LHC) at CERN shows a complex winding structure consisting of eight compact layers each of them electromagnetically and thermally coupled with the others. This magnet is only one part of an electrical circuit; test and operation conditions are characterized by different circuits.

In order to study the quenching process in this complex system, design adequate protection schemes, and provide a basis for the dimensioning of protection devices such as heaters, current breakers and dump resistors, a general simulation tool called QUABER has been developed using the analog system analysis program SABER.

A complete set of electro-thermal models has been created for the propagation of normal regions. Any network extension or modification is easy to implement without re-writing the whole set of differential equations.

This new, generally-applicable, simulation package is very flexible both with regard to the definition of the network and that of coil geometry. QUABER also serves for the modelling of the quenching process in other superconducting magnets for the LHC such as quadrupoles, tuning quadrupoles, and correction elements.

Results of the simulation of the quenching of 1 meter long LHC dipole models are presented and compared to experimental results.

I. INTRODUCTION

Studying the behaviour in case of transition to the resistive state (quench) is an important aspect of the design of superconducting magnets. The conclusion that one should reach after these studies concerns whether the magnet is self-protected against resistive transitions or not, and how to protect it in case the quenches should threaten the integrity of the magnet.

In the case of superconducting magnets for accelerators, such as the superconducting magnets for the proposed LHC at CERN, one has to distinguish between test conditions (energy extraction by resistors is performed when the transition is detected) and operating conditions (no energy extraction from the quenching magnet). These two different cases, test and machine operation, imply different circuits, each one being a complex network composed of the magnet itself, the power supply, the quench detection device, the protection elements and their electronics and powering systems, resistances, switches, etc. All this can be much more complicated if one considers a string of magnets.

It is important to perform simulations when preparing a test programme for a magnet or to predict its quench behaviour once installed in the accelerator. Results coming from magnet testing establish a perfect feed-back in order to improve the simulation model; so then a more reliable model can be obtained. A general quench program is also a helpful tool for the dimensioning of protection devices (e.g. heaters, current breakers, dump resistors).

Up to now computer programs such as QUENCH [1] and TMAX [2] have been widely used for quench calculations. These programs were written for very specific types of magnets and any modification either in the type of magnet or in the electrical circuit implies large changes in the codes, since the set of differential equations defining the circuit is not valid anymore and the quench propagates in a different way through a different coil.

All these considerations brought the authors to the idea of creating a new quench simulation program with two major conditions: a) coil geometries should be easy to implement; and b) the program should be flexible with regard to the definition of the electrical network, i.e. network extensions or modifications are easy to implement without re-writing the whole set of equations. These two requirements can be accomplished if a System Analysis Program (SAP) is used as a base for the simulation. In addition, the SAP should have the following features:

- 1) Possibility of defining new elements by means of a simulator programming language,
- 2) Capability of communicating with external programs, written in standard languages (e.g. FORTRAN or C) and ability to perform a certain part of the calculations which cannot be done in a straightforward way by the simulator itself (i.e. iterations, quench tracking through the coils),
- 3) Good graphic interface.

The chosen SAP was SABER [3] since it complies with all the points stated before.

II. QUABER: SIMULATING THE QUENCH PROPAGATION

The analog simulator in SABER provides a long list of accessible templates (simulator subprograms which describe the characteristics of a real element) already prepared and included into a standard library. Nevertheless, when one has to model the quench propagation process in a superconducting magnet, new elements must be defined; especially the one corresponding to the quench resistance. This resistance is a non-linear function of temperature and magnetic field; both temperature and magnetic field are non constant over the normal volume, this normal volume being itself time dependent.

The application package has been named QUABER (Quench simulation with SABER) and consists of:

- 1) The simulator itself,
- 2) A collection of templates which define the quench propagation,
- 3) A FORTRAN subroutine library performing the tracking process of the thermal propagation throughout the coils; this library also contains the information concerning the different material properties,
- 4) The electrical netlist file,
- 5) The data file containing the coil geometry and the main electrical parameters such as initial current, self-inductances of the different parts and their couplings, etc.

In order to perform a simulation when studying the quench behaviour of one superconducting magnet type, the user modifies only the files corresponding to the last two points.

A. Inputs

There are several types of inputs in QUABER as can be seen from the previous enumeration, which are analyzed separately:

1) *Cable characteristics*: The cable is defined by its components (superconductor, matrix, insulation) and cross section, the type of impregnation, the cooled perimeter and the voids. These values and the material properties as functions of temperature and magnetic field allow to obtain the curves which give the temperature of a certain region of the windings by knowing both the MIIT number (the integral of the current squared along the time in $10^6 \cdot \text{ampere squared-seconds}$) and the magnetic field for that local area: by considering the heat balance of unit volume of winding [4], we get the expression

$$J^2(t) \cdot \rho(T, B) \cdot dt = C(T) \cdot dT, \quad (1)$$

where J is the time dependent current density, ρ is the resistivity as a function of temperature T and magnetic field B , and C is the temperature dependent heat capacity per unit volume; all these quantities are averaged values over the cable cross-section. This equation leads to the general expression for the MIIT curve:

$$T_{max} = f\left(\int_0^\infty I^2 \cdot dt, B\right). \quad (2)$$

The critical current of the cable as a function of temperature and magnetic field has to be defined as well.

2) *Material properties*: All the cable components and the magnet components which intervene in the quench process (such as metallic parts where energy dissipation can take place because of induced eddy currents) have their properties, as specific heat, electrical resistivity (including magneto-resistance effects) and thermal conductivity, included in the library for that purpose.

3) *Magnet geometry*: Each pole, layer or block is represented by the number of turns. Wedges, separating blocks, are defined by the delay that they introduce into the transversal propagation of the normal zone; the position of the spacers is known by the external subroutine which performs the three-dimensional process calculations. For coils provided with heaters, the simulator has to know their position and the number of turns they cover (i.e. the covered volume). The heater performance is represented by the delay between the quench detection and the moment at which the resistance growth underneath the heaters starts.

4) *Electrical network*: The user fixes easily the electrical network in which the magnet is working by means of a general netlist language (really similar to languages of other commercial analog simulators, such as SPICE [5]), so then the elements to be included in the circuit and their connections are established.

5) *Magnetic field map and load line*: The magnet is subdivided in domains where the magnetic field is assumed to be constant. Each one of these domains is identified by the average of the magnetic field over its volume, according to the working point on the magnet load line. Usually, the number of domains per coil is taken between 5 and 10, depending on both the coil size and the magnetic field shape.

B. Simulation process

SABER allows working with a large range of elements having non-linear behaviour (e.g. diodes, quench resistances). In order to get an idea of how the simulation is worked out by QUABER, let us explain briefly the solution process (see Fig. 1).

The transient behaviour of a system is determined by a set of differential equations. The simulator performs two transformations on the set of equations in the circuit [6]:

Fig. 1. SABER's solving method.

1) One of the three different integration methods is used in order to transform the set of differential and algebraic equations into a set of non-linear algebraic equations.

2) A non-linear solution algorithm (either Newton-Raphson or Katzenelson) is used in order to transform the non-linear equations into a set of linear equations; after this, the set of linear equations is solved.

One of the main variables for the analysis is the truncation error variable, which is an upper bound on estimated errors produced when the simulator replaces the original set of differential equations with a set of non-linear algebraic equations. Calibrating the accuracy of the model is an essential study before performing any analysis.

C. The quench propagation

The locus where the quench starts is fixed by the user. At time equal zero the transition begins propagating with a velocity v which comes out from solving the general differential equation

$$\frac{\partial}{\partial z} \left(k \cdot A \cdot \frac{\partial T}{\partial z} \right) - v \cdot C \cdot A \cdot \frac{\partial T}{\partial z} - h \cdot P \cdot (T - T_0) + G \cdot A = 0, \quad (3)$$

where the propagation is assumed to develop along the z axis; T is the temperature profile, function of time and coordinate z ; C is the heat capacity per unit volume; k is the temperature dependent thermal conductivity in the propagation direction; A is the cable total cross-section; h is the heat transfer coefficient; P is the wetted perimeter; T_0 is the bath temperature and G is the heat generation per unit volume of cable, for which the current sharing process is taken into account.

The initial velocity can be either given as input or calculated by using (3). Concerning the second possibility, up to now this value is calculated separately, introduced as input into the application program and corrected according to the current level by the following approximation:

$$v = v_0 \cdot \frac{I(t)}{I_0} \cdot \left(1 + a \cdot \frac{I(t)}{I_0} \right) \cdot \frac{1}{1+a}, \quad (4)$$

where v and I are the quench velocity and the current through the magnet, respectively; a is a parameter which includes cable characteristics such as the critical current at zero magnetic field, the critical magnetic field at zero current, as well as the load line for the natural quench area; usually, a varies within the range from 0.2 to 0.5. The subscript "0" designates initial values.

In the near future, a new FORTRAN subroutine will be incorporated to QUABER so that the longitudinal quench velocity can be calculated according to (3) by a finite difference method.

The transverse propagation from turn to turn can be characterized either by the transverse quench velocity, given by the formula [4]

$$\frac{v_{\text{transverse}}}{v_{\text{longitudinal}}} = \frac{C_{\text{avm}}}{C_{\text{av}}} \cdot \sqrt{\frac{k_{\text{transverse}}}{k_{\text{longitudinal}}}}, \quad (5)$$

where C_{av} is averaged over the total cross section and C_{avm} is taken over the metallic constituents only; or by the so-called turn-to-turn delay. This delay represents the time for the quench to go from one turn to the next through the insulation between them. Normally, the value of the turn-to-turn delay is either obtained from experimental data or evaluated from (5).

For graded coils (multilayer geometries wound with different types of cable) the transversal propagation from one layer to other is simulated by characterizing the effect of the insulation between them as for the turn-to-turn propagation. The longitudinal propagation from layer to layer can be allowed (for instance, introducing a certain delay for the quench to go from one cable to the other through the solder; this delay can be evaluated from experimental data).

In the case of a magnet provided with heaters, there is another important parameter: the heater delay, that is the time which elapses from the moment the quench is detected until the resistance growth under the heaters is observed. Usually the value of the heater delay is obtained from experimental measurements.

The quench detector is also simulated and the detection threshold (the resistive voltage across the magnet) can be stated via input.

As soon as the winding volume underneath the heaters has become resistive, this normal volume grows by longitudinal and transversal propagation to the rest of the coil. Therefore, two different areas are subject to quench propagation analysis: the original quenching area and its further propagation, and the zone underneath the heaters and its further propagation.

Concerning the appearance of new resistive fronts by coupling losses in the cables under the effects of a varying magnetic field, the so-called "quench back" process, the main parameter to give as input is the critical value of dB/dt (or the critical dI/dt). If this value is exceeded, new resistive volumes appear in the magnet coils (the user can establish how large these volumes are and after which delay the resistance increases once the critical dB/dt is reached). Normally, the values of these parameters are obtained from experimental data.

D. Eddy currents in metallic parts

The effect of induced eddy currents in metallic parts of the magnet, when discharging the magnet after a quench, can be also taken into account. For that purpose, new circuits coupled with the magnet coils are considered.

E. Output

A user-friendly graphic package allows the presentation of temperatures and electrical parameters versus time for turns, layers and poles inside the magnet and for any selected circuit element outside the magnet. Coil temperature maps versus time are obtained in a rather simple way.

III. THE QUENCH SIMULATION FOR THE LHC SUPERCONDUCTING MAGNET SYSTEM

One of the main goals of the quench simulation with QUABER for the LHC magnet system was to study whether the magnets could withstand a resistive transition without any protection (natural quenching coils) or if heaters are required in order to accelerate the resistance growth in the coils and get a faster decay of the magnet current after the quench (heater protected coils).

Simulations were performed for the 10 meter long, twin bore dipole (15000 A as nominal current). The conclusion after these studies was that heaters were required; otherwise, the hot spot temperature goes beyond 600 K and the maximum layer voltage reaches values above 1300 V. The quench simulation package has also allowed us to design and optimize the heater configuration for that magnet, analyze the eddy current flow through the vacuum pipe in case of a quench, and determine its thermo-structural behaviour in case of a sudden transition to the resistive state [7].

QUABER has been also used for the quench behaviour analysis in the lattice quadrupoles, the tuning quadrupoles and the combined sextupole and corrector dipole magnets for the proposed LHC.

Quench simulations were also performed for the Twin Aperture Prototype (TAP Magnet). Results obtained from these simulations (with rather pessimistic assumptions) show maximum temperatures around 350 K and maximum layer voltages in the order of 700 V, with 9500 A magnet current before the quench [8].

At present QUABER is also being used for simulating the environment of the LHC machine, where a large number of dipole magnets are connected in series. The transient behaviour after a quench in one or several magnets at the same time is being analyzed.

IV. COMPARISON BETWEEN EXPERIMENTAL RESULTS AND SIMULATIONS FOR THE 1 METER LONG LHC DIPOLE MODELS

Several series of tests have been recently carried out on the 1 meter long LHC dipole models [9]. Calculations with QUABER have been performed in order to simulate the quench propagation throughout the coils of those magnets. Once the transition was detected, the power supply was switched off after few milliseconds and the magnet discharged through a 20 milliohm dump resistor, which dominates the quenching process (see Fig. 2).

Fig. 2. Electrical scheme for the twin aperture model quench simulation.

Fig. 3. Comparison between experimental data and simulation results for the quenching pole voltage and the current decay after a quench of a LHC dipole model.

Results coming from the data recording system gave information -among others- on magnet current reached before quenching, the resistive voltage rise rate just after the quench started (from which we estimated its initial velocity), the current evolution versus time and the MIIT number curves.

Fig. 3 shows the voltage across the quenching pole and the current decay in the magnet after one of the quenches, compared to the simulated curves. The hot spot temperature was 80 K according to the experimental MIIT number; the calculated value was 83 K. No heaters were used for the quench here presented.

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