Quench Propagation in YBCO Racetrack of a Rotor Winding

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Abstract: High temperature superconductors (HTS) such as YBCO coated conductors show great promise for future application where high magnetic field is needed. The superconducting state only exists under a critical surface defined in the (J,T,B) space, with J being the current density carried by the superconductor, T the operating temperature and B the applied magnetic flux density. Therefore electro-thermal instabilities can occur when one of the critical values of J, T or B is exceeded. Quench is the process by which a current carrying superconducting conductor changes rapidly and irreversibly from the superconducting state to the non-superconducting state (normal state) creating a dissipative area leading to an increase of the temperature. As a result, a hot spot may potentially damage the superconductor if left unprotected. During a quench in a HTS magnet, the normal zone spreads throughout the coil, raising the voltage across the winding that can be used for detection. A detection voltage threshold is implemented to detect the quench and take protective actions. When the voltage reaches the set threshold, the current in the winding is decreased exponentially in order to simulate the discharge of the energy stored in the magnet in an external resistor. A COMSOL® model was developed to simulate the quench propagation in a HTS magnet as well as the detection and protection. The model uses thermal and magnetic studies and is highly non-linear and anisotropic with the magnetic field. The winding electrical and thermal properties have been homogenized so as to speed up the simulation. The quench analysis of an YBCO racetrack is studied with varying parameters, including operating temperature, current density and conductor topology. COMSOL Multiphysics® was used in this study because of its ability to perform multiphysics simulations, handle highly non-linear problems and its parametric analysis capabilities allowing for automated determination of the minimum quench energy.

Keywords: quench simulation, YBCO, thermal analysis

For the design of superconducting devices, quench protection is a very important issue. Therefore the limits of safe operation of the superconductors must be well understood. A model implemented in COMSOL is used to simulate quench behavior in the rotor winding of a superconducting machine. The equations implemented are described in the first part of this paper. The second part shows, how the model and quench detection were implemented in COMSOL.

1-Physical Behavior

1.1-Quench phenomena

Superconductivity is the property of some materials to exhibit nearly zero electrical resistivity when carrying DC currents. Superconductors present this characteristic is a domain defines by a critical surface in the space (temperature, magnetic flux density, current density). Quench is the process by which a superconductor changes rapidly and locally from the superconducting state (sc state) to the non-superconducting state (normal/resistive state). A quench induced by local disturbances resulting in a local temperature elevation. During a quench the current flows out of the superconducting material and flows in the resistive parts of the conductor, creating local Joule losses and creating a voltage across the winding. The quench is an avalanche phenomenon leading to a normal dissipative zone propagating in the coil. The quench is characterized by a peak temperature and propagation velocity. Figure 1 schematically represents the current flow around a hot spot in the conductor.

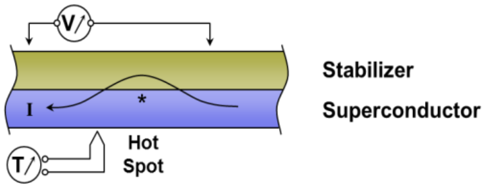

Figure 1: quench phenomena

High temperatures may degrade or physically damage the conductor, either of which may damage the magnet permanently [1], if a detection set is not properly implemented. The aim of the detection is to detect the quench rapidly and discharge the energy stored in the inductance in an external dump resistor. During the discharge of the current, the energy remaining in the inductance is still heating the normal zone of the winding. To insure a good recovery of the system after a quench and avoid damage from thermally induced stress, the maximum admissible temperature during a quench event was set to 300 K in the studies. For the quench, the detection threshold and the time taken to discharge the coil are key parameters for the design of the protection circuit. The simulations presented consider a rotor winding wound with YBCO superconducting tapes.

1.2-Model description

The problem was implemented as a 3D homogenous anisotropic model based on equivalent electrical and thermal properties of the winding pack. Electrical and thermal equivalent resistances can be calculated to assess the equivalent electrical and thermal conductivities of the tape[2]. The YBCO tape geometry and data used in the model were provided by SuperPower Inc. and Cryocomp®. The YBCO tape configuration is shown below (Figure 2).

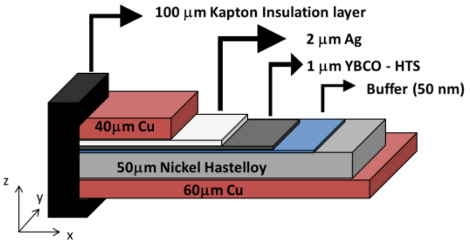

Figure 2: YBCO tape

In order to compute the temperature in the winding, the heat equation is used:

$$\gamma C_p(T).\frac{\partial T(x,y,z,t)}{\partial t} = \nabla.(\bar{\bar{k}}(T,B).\nabla T(x,y,z,t)) + Q_J(\mathrm{T,B})$$

With Q_J: heat dissipation-Joule losses (W/m^3), γCp: density*heat capacity (J/m^3/K) and

$$\bar{\bar{k}}(T) = \begin{bmatrix} k_x(T) & 0 & 0 \\ 0 & k_y(T) & 0 \\ 0 & 0 & k_z(T) \end{bmatrix}$$

The matrix k represents the thermal conductivity of the model in the 3 dimensions. The model operates in a wide range of temperature so non-linear thermal conductivities of materials used in the model were implemented. The electrical resistivity of the superconductor depends on current density, temperature and magnetic field. The COMSOL simulations include:

- Steady-state magnetic study computed first to evaluate the magnetic field distribution in the winding
- Time-dependent thermal analysis using the magnetic field distribution calculated before defining the heat source.
- The current in the coil was consider constant during the simulations.

1.3-Electrical model

The electrical model was computed using the equivalent electrical resistivity of the winding in the longitudinal axis of the tape. Layers of Kapton insulate electrically the tape in the transverse direction. In Figure 2, the two copper layers shown in figure 1 are merged into one. In the longitudinal axis the layers are in parallel as shown in Figure 3.

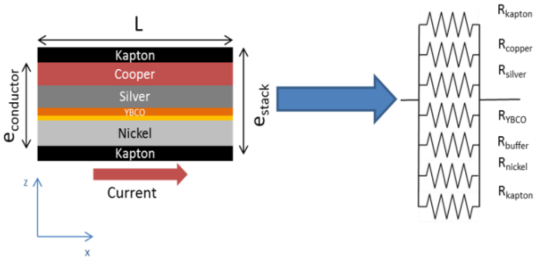

Figure 3 :Equivalent

The equivalent conductivity of the tape can be calculated in COMSOL using the configuration of Figure 2.

Locally the Joule heat source can be expressed as [4]

$$Q_J = \rho(J,T,B).J^2$$

With ρ the equivalent electrical resistivity of the tape, J the current density in the superconducting layer tape. Figure 4 shows the Joule losses as a function of temperature at 2 Tesla.

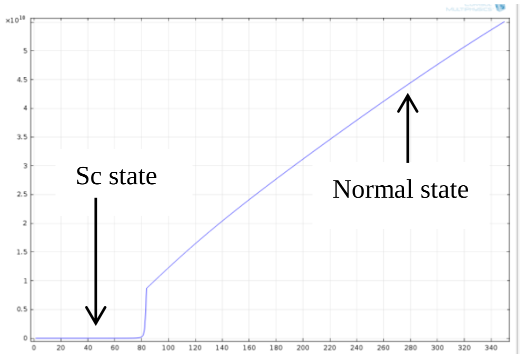

Figure 4: Joule losses against temperature at 2 Tesla

Below the critical temperature, the equivalent electrical resistivity of the coil is mainly the resistivity of YBCO because its resistance extremely small and lower than the resistances of the other layers of the tape. When the temperature rises above the critical temperature, the current flows in the other layers (Figure 3) and the equivalent resistivity of the coil increases.

1.4-Thermal model

The equivalent thermal conductivity of the tape can be calculated if the conductivities of all the layers are known. Thermal conductivities for the different materials composing the tape can be found in literature. The equivalent thermal resistance is calculated as follows:

$$R_{th}(T) = \frac{L}{k(T).A}$$

With k(T) the thermal conductivity of the material (W/m.K), L the length of the considered part (m) and A the cross-section area (m^2). The resistance R_{th} is in K/W. First the equivalent thermal resistance is calculated for each direction of the tape, then the equivalent conductivities are estimated.

The thermal conductivities of Copper, Silver, Nickel, YBCO and Kapton are extracted from CryoComp©. The conductivity is much higher along the direction of the tapes in the winding.

The specific heat capacity can be calculated using the equation below if the heat capacities of all layers and theirs densities are known,

$$C_{eq} = \frac{\sum m_i \cdot C_i}{\sum m_i}$$

where C_{eq} is the equivalent heat capacity and C_i the heat capacity (in J/kg/K) and m_i the mass, of each layer (kg).The heat capacities of Silver, Nickel, Kapton, YBCO and Copper are obtained from Cryocomp©.

1.5- Detection set

Previous work validated the simulation of quench propagation using COMSOL with experimental data, but without the detection set and the current discharge. During a quench, the voltage increases across the winding and when it reaches a value above the voltage threshold Vt (set as 400 mV in this study), the coil is discharged in an external resistor. The energy remaining in the coil is discharged following a decreasing exponential rate (with τd the time constant of the exponential decrease); simulating a discharge of the remaining energy into a dump resistor [5].

2-Comsol model

2.1-COMSOL Geometry

The geometry of the whole machine is shown in Figure 4.

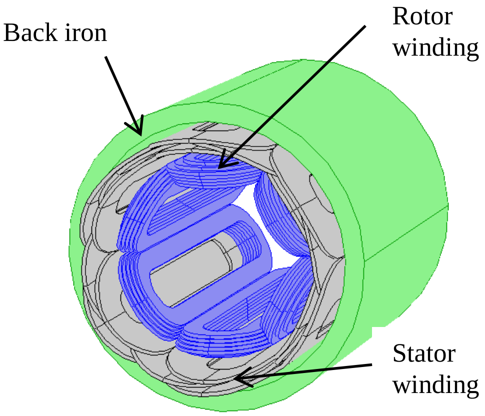

Figure 5: machine geometry

The study was done on a racetrack part of the rotor winding. The geometry of the racetrack coil is shown in figure 5. With the use of proper boundary conditions, only a quarter of the total racetrack is modeled to study the quench. The tape z-axis in part 1 is along the y-axis

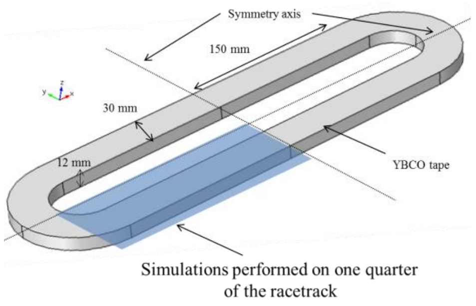

Figure 6: windings configuration

2.3-Study

Due to the magnetic field and temperature dependency of the problem, two studies are implemented in the study:

- *Magnetic field*: to calculate the magnetic field distribution in the geometry.
- *Heat Transfer*: to calculate the temperature in the winding.
- *Global ODEs* and *DAEs*: set equations for detection set.

The magnetic field is performed using stationary solver because the current density in the winding was set as constant during computations. The Heat transfer is time dependent.

2.3.1-Magnetic field physics

The boundary conditions of the simulation domains are set as in figure 7.

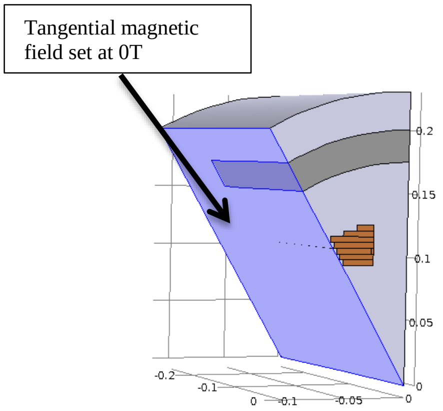

Figure 7: Simulation domain

This symmetry boundary in blue in figure 7 is set with the tangential component of the magnetic field at 0 Tesla. The others boundaries are set as *Magnetic Insulation*, with the normal component of the magnetic field at zero.

The aim of the magnetic field study is to calculate the magnetic field distribution in the coil. The peak value of the magnetic field is used to verify the current margin of the YBCO tape.

External current density

An external current density in set the winding (blue part in figure 13).

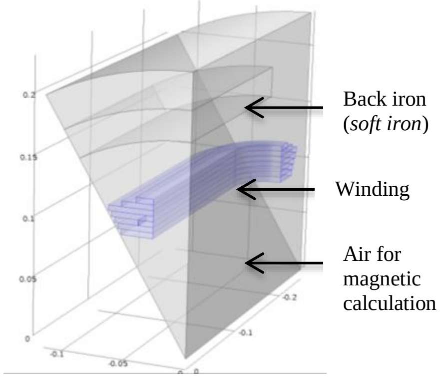

Figure 8: External current density in the model

The current density distribution in one coil and the magnetic flux density in the coil plane are shown in figure 9.

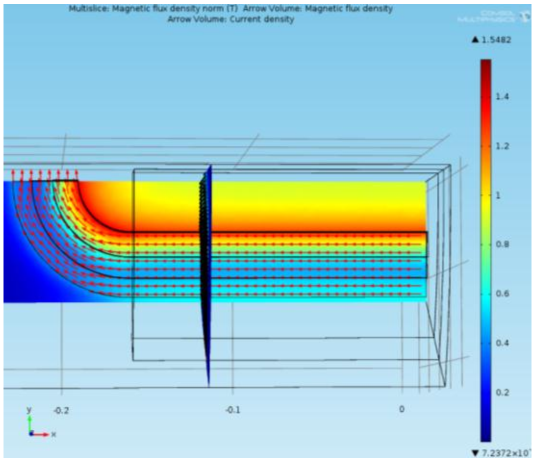

Figure 9: Current density in the winding

2.3.2-Quench ignition

Heat source

A heater was modeled in the winding (in blue in figure 10) to trigger the quench, its width and thickness are the same as the tape. A pulse of heat is generated to drive the surrounding conductors out of the superconducting state and induce an electro-thermal instability.

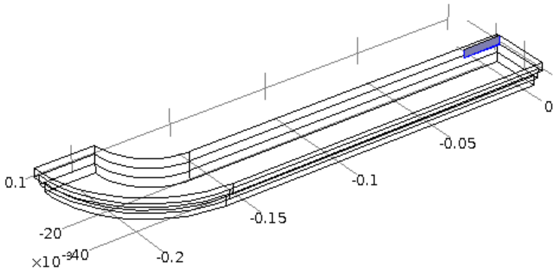

Figure 10: Quench trigger

The following power profile was implemented in the heater:

P_{tot}= pulse.rect1(t)

With pulse the value of the input power and rect a rectangle function.

2.3.4-Computing values

Inductance

In order to calculate the inductance of the winding, a probe integrates the magnetic energy density in the all volume as shown in the following equation.

$$W = \frac{1}{2}.L.I(Top)^2$$

With W the magnetic energy store in the volume (in Joules), I the current flowing into the coil at T_{op} in Amps and L the equivalent inductance of the volume.

Voltage across the coil

Simulations are performed in adiabatic conditions; the heat source in the winding is equal to the electrical power in the coil. A second probe evaluates the total heat source generation in the winding. The following equation allows for the calculation of the Voltage threshold in the coil during a quench:

$$Q = V.I(Top)$$

With Q the total heat source in Watt, V the voltage drop across the coil (in Volt), and I the current flowing into the coil in Amps.

2.3.5-Protection circuit

In COMSOL, some equations have to change when the voltage across the winding is higher than the voltage threshold.

A variable t_1 is set as:

$$t_1 = (V > Vt)$$

With V_t the voltage threshold, and V the voltage in the coil. Before the quench is detected the variable t_3 is set to zero. When the voltage is higher than 0.2 V, then t_1 is equal to 1 for the first part of the current discharge. t_3 is set as :

$$t_3 = \int t_1 \, dt$$

When the voltage is above the voltage threshold, t_3 will increase from 0 to a non-zero value and stay different from zero even if the voltage becomes lower than the threshold during the discharge.

t_2 is a variable defined to go as a step from 0 to 1 when t_3 is different from 0. The value t_2 is a logical signal to trigger the detection. In order to get the time of detection t_6, integration is also used with the intermediate variable t_5 as follows.

$$t_6 = \int t_5 dt = \int (t_2 < 1) dt$$

When the quench is detected, an exponential decrease of the heat source is implemented to mimic the decrease of the current and the Joule losses in the winding. The voltage detection implementation is summarized in the figure below.

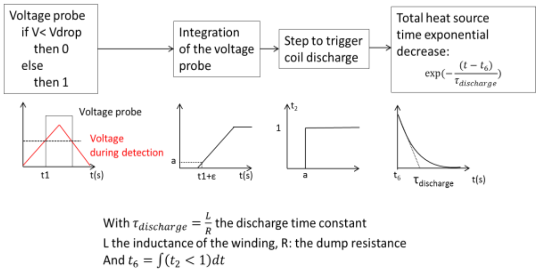

Figure 11: COMSOL detection set implementation

3-Results

3.1- Quench phenomena

Simulations were performed with an operating temperature of 77K and a Heat pulse of 25 W during 31 ms. The maximum temperature and voltage in the winding versus time are plotted in figure 12.

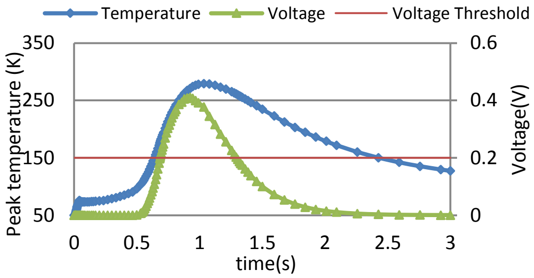

Figure 12: Quench propagation in the winding

The quench propagates in the winding as shown as Figure 13. The plot shows the iso-surface of the Joule losses created during the quench.

3.2-Normal Quench Propagation Velocity

The velocity of the normal zone in the winding can be calculated from the COMSOL simulations. The spreading of the quench is an issue because, with YBCO tape, the velocity of the quench is an order of magnitude lower than for low temperature superconductors such as NbTi [6], as a result, the hot spot temperature is much higher and potentially harmful for the winding. In order to assess the normal propagation velocity, the total heat source along the three main axes are plotted as function of time. When the tape goes out locally from the superconducting state, Joule heating occurs, and the propagation of the normal front can be plotted. Figure 14 shows the propagation of the quench along the x-axis at 40 K

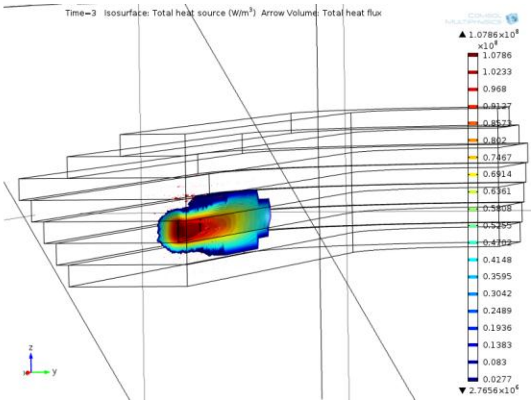

Figure 13 : Quench propagation in the winding

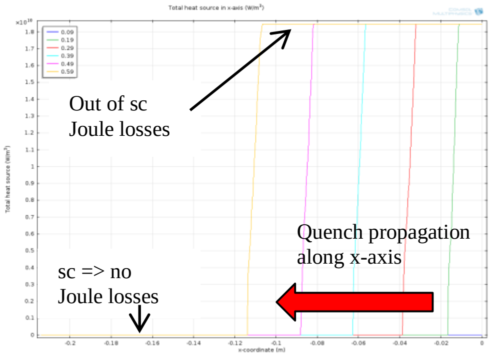

Figure 14: Total heat source propagation along the x-axis

The total heat source is plotted versus position along the x axis and allows for the calculation of the normal zone propagation velocity. The normal zone propagation velocities are plotted versus the copper layer thickness in the tape.

When the thickness of the copper layer in the tape increases, the normal zone propagation velocity increases, making quench detection form the voltage very challenging and leading to high hot spot temperatures.

3.3- Quench detection

Quench simulations were performed with different time constant values for the current discharge; the simulations are performed at 30% current margin and an operating temperature of 77 K.

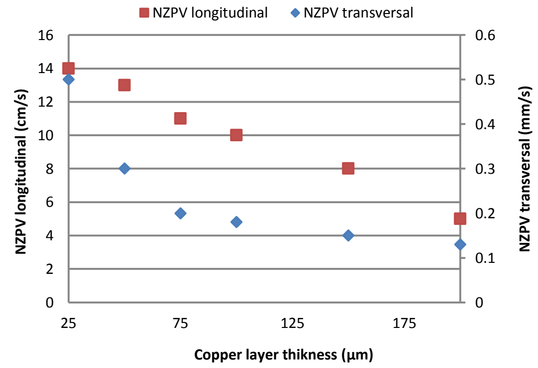

Figure 15: Normal Propagation velocities

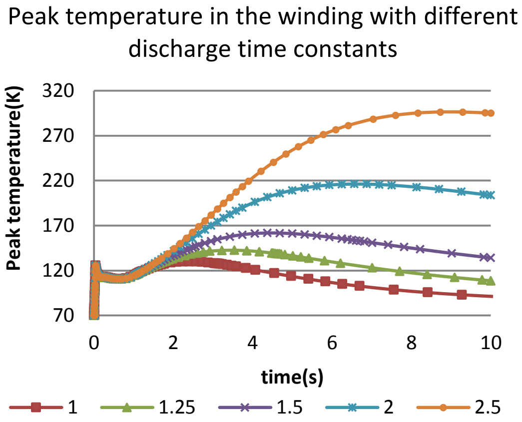

Figure 16: Peak temperature at different time constants

Figure 16 shows the peak temperature in the winding as function of time with different discharge time constants. The peak temperature increases with the discharge time constant, thus imposing low inductances and high current operation for the winding in order to be safely protected against quench.

Conclusion

COMSOL was successfully used to develop a parameterized model able to simulate quench propagation and protection for superconducting coils. The simulations showed very promising results that will eventually need to be validated experimentally.

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